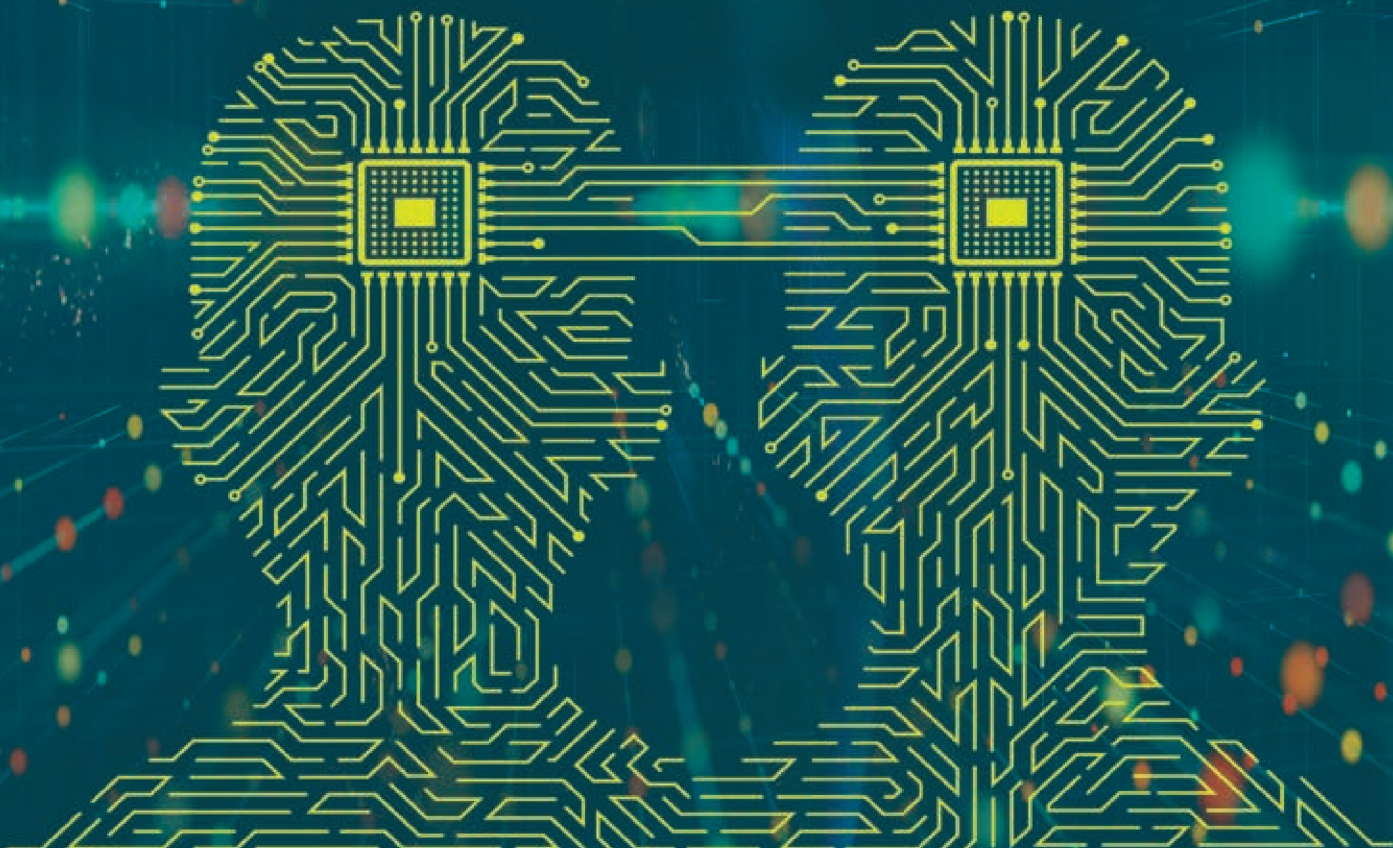
IEEE power&energy magazine

Volume 22 • Number 1 • January/February 2024

for electric power professionals

Digital Twin Solutions For Power Systems

Transitioning to a Clean Energy Future



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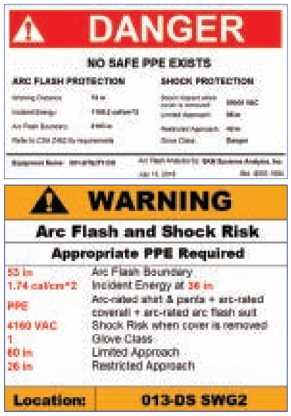

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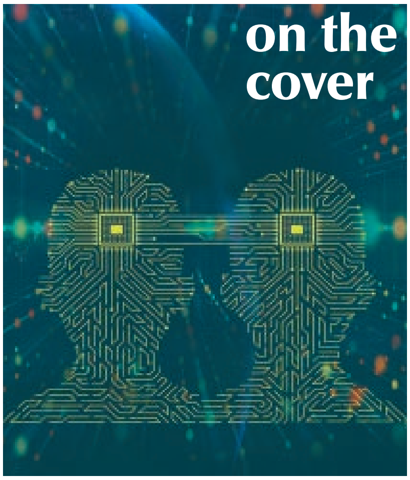

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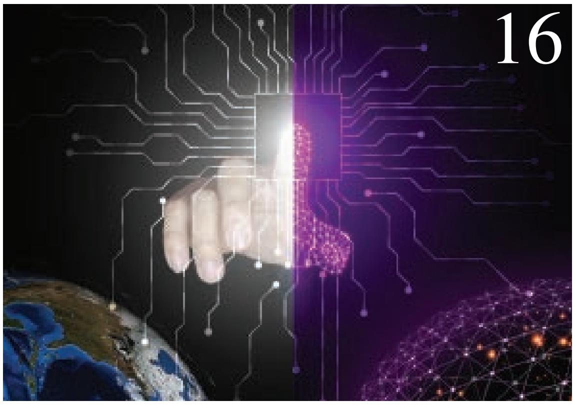

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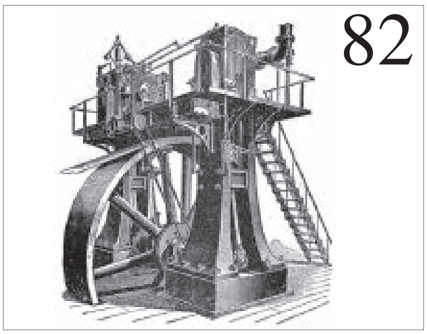

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Digital Object Identifier 10.1109/MPE.2023.3339354

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IEEE Power & Energy Magazine

IEEE Power & Energy Magazine (ISSN 1540-7977) (IPEMCF) is published bimonthly by the Institute of Electrical and Electronics Engineers, Inc. Headquarters: 3 Park Avenue, 17th Floor, New York, NY 10016-5997 USA. Responsibility for the contents rests upon the authors and not upon the IEEE, the Society, or its members. IEEE Operations Center (for orders, subscriptions, address changes): 445 Hoes Lane, Piscataway, NJ 08854 USA. Telephone: +1 732 981 0060, +1 800 678 4333. Individual copies: IEEE members US$20.00 (first copy only), nonmembers US$89 per copy. Subscription Rates: Society members included with membership dues. Subscription rates available upon request. Periodicals postage paid at New York, NY, and at additional mailing offices. Postmaster: Send address changes to IEEE Power & Energy Magazine, IEEE Operations Center, 445 Hoes Lane, Piscataway, NJ 08854 USA. Canadian GST #125634188
Printed in U.S.A.

Innocent Kamwa

from buzzword to solutions

digital twins in power systems

THE DIGITAL TWIN CONCEPT has been around for a while—as early as 2002, according to *Wikipedia* and the authors in this issue. However, my first encounter with this concept was just about five or six years ago. Around that time, Gartner reported the entering of digital twins into mainstream use: 75% of companies implementing the Internet of Things were already using digital twins or planned to within a year. My organization was contemplating digital twins as an enabling technology for grid modernization. During the process of road mapping the strategic innovation, we were asked how/where to position and prioritize this emerging research field in the transmission portfolio. We had two camps: networks versus assets. In the end, upper management, advised probably by consulting firms, such as McKinsey or Gartner, assigned the digital twin track to the asset group and excluded it from network research activities. Applying the digital twin buzzword to "networks" was deemed an abuse of language—a source of confusion in use case definitions and business value analyses of digital twins.

As a network engineer, I was naturally upset by this decision because, at that time, I was assimilating "detailed real-time simulation" with digital twins in an automatic way. Today, I realize in retrospect that this was a far stretch. Simulation is key for digital twinning, of course. It is also key for network planning and operations. Some aspects of simulation tools, processes, and requirements are even standardized and mandated by regulatory bodies, such as North American

Digital Object Identifier 10.1109/MPE.2023.3331189
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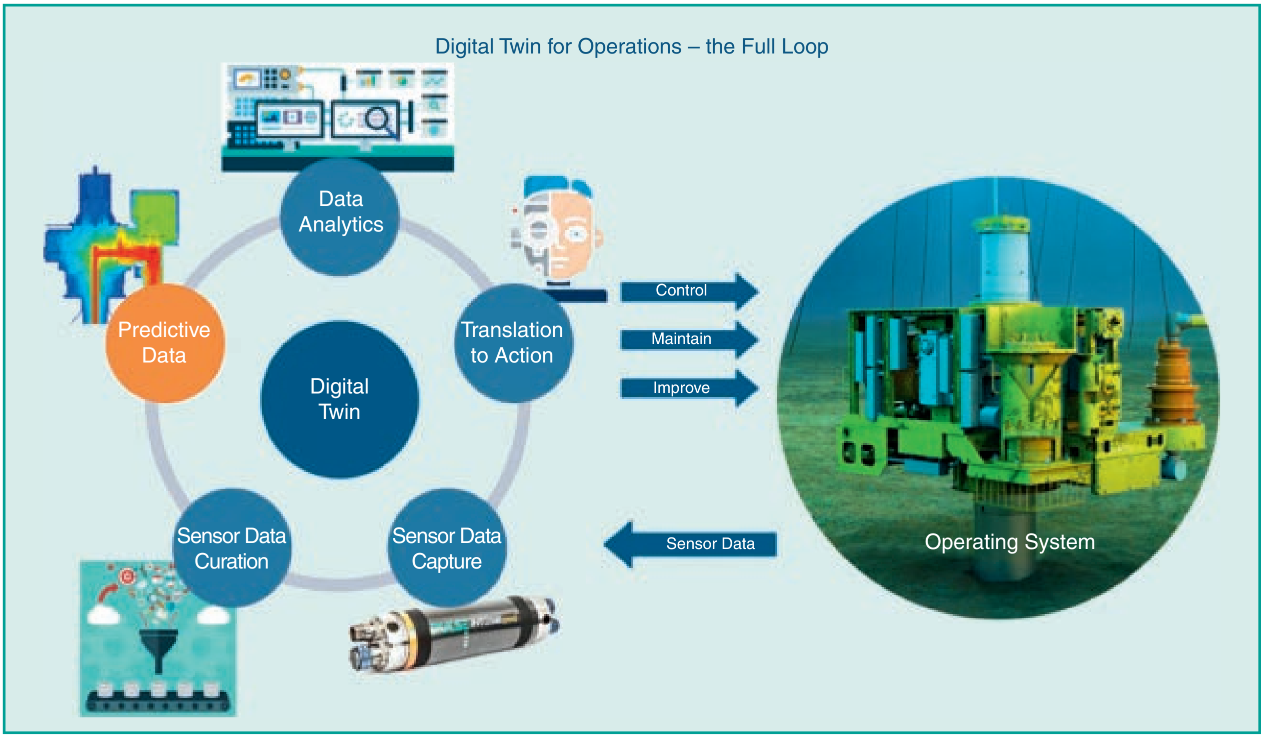

figure 1. The role of the digital twin in energy operations. (Source: https://siemens.com; used with permission.)

Electric Reliability Corporation and nuclear power agencies. However, a digital twin is more than a simulator (Figure 1). An offline—or even real-time—simulator of an object does not qualify as a digital twin of that object.

Although various definitions of *digital twin* exist, it is common to consider a digital twin to be a digital model that faithfully reconstructs an object, an operation process, or a system comprising multiple objects (GE Digital, 2016). The digital twin is not only a perfect replica of an object at a specific time, but it also includes the process the object went through from its conception to its final state. As a result, we can understand the life span of the item in its entirety, even after it has been delivered and the 10- to 30-year warranties have expired, which is critical in the capital-intensive energy sector. A digital twin, therefore, provides both the constituent details and the operational dynamics of an element of the Internet of Things (Figure 2) throughout its existence.

In isolation, the digital twin is a weak technology whose business value is limited.

From a network viewpoint, the energy management system—with its built-in supervisory control and data acquisition hosting a huge number of measurements devices, which are distributed at all electrical nodes, constituting the grid—is a sort of digital twin of the power grid. However, this doesn't meet all of the terms of reference for a digital twin. According to the Singapore Electric Utility, which claimed to have operationalized the first "Digital Twin for National Power Grid" (SP Group, 2022), the latter consists of two interacting building blocks: assets twins, for the health management of grid assets (such as substations, transformers, and cables), and network twins, used to assess grid economics, security, and reliability when connecting new energy sources or consumers to the grid and operating the grid routinely. In this sense, developing a digital twin of the grid requires close cooperation between network and assets experts.

In isolation, the digital twin is a weak technology whose business value is limited. Only collectively, as a system of digital twins, can this technology enable a true sustainable digital transformation. Complexification of the digital twining of many components to achieve an ultimate systemwide operational, economic, or societal goal is not relevant for autonomous manufacturing only, as once thought. Think about the "Earth digital twin," illustrated in Figure 3, that is being developed in Europe to enable the green transition. Such a digital twin is envisioned as a federated infrastructure for both real or simulated data production and user access. It is accompanied by interactive tools to allow users to directly intervene and perturb the digital twin workflow. Such a construct, therefore, includes complex meteorological, energy system, and sociotechnical models for data generation (National Grid ESO, 2022).

Similarly, the definition of *digital twins in power systems* (*DTiPS*), as posited in the first article of this special issue, is an integration of model, data, and functions overlapping at least two physical or functional domains. However, this is only part of the equation since power systems are embedded in weather systems and, more broadly, in the smart cities. Social systems (community, political, cultural, economic, etc.) are equally embedded in climate systems. Social systems and energy systems are mutually dependent, so the business goals and functionalities of the grid operator or grid owner cannot be easily achieved in isolation. The energy justice (National Renewable Energy Laboratory, n.d.) and smart communities themes, so prevalent in

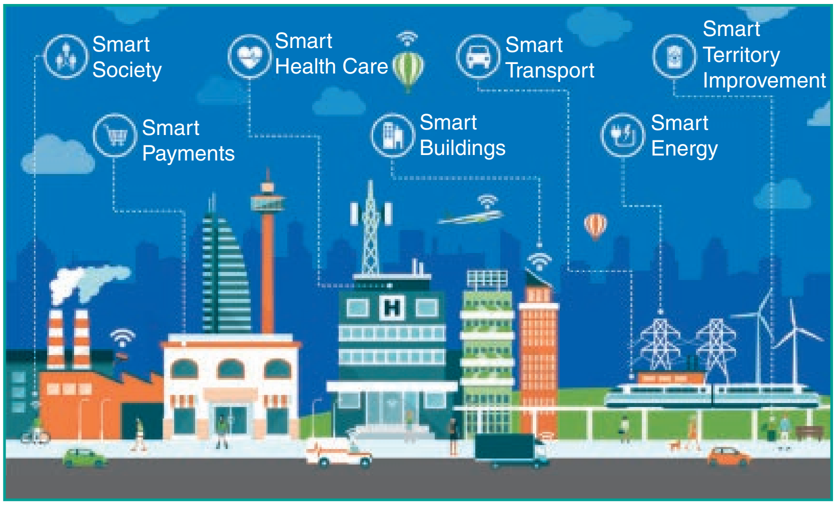

figure 2. The Internet of Things. (Source: https://www.iot-now.com/2017/09/25/67259-everything-can-smart-key-traits-newest-smart-cities-part-1; used with permission.)

figure 3. A digital twin of Earth for the green transition. (Source: Nature Climate Change, Freepik; used with permission.)

In This Issue

The transition to a clean energy future requires a thorough understanding of increasingly complex interactions among conventional generation, network equipment, variable renewable generation technologies (centralized and distributed), and demand response, among others. Secure and reliable operation under such complex interactions requires a more extensive and interactive use of data and models between different power system equipment and networks, both cyber and physical; this also includes transmission and distribution networks and microgrids, their control and protection systems, and multiphysics and domains. The term *digital twin* has recently emerged to encompass the increasing need for a higher quality and quantity of data and models as well as enhanced integration of the aspects discussed, establishing a single source of truth. The seven articles in this issue cover a wide range of topics related to digital twins, including the definition, applications in transmission and distribution systems and microgrids as well as energy systems in general, and the interactions between cyber and physical power systems:

- Noting the sometimes inconsistent use of the term *digital twin*, [A4] focuses on developing an unambiguous definition of *digital twins in power systems* (*DTiPS*) as a virtual representation of an existing or future real object. As proposed, DTiPS comprises at least two domains, for example, in the form of several physical power system equipment pieces (e.g., protective devices, overarching power systems, or a combination). These domains are coupled with bidirectional communication with the respective real object and between themselves. Another dimension is the coverage of various time horizons of interest, ranging from long-term planning to the operational and implementation aspects.
- The application of digital twins in real-time and near-real-time power system operation with a focus on energy management systems and distribution management systems to achieve a higher level of process automation and certainty in decision making is the focus of [A5]. Key enablers are improved measurements and data processing as well as accurate power system models. The key objectives are better integration of the physical power system and IT domains, improvements in online and offline dynamic security assessment decision making, and the determination of the level of "trust" or confidence accounting for varied levels of uncertainty when making various operational decisions.
- The second application of digital twins discussed in this issue is found in [A6], which focuses on bringing together various aspects of microgrids, including the control, protection, maintenance, real-time operation, real-time simulation, and testing, allowing for consolidated decision making. An end-to-end integration, ranging from the device level (e.g., loads or distributed energy resources) to the interaction with the distribution system operator, is considered.
- The interaction between the cyber and physical power systems via a "gateway" layer and their delineation is discussed in [A7]. A focal point of this article is the coordination of the key objectives of various stakeholders, including consumers, producers, grid operators, and governments, and its impact on designing the infrastructures required for the digital twin. This is demonstrated on a "self-organized" voltage control strategy applied in a distribution network.
- Recognizing the emerging importance of the interactions between cyber and physical power systems, [A8] is the second article devoted to this topic, with the primary focus of leveraging digital twins to build a resilient "control room of the future" against cyberattacks through the use of artificial intelligence. This approach allows an understanding of the impact of cascaded failures due to cyberattacks, the practical implementations of which are presented in university campus environments.
- Reiterating the point highlighted in several articles in this issue on the need for better integration of multiple domains; devices; controls; phenomena; and systems, including both the physical and cyber systems, the application of digital twin-based cosimulation for integrated energy system planning is the focus of [A9]. The possibility and benefits of a multidimensional cosimulation accounting for many aspects—such as network and resource types; physics; timeframes ranging from milliseconds to several hours; and domains, such as market design, policy development, or infrastructure planning—are elaborated with the use of various examples.
- The application of cloud-based digital twins for gaining better visibility in the low- and medium-voltage sections of distribution systems is covered in [A10]. The approach uses machine learning to continuously train the model against measured responses. The continuously

calculated power flow then provides a state estimation for the entire distribution system. This avoids the need for infrastructure investment, e.g., as required for developing more detailed simulation models.

Discussing the need for a single source of truth, while, at the same time, accounting for different objectives of several stakeholders, the "In My View" column of this issue [A11] highlights that the digital twin of a power system is a powerful evolution of the existing digital "multiples" in their usually isolated process and data domains. The column brings varying views, modeling approaches, and interpretations of the power system together by connecting them logically, hence creating more efficiency in handling data and information in a multidisciplinary environment.

—*Babak Badrzadeh*

governmental and academic circles nowadays, can only be addressed through transversal digital twins, encompassing both the weather-driven power systems engineering fabric and the societal and organizational aspects. DTiPS cannot (and should not) be developed in a silo, at the risk of being irrelevant in a broader context. Fortunately, we have recently witnessed increased interdisciplinary cooperation among energy engineers as well as climate and social scientists, often stimulated by research and development funding agencies, such as the National Science Foundation, U.S. Department of Energy, or European Union, engaged in promoting the green transition and energy justice against the backdrop of a digitized society.

Do we have a sustainable business case for DTiPS? Perhaps. It is a promising approach to realize cyberphysical systems for power systems, which are facing huge challenges and opportunities due to the transition toward a sustainable and renewable-energy-centered power system. According to the *IEEE SmartGrid* website, the digital twin market is expected to grow rapidly in the next decade, reaching US$125.7 billion by 2030 from only US$6.5 billion in 2021, with a compound annual growth rate of 39.48% (Ghosh et al., 2022). On the other hand, a 2023 analysis of market research data from various firms performed by the Concordia University Digital Twin Innovation Hub (Montreal, QC, Canada) found that the market growth expectations from 2020 to 2030 vary from a pessimistic 32.1% compound grow rate to an optimistic maximum of 61.94% (Figure 4). More specifically, the digital twin technology can enable the integration of distributed energy resources, such as renewable energy sources and microgrids, into virtual power plants, which can improve the efficiency and flexibility of power generation and consumption. The digital twin technology can also facilitate the simulation and planning of power systems, especially for complex and large-scale scenarios, such as the Australian energy market and the Chilean electric grid (OPAL-RT, n.d.). However, its implementation requires the convergence of several enabling technologies, such as the Internet of Things, big data analytics, artificial intelligence, and data fusion, which pose various technical and operational challenges.

This issue began with informal e-mail exchanges between the editor in chief and Prof. Christian Rehtanz, a colleague in Germany and one of the coguest editors, in spring 2022. We were seeking an impactful topic for the magazine and quickly concluded that it was time to raise awareness about the digital twin technology among power systems engineers and energy specialists. Christian built a transitional team with roots in both academia and utilities. It is true that the power equipment manufacturing sector is not well represented in the present issue, but we promise that this is not the last on this important topic.

We succeeded first in defining the *digital twin* concept in power systems by exploiting the findings of EXPERT VDE [Association for Electrical, Electronic & Information Technologies https://www.vde.com/en (Verband der Elektrotechnik Informationstechnik e.V.)] the standards body of Germany. We then found well-respected authors to address digital twin applications in every segment of power systems, ranging from microgrids, transmission and distribution operations, and power grid control to cybersecurity. To bridge the gaps between all of the previous twins and bursting business unit data silos, the cosimulation of federated heterogeneous DTiPS is posited in one of the articles as a credible approach. Over the last 16 months, the writing and peer review were not easy tasks because the complexity of the digital twin makes it more suitable for the transactions style of papers, often of interest to only a niche audience. We believe that making the concept more readily available with the assistance of carefully selected experts in the field has been successful in producing effective magazine articles, which we hope will be enjoyed by our faithful readers.

History Column

In this issue's "History" column [A1], we welcome back Robert D. Barnett for his eighth contribution to our pages, as he provides a treatment of the evolution of the universal power system from the steam engine, to early dc systems, to the universal polyphase ac system. The article is described from the viewpoint of the industrial and electrical development of the Niagara Falls region.

Leader's Corner

Our guest editor in this issue is no more, no less than IEEE Power & Energy Society (PES) President Shay Bahramirad, who is the senior vice president of engineering and asset management at LUMA Energy. The president is the chief executive officer of PES, responsible for leading the Society in fulfilling its mission, vision, and goals as well as overseeing the administration and management of Society affairs in accordance with the rules and regulations of IEEE and the constitution, bylaws, and operations manual of the Society. For your information, the PES president is elected by the voting members of PES for a two-year term. The past president is Jessica J. Bian, who is the founder and president of Grid-X Partners. The president-elect (2022–2023) is C. Y. Chung, who is Chair Professor of Power Systems Engineering and head of the Department of Electrical Engineering at the Hong Kong Polytechnic University. (For more information about the Governing Board, visit https://ieee-pes.org).

We are pleased to read Shay's update [A2] about the Society's activities and her vision of the future of our Society and community.

Letters From the Readers

We have indirect evidence that the September/October 2023 issue on "Grid Communications" has generated instructive discussions in the power and energy community, not to mention an impressive number of downloads on the IEEE *Xplore* website. In this issue, you will find one of the letters received, authored by Stig Nilsson [A3], principal engineer at Exponent (Phoenix, AZ, USA) and an IEEE Life Member. His letter is proof that we are not speaking in a vacuum or writing for ourselves but that we are reaching out to an actual audience. Stig claims, rightly, that "we have been enamored by high

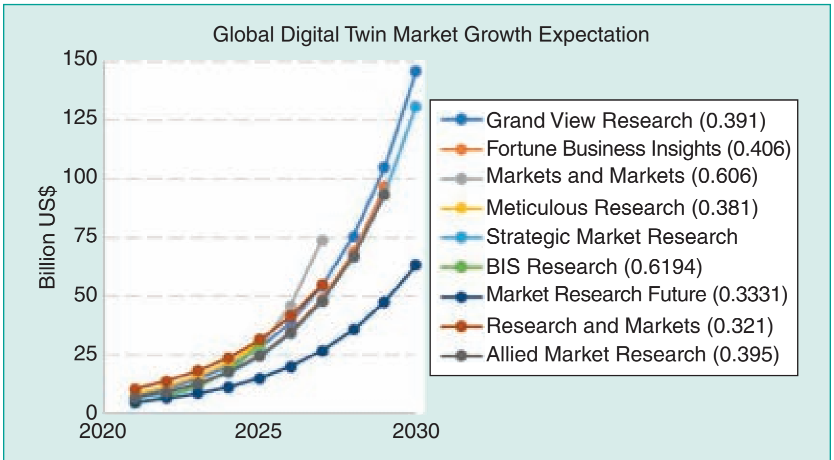

figure 4. Research data on digital twin markets. In parentheses is the percent compound growth rate multiplied by 100. USD: U.S. dollars. (Source: Concordia University Digital Twin Innovation Hub, Montreal, 2023; used with permission.)

tech to the point that we are ignoring the system weaknesses." It is a position statement about the lack of value proposition analyses in the conversation about the emergence of "millions" of intercommunicating sensors in modern utilities. We invited our readers to consider this "real cost benefit" side of the equation carefully in making up their minds on the articles published in the September/October 2023 issue of the magazine.

News From the Magazine Desktop

I am pleased to report to the IEEE *Power & Energy Magazine* (*PEM*) community that we are now fully operational on the Scholar One website for the sake of article submission and review. Here is our website for article submission and review: https://mc.manuscriptcentral.com/pemag. Gone is the era of e-mail-based article submissions at *PEM*. While some fine-tuning remains to be done, eight articles featured in this issue were reviewed in and submitted to production from Scholar One, which, as you can imagine, reduces the clerical burden on our volunteers. Because the magazine is a special publication with alternative content, obtained and organized differently than transactions titles, we will continue to process unreviewed material, such as meetings columns, letters to the editor, books reviews, and so on using an e-mail-based process. But what progress compared to a year ago!

I am also pleased to announce that Sharri Shaw has been confirmed as our new assistant editor. Welcome onboard, Sharri! Your expertise in working with *IEEE Journal of Microwaves* and other prestigious IEEE venues is a huge asset for us moving forward, especially in the context of a hybrid operation between e-mail and Scholar One submissions. We have already been able to witness the professionalism and high dedication Sharri brings to the magazine.

I conclude my introduction to this issue by asking all of you to join me in giving a well-deserved accolade to the guest editors, Christian Rehtanz, Ulf Häger, and Chen-Ching Liu. Without their tireless work, this special issue on a rather complex topic would have never been brought to light. The great team of authors they assembled to suit this daunting task deserves a round of applause as well. Last but not least, I want to stress the extraordinary dedication of Associate Editor Babak Badrzadeh, who worked during business travels to ensure meeting the constraining timelines of the magazine.

If the appearance and technical richness of this issue leave you with a desire to contribute to the magazine, you are most welcome to do so! Despite the strong lineup of topics scheduled on the magazine website, we are always seeking new and innovative topics of interest for our broad audience. We encourage unsolicited article submissions that may or may not be aligned with the future topics posted on the magazine website. Please note that your article must not be a rejected transactions paper or a paper written for a transactions publication. It must carefully follow the magazine template and writing style described on the website. You can always write to us for inquiries regarding the magazine policies and activities at powerandenergymagazine@gmail.com. This is also the e-mail for sending letters to the editor in chief, which we are eager to read and publish as you see fit with only minor edits.

For Further Reading

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Appendix: Related Articles

[A1] R. D. Barnett, “The universal power system: An evolution,” *IEEE*

Digital Object Identifier 10.1109/MPE.2024.3349889

Power Energy Mag., vol. 22, no. 1, pp. 82–88, Jan./Feb. 2024, doi: 10.1109/MPE.2023.3331170.

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[A3] S. Nilsson, "Share your thoughts: Send comments to pem-eic@ieee.org," *IEEE Power Energy Mag.*, vol. 22, no. 1, p. 81, Jan./Feb. 2024, doi: 10.1109/MPE.2023.3331470.

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[A5] C. Brosinsky, M. Naglič, S. Lehnhoff, R. Krebs, and D. Westermann, "A fortunate decision that you can trust: Digital twins as enablers for the next generation of energy management systems and sophisticated operator assistance systems," *IEEE Power Energy Mag.*, vol. 22, no. 1, pp. 24–34, Jan./Feb. 2024, doi: 10.1109/MPE.2023.3330120.

[A6] Y. Wu et al., "Digital twins for microgrids: Opening a new dimension in the power system," *IEEE Power Energy Mag.*, vol. 22, no. 1, pp. 35–42, Jan./Feb. 2024, doi: 10.1109/MPE.2023.3324296.

[A7] A. van der Veen, C. van Leeuwen, and K. A. Helmholt, "Self-organization in cyberphysical energy systems: Seven practical steps to agent-based and digital twin-supported voltage control," *IEEE Power Energy Mag.*, vol. 22, no. 1, pp. 43–51, Jan./Feb. 2024, doi: 10.1109/MPE.2023.3327065.

[A8] P. Palensky, P. Mancarella, T. Hardy, and M. Cvetkovic, "Co-simulating integrated energy systems with heterogeneous digital twins: Matching a connected world," *IEEE Power Energy Mag.*, vol. 22, no. 1, pp. 52–60, Jan./Feb. 2024, doi: 10.1109/MPE.2023.3324886.

[A9] A. Srivastava et al., "Digital twins serving cybersecurity: More than a model: Cybersecurity as a future benefit of digital twins 2," *IEEE Power Energy Mag.*, vol. 22, no. 1, pp. 61–71, Jan./Feb. 2024, doi: 10.1109/MPE.2023.3325196.

[A10] C. Köhler, R. Kersten, and M. Schöpf, "Cloud-based digital twin for distribution grids: What is already available today," *IEEE Power Energy Mag.*, vol. 22, no. 1, pp. 72–80, Jan./Feb. 2024, doi: 10.1109/MPE.2023.3336255.

[A11] J. Kays, "The digital twin: New species, evolution, or revolution?" *IEEE Power Energy Mag.*, vol. 22, no. 1, pp. 92–93, Jan./Feb. 2024, doi: 10.1109/MPE.2023.3328292.

Shay Bahramirad

a new vision for PES

doubling down on our efforts

THE ELECTRIC GRID IS AT THE precipice of extraordinary change and opportunity. Across the world, we are seeing incredible investments in technologies such as renewable generation, battery storage, and electric transportation, which represent both new capabilities for the grid as well as an intense demand. Meanwhile, communities are becoming more reliant on access to reliable and resilient electricity, including those communities that still struggle to gain access to consistent electricity supplies, at exactly the same time that climate change is posing additional stress in the form of hotter days, colder nights, stronger winds, more intense flooding, and more severe weather events.

The goals are immense, but what is needed to get there doesn't require science fiction. It entails a recommitment to excellence in technological choices, our technical capabilities, collaboration, and the talent that is available to us. This is what the IEEE Power & Energy Society (PES)'s leadership is committed to doing now: aligning internal and external stakeholders to mitigate and adapt to climate change while also leveraging the fully diverse talents from every part of the world. With this combined effort, we can then develop the necessary standards, guidelines, and technical frameworks.

> The goals are immense, but what is needed to get there doesn't require science fiction.

Digital Object Identifier 10.1109/MPE.2023.3331610
Date of current version: 12 January 2024

PES represents a key element in achieving this and more. In the more than several decades since it was founded, PES has demonstrated core competencies that provide significant value to its close to 40,000 members across the world. This includes conferences that bring people together and allow them to learn about innovative technologies (from those that were recently tested in labs, to those being deployed in large-scale projects) and to transparently share best practices and pain points. It entails publications whose reputations set the gold standard for consequential research. PES's developed standards and technical guidelines are used across many jurisdictions to determine the policies that allow us to meet goals in reliability, resiliency, and sustainability. Still, more remains to be done to achieve our shared objective of being the leading provider of technological development in the power and energy industry for the betterment of humanity.

For all of the focus on technology, PES is, in essence, a collection of experts who represent every portion of the electric industry. This collection ranges from students learning the discipline, to researchers developing the next generation of innovations, to the utility professionals who deploy these technologies to serve communities across the world. Our focus must be on helping these professionals succeed in their objectives, which also encourages more people to get the benefits of membership.

Chapters are the core of many members' experiences. They offer the possibility to meet and learn from colleagues in a geographically coherent activity. Strong Chapters are rooted in local institutions, including universities, engineering firms, technology enterprises, electric utilities, and regulatory bodies. By connecting different stakeholders who are focusing on related issues from their own perspectives, they make it possible for members to have access to a more diverse professional network and a richer intellectual understanding of these complex issues.

At its best, PES is more than a sum of its parts; of its Chapters. PES University helps its members learn to develop by consuming impactful content in forms ranging from magazines and journals to webinars. With this assistance, existing members are better able to develop their careers and make the organization more vibrant.

PES operates in a large global ecosystem of groups who recognize the growing importance of correctly making energy decisions. Governments at every level are looking for technically sound information to allow them to make policy decisions, including which forms of generation to incentivize, how to allow for the planning of large-scale grid decisions, and the forms of clean energy technologies to support, including beneficial electrification. The global partnerships that PES forms with these external institutions are critical, both to make sure that PES's work is relevant to the broader community and also to support PES members' goals to have the impact that their work deserves.

To accomplish this, PES needs as broad and deep a talent pipeline as possible, with a strategy for workforce development. Historically, the industry, like so many others, has struggled to access the full breadth of extant talent; failing this talent is no longer an acceptable possibility for the industry or the globe. As we face increasingly critical challenges, PES recognizes not only the desire, but also the requirement, to be an inclusive Society. We need to better engage all of our Chapters and make sure that members from all parts of the globe have the leadership opportunities that are too often focused on specific regions.

This commitment to the next generation has helped drive critical PES initiatives, including science, technology, engineering, and mathematics education. PES members are multiplying their impact through participation in programs like PES Day, where members across the world meet with students and young professionals, both online and in person, to share their experiences and to model their impact on the world through technical rigor.

This type of work has significant societal effects, including helping young professionals develop the skills they need to prepare for remunerative careers. It also supports PES and the industry in ensuring that we have the talent we need to prosper. More importantly, it makes the world a better place because it helps us develop the skills we need to fight climate change.

To make this possible, we are doubling down on our efforts to provide visibility to technical accomplishments and guidelines, lay the foundation to adapt and mitigate climate change impacts, develop global strategic partnerships, and engage young professionals in a structured and meaningful way to drive social change. This is why PES is formalizing four member-at-large positions, which will focus on multiplying existing efforts and achieving these larger goals, namely, member experience, leadership development, diversity and inclusion, and climate change initiatives.

The member at large for membership experience will cross all of the various focus areas of PES and ensure that members can leverage the full breadth of opportunities available in PES. New members need easy access points, including mentors who can help them identify the right way to participate, to navigate what can be an overwhelming menu of options. More experienced members not only need continued access to the resources they have been using but also need to be introduced to other potential opportunities, which might have been obscure to them. This particular member at large will help develop technical tools that will make it easier for both new and old members to do more with PES.

PES is a great force in the large army that we as a human race need to make that possible.

PES needs more leaders from every part of the Society, which requires an inclusive and transparent approach to socialize these opportunities. The member at large for leadership development will work with stakeholders across the organization to identify potential leaders and develop capabilities to support them so that they can rise. This can include training modules and the identification of mentors to support the next generation of leadership.

This leadership must represent the rich diversity of PES's membership. The member at large for diversity and inclusion will pay special attention to ensuring that PES benefits from every available talent stream, including each Region as well as historically underrepresented groups in the Society and, most importantly, will focus on a new dimension of diversity, by providing access. This leader will also focus on supporting engagement with communities to identify new members, including those in areas where PES has traditionally struggled to recruit sufficient engagement, such as in the community and technical colleges, which may represent PES's next generation of members.

The final new member at large will focus on climate change, identifying opportunities to highlight what PES is already doing to respond to challenges as well as increasing PES's impact. This may include holding events and conferences and backing the publication of journals and white papers, with a focus on the role of the power grid in the response. This role is incredibly important to coordinate all activities in this space at PES, participate at IEEE ad hoc activities, and position PES globally as a technical thought leader.

Today, climate change is no longer a debatable topic; it is a crisis that affects us all in different ways. Some face fire, others flooding, but none are immune from its effects. To meet this crisis head-on, we need our best professionals focused on deploying a clean and resilient energy system that allows people everywhere to live with dignity as they deal with the daily stresses and disruptions that plague us. PES is a great force in the large army that we as a human race need to make that possible. I hope that together we can make it even more formidable.

Christian Rehtanz, Ulf Häger, and Chen-Ching Liu

digital twin

from buzzword to solutions

WHEN WE TALK ABOUT DIGITIzation and digitalization, the term *digital twin* is not far away; data and information are the new oil for the economy. But hasn't electrical power always been at the forefront with computational models and computer applications for the secure operation of power systems? With the development of computer systems in the middle of the last century, power systems were one of the first civilian applications. Many standard computing methods and models in power systems have been established for more than half a century. Why are we suddenly researching and talking so much about digital twins, and which new solutions will really be established in practice? In this special issue, we want to explore these questions and examine them from different perspectives.

Data and models must be kept consistent, and this is where digital twins come into play by providing consistent data and models for different processes.

Fundamentally, energy systems are becoming more complex due to the decentralization of converter-based renewable generation to lower grid levels. Their volatility requires more flexibility in control. This also results in a greater need for automation to manage the complexity of multiple plants and integrate them into the grid and markets. The need for grid expansion forces increased economic efficiency, which must lead to better security with reduced reserves but also to optimized asset management.

The processes of power system operation, planning, and asset management under the constraints of markets and increasing intermittent renewables require increased data and information. These processes no longer run side by side but must be considered together. Therefore, models must be maintained together on common data and information bases. Data and models must be kept consistent, and this is where digital twins come into play by providing consistent data and models for different processes, thus leading to coordinated solutions and results. Individual processes become parts of a joint overall process, described by the digital twin. This digital twin covers time ranges from short-term operation to long-term planning.

This special issue is dedicated to selected aspects of and trends toward usable digital twins. It begins with a definition of what a digital twin is. It also looks at approaches for initial solutions in the areas of control centers and microgrids. The emerging cyber-physical systems that use digital twins offer opportunities for newly structured applications. The aspect of cybersecurity is also important. First implementations in the areas are also presented, and the contributions show the views from research as well as industry.

The first article, "Digital Twins in Power Systems: A Proposal for a Definition" [A1], presented in this issue is dedicated to the definition of digital twins in power systems. The basis for this was developed in an expert working group consisting of various representatives of network operators, power equipment manufacturers, and researchers in Germany.

The second article, "A Fortunate Decision That You Can Trust—Digital Twins as Enabler for the Next Generation of Energy Management Systems and Sophisticated Operator Assistance Systems" [A2], is dedicated to the view of control centers, including energy management systems (EMSs) and distribution management systems, and their next architecture according to the approach and use of digital twin technologies. Securing systems through dynamic security assessment in the face of the higher volatility of power feed-ins and operation closer to grid limits offers new challenges that can be addressed with the approach.

While the perspective here is primarily focused on transmission networks, the third article, "Digital Twins for Microgrids" [A3], is about lower network levels—and particularly microgrids. Processes in these levels

Digital Object Identifier 10.1109/MPE.2023.3339094
Date of current version: 12 January 2024

and the benefits of digital twins for operation, planning, and maintenance are presented and discussed.

The fourth article, "Self-Organization in Cyberphysical Energy Systems" [A4], takes up the necessary aspect of automation within cyberphysical energy systems. The question here is how to implement highly automated and self-organized solutions for the operation of energy networks in a practicable way by means of a structured approach using digital twins.

The modeling aspects of digital twins are discussed in the fifth article, "Cosimulating Integrated Energy Systems With Heterogeneous Digital Twins" [A5]. The integration of and coupling with different sectors with the electric power system also requires the coupling of models. Cosimulations must link suitable models for this purpose. Different functional layers as well as spatial and temporal dimensions must be made scalable for diverse applications. The complexity of the multiple players in the evolving energy system cannot be represented by a single-world simulator but must be created by cleverly combining individual components into a holistic digital twin.

The sixth article in this issue, "Digital Twins Serving Cybersecurity" [A6], is devoted to this important topic of the cyberphysical systems and interlinked digital components that form complex digital twin structures and require the highest standards in cybersecurity. The consideration here is to what extent digital twins also offer opportunities for improved cybersecurity. Examples from real campus implementations are taken up, which enable intrusion detection by means of artificial intelligence and a digital twin. Further aspects of cybersecurity for planning and decision support up to cyber-induced cascading failures are presented and discussed.

The seventh article, "Cloud-Based Digital Twin for Distribution Grids: What Is Already Available Today" [A7], presents a practical perspective on a system that is available today as a digital twin approach for the operation, planning, and asset management of distribution networks. Cloud technologies enable the linking of many data and information sources to estimate network conditions for current operations but also for future developments. The evaluation of various data and measurements leads to efficient and secure system operation and, ultimately, avoids costly distribution grid expansion through the use of the digital twin.

This special issue concludes with a practical opinion from the perspective of a transmission system operator (TSO) [A8]. The challenges and benefits in the area of digital twins are finally classified and evaluated from the personal viewpoint of the daily work of a TSO expert.

We, as the team of guest editors, would like to thank the authors for their outstanding contributions that provide an overview of the state of the art in the research and practice of digital twins. We are convinced that the term *digital twin* is not just a buzzword but, if defined precisely and applied well, will bring great benefits to improve the security and efficiency of power system operation and planning.

Appendix: Related Articles

[A1] T. Wagner, C. Kittl, J. Jakob, J. Hiry, and U. Häger, "Digital twins in power systems: A proposal for a definition," *IEEE Power Energy Mag.*, vol. 22, no. 1, pp. 16–23, Jan./Feb. 2024, doi: 10.1109/MPE.2023.3328581.

[A2] C. Brosinsky, M. Naglič, S. Lehnhoff, R. Krebs, and D. Westermann, "A fortunate decision that you can trust: Digital twins as enablers for the next generation of energy management systems and sophisticated operator assistance systems," *IEEE Power Energy Mag.*, vol. 22, no. 1, pp. 24–34, Jan./Feb. 2024, doi: 10.1109/MPE.2023.3330120.

[A3] Y. Wu et al., "Digital twins for microgrids: Opening a new dimension in the power system," *IEEE Power Energy Mag.*, vol. 22, no. 1, pp. 35–42, Jan./Feb. 2024, doi: 10.1109/MPE.2023.3324296.

[A4] A. van der Veen, C. van Leeuwen, and K. A. Helmholt, "Self-organization in cyberphysical energy systems: Seven practical steps to agent-based and digital twin-supported voltage control," *IEEE Power Energy Mag.*, vol. 22, no. 1, pp. 43–51, Jan./Feb. 2024, doi: 10.1109/MPE.2023.3327065.

[A5] P. Palensky, P. Mancarella, T. Hardy, and M. Cvetkovic, "Cosimulating integrated energy systems with heterogeneous digital twins: Matching a connected world," *IEEE Power Energy Mag.*, vol. 22, no. 1, pp. 52–60, Jan./Feb. 2024, doi: 10.1109/MPE.2023.3324886.

[A6] A. Srivastava, "Digital twins serving cybersecurity: More than a model: Cybersecurity as a future benefit of digital twins 2," *IEEE Power Energy Mag.*, vol. 22, no. 1, pp. 61–71, Jan./Feb. 2024, doi: 10.1109/MPE.2023.3325196.

[A7] C. Köhler, R. Kersten, and M. Schöpf, "Cloud-based digital twin for distribution grids: What is already available today," *IEEE Power Energy Mag.*, vol. 22, no. 1, pp. 72–80, Jan./Feb. 2024, doi: 10.1109/MPE.2023.3336255.

[A8] J. Kays, "The digital twin: New species, evolution, or revolution?" *IEEE Power Energy Mag.*, vol. 22, no. 1, pp. 92–93, Jan./Feb. 2024, doi: 10.1109/MPE.2023.3328292.

Digital Twins in Power Systems

A Proposal for a Definition

THE TERM "DIGITAL TWIN" WAS ALREADY INTRODUCED BY Michael Grieves in 2002 (see Grieves, 2016), and after about 20 years the concept has found its way into the energy sector on a broader base. The first applications of digital twins were for product lifecycle management within the aerospace industry at NASA. After this initial implementation of digital twinning, the digital twin technique for lifecycle management was supplemented by networkability. Since then digital twins have been widely embraced by many industrial stakeholders, allowing machines and processes to optimize their production. Today this development is considered as the fourth industrial revolution (Industry 4.0).

Introduction and Article Outline

In recent years the approach and the potential for digital twins in power systems have been investigated, even if the number of stakeholders and participants usually is higher than in Industry 4.0. In the past there was no strong need for digital twins in power systems. However, with the change of conventional power generation and the unidirectional power flow from high voltage levels to low voltage levels, power systems become more complex. The increasing renewable energy generation at all voltage levels in the power system leads to bidirectional power flows, resulting in higher requirements for the grid and the corresponding grid operator. The digital twin offers a great opportunity to overcome these new requirements. Conventional solutions of grid expansion often have acceptance issues and high costs, which must be avoided. The new possibility to apply digital twins arises from the flexibilization of the power sector achieved by a high penetration of measurement units and the associated digital data processing.

Several definitions of digital twins are available in the literature, but they are not always consistent, and details of the definition usually depend a lot on the specific industry sector applying the digital twin. For this reason, we provide a brief overview on the available definitions and classifications. A definition for the term *digital twin* was proposed by Michael

Digital Object Identifier 10.1109/MPE.2023.3328581
Date of current version: 12 January 2024

By Timo Wagner, Chris Kittl, Joshua Jakob, Johannes Hiry, and Ulf Häger

Grieves (see Grieves, 2016). According to this definition, a digital twin consists of three parts: the entity in the real world, the virtual model in the digital space, and the data and information interaction channels between the entity and the virtual model. In this context, the digital twin can form a bridge between reality and the digital space. Several scientific publications support this definition and refer to the digital twin in a broader sense as a virtual or software-based representation of a real object that is connected to the real object via interfaces. Other definitions of digital twins focus on special perspectives, such as the product lifecycle or the customer's perspective including customer experience. In other publications the possibility of applying digital twins to further improve the monitoring and control systems at the grid control center of power grids is investigated. Furthermore, digital twins are considered in the context of networked and autonomous manufacturing systems. For this purpose, Stark and Damerau present an architectural design approach and possibilities for modular design. Another perspective of digital twins is the business model perspective. For this purpose, an article may conduct case studies in, e.g., four companies and a comparative analysis. Another perspective of

> The use cases include power generation and distribution, renewable energy, nuclear energy, electric vehicles, energy storage, and energy project planning.

digital twins is the business model perspective (see Schnicke et. al., 2020). This article conducts two different case studies from the industry 4.0 sector. In the previous summarized literature, the digital twin as a simulation model is only mentioned implicitly. However, digital twins are more than just data. They contain algorithms that accurately describe their real-world counterparts. These are often simulation models that simulate, for example, functional or physical properties of the digital twin. If these simulation models are executed with real data, then the digital twin ideally behaves exactly like its real counterpart (see Adamenko et. al., 2020).

Our main focus in this article is on *digital twins in power systems* (*DTiPSs*). The term digital twin is gradually gaining consideration in the power and energy system industry. Various publications can be found in which DTiPSs have been studied in the context of use cases in the electricity and grid industries. The use cases include power generation and distribution, renewable energy, nuclear energy, electric vehicles, energy storage, and energy project planning. For example, a DTiPS was used to flexibly operate a power generation facility. In another example from the literature, a DTiPS was used to predictively maintain wind turbines. A listing of other use cases and related publications can be found in Stark et al., 2019. However, at the current time, a specific definition of digital twins in the context of electricity and network management cannot be found in the literature.

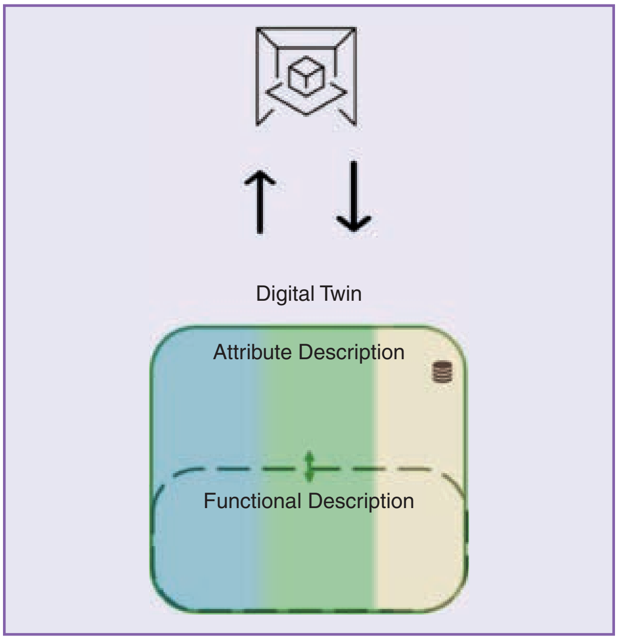

figure 1. A DTiPS linking several domains (illustrated by different colors).

For this reason, we propose a specific definition of the term digital twin from the perspective of the power system industry in this article. This work was carried out by a task force of the German Association for Electrical, Electronic, & Information Technologies (VDE). The references of the various definitions summarized in this article can be found in detail in the task force report (VDE Study, 2023).

The article is structured in six sections. The next section provides our definition of a DTiPS. It is followed by the development from a model for simulations to digital twins in the section "From Model for Simulations to Digital Twins: A Classification of Terms." Added values and challenges of digital twins for power systems are discussed in the section "Discussion of Added Values and Challenges." An example of a digital twin is presented in the section "Example: Integrated Microgrid and Macrogrid Planning Process." Finally, the section "Conclusion" summarizes the article and draws a conclusion.

Definition of a DTiPS

The DTiPS is a virtual representation of an existing or future real object. A DTiPS constitutes the description of its attributes and functional properties and is coupled with the real object accompanying it, from planning to disposal. This coupling is achieved through a digital autonomous communication infrastructure, but manual indirect adjustments are allowed as well (Figure 1).

The ideal DTiPS includes a holistic data collection of its real object, e.g., 3D data, delivery times, or prices. In the case of partially missing detailed data sources, simplified views can also be used during the initial setup of a digital twin, but this requires a continuous reduction of missing-data white spaces.

Compared to classical models, the DTiPS maps a linkage between digital models of at least two domains. For example, a protection device communicates via management shells with objects from the primary technical components, e.g., to trigger a switching simulation in the model of the primary component. A DTiPS can represent a combination of several DTiPSs. This means that a DTiPS can be integrated into other DTiPSs of different domains or can communicate with other DTiPSs of other objects. DTiPSs can be products from different manufacturers but are required to be interface compatible with each other. As a result, the DTiPS can provide a holistic view of the physical asset it represents, including all details that the deploying entity, a company, collects about itself, e.g., financial, maintenance, and operational data. In

A DTiPS constitutes the description of its attributes and functional properties and is coupled with the real object accompanying it, from planning to disposal.

addition, the DTiPS may generate insights derived from the available data using basic or advanced data analytics.

The DTiPS of an object or system essentially consists of two parts, an attribute description and a functional description; the attribute description is composed of a model description and concrete attribute values. The access to the attribute description as well as further processing of the attribute values, e.g., in the context of analysis and evaluation functions, is made possible by the functional description.

Model Description

The models on which the DTiPS is based should reproduce a sufficiently accurate and plausible behavior of the real object according to the application case and can be composed of several cross-domain submodels. By the utilization of different models, the DTiPS states are enriched to cover more information than the observations themselves. In general, a model for a DTiPS should have the following properties:

- ✔ *Timeliness*: The updating of parameters within the model based on modified or measured data is mandatory.
- ✔ *Representation accuracy*: The model must be sufficiently accurate so that the updated parameter values are of interest and usable for the application in question.
- ✔ *Response time* (*in the context of the functional description*): Decisions can be made within the time frame required for the use case.

Attribute Values

The fundamental component of the DTiPS is the description via attribute values for which responsibility is taken in terms of a single source of truth (SSOT) or that are obtained from other DTiPSs. The data are object related, always kept up to date, and archived. In particular, this represents the basis for the description of different functions. For all digital processes, the attribute description of the DTiPS is the only and exclusive digital image of the real existing object (SSOT) in sufficient quality. There is an absolute necessity to be able to uniquely designate the objects in the digital image and to provide a time dimension. The time dimension can be used to enable synchronization of the current or historical attribute values to a specific temporal state (snapshot).

Functional Description

In the context of the functional description, the data and models from the attribute description can be further processed to map downstream functions with reference to current or historical states of the real object. These can be, for example, analysis, monitoring, optimization, or control/regulation functions. The decisive factor here is that any functions always draw exclusively on the information from the attribute description of their own or other DTiPSs, thus implementing the concept of the SSOT.

Snapshot Twin

For simulation purposes, a snapshot twin can be decoupled to freeze information of a specific point in time to perform analyses with it, such as for planning purposes, "what-if" analyses, real-time simulations, virtual reality, training systems, etc. Following the paradigm to keep all information of the real object within the DTiPS, the snapshot twin and its simulation results are always kept in the database of the DTiPS.

The interplay between the real object and the DTiPS over the different lifecycle phases as well as the model decoupling of the snapshot twin are shown in Figure 2.

Finally, Table 1 summarizes the different terms presented in this article. The following section will delimit those terms from commonly known concepts in academia and industry.

From Model for Simulations to Digital Twins: A Classification of Terms

The term DTiPS implies that a physical asset, e.g., a device, a system, or a process, is mapped as a digital copy of the original object. This understanding narrows down the general, industry-agnostic definition, which covers not only physical assets, but also persons or processes. The representation of a physical asset as a (digital) copy creates a proximity to well-known concepts of modeling and simulation. While both concepts, *digital twin* and *modeling and simulation*, share common ideas, they differ in crucial aspects. The following summarizes how the terms *model* and *simulation* are defined in the literature and how their concept is distinguished from that of a DTiPS.

Modeling and simulation are used to investigate the behavior of a real object without performing these investigations on the object itself. While the *model* can be a real or virtual image of a real object, its experimental execution is called *simulation*.

To create a *model*, the object of interest is viewed through an *experimental framework* that specifies relevant properties and relationships to the planned investigation. This foundation of the model's constitution is the main differentiator from a DTiPS: because of the experimental framework, only properties and interrelationships of a real object that are relevant for a *specific and clearly delineated* problem are considered. Therefore, a model only approximately replicates a physical entity. Different experimental frameworks can lead

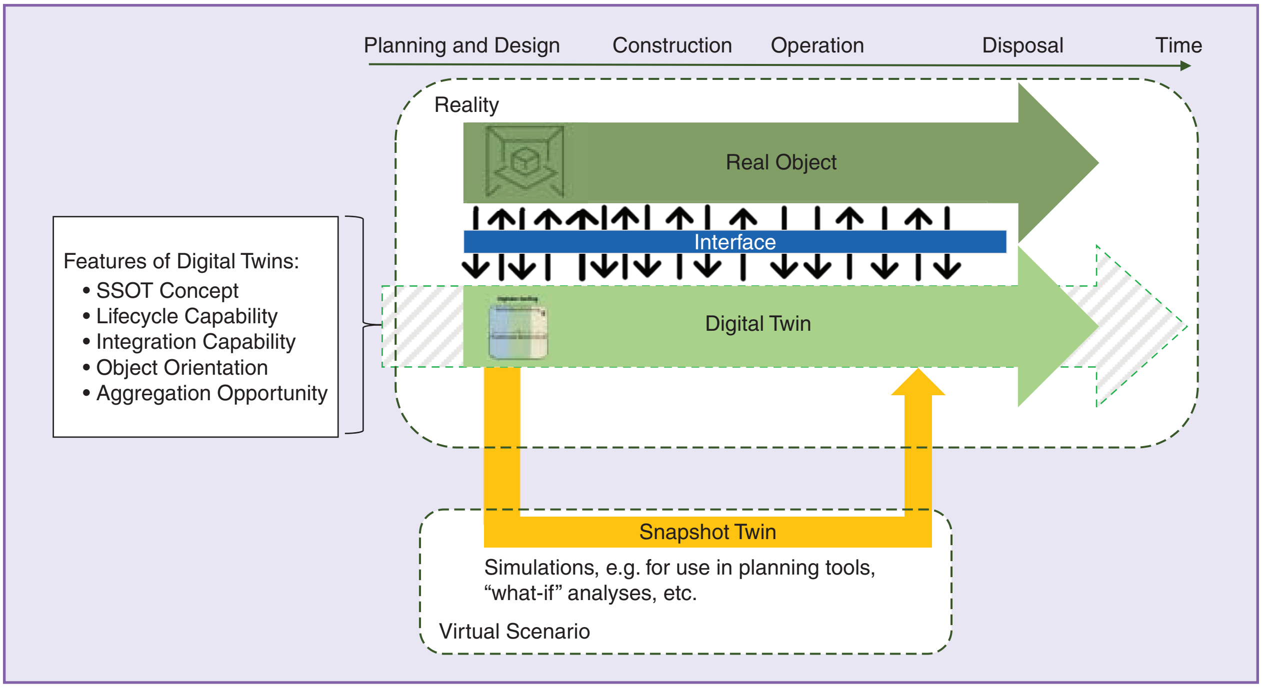

figure 2. Interplay between real object and DTiPS over different lifecycle phases.

to different models of the same physical entity. In theory a model can be any kind of model, such as a thought model. By contrast, the definition of a DTiPS's properties and relationships specifically demands a *digital* representation, technical feasibility, and a high grade of generality for a range of experiments. Summarizing, a model is only created for a single kind of investigation, while a DTiPS tries to reach generality for the physical object it represents.

table 1. Overview of terms as part of the definition.

The DTiPS…
- ✔ is a virtual representation of an existing or future real object
- ✔ has attributes and a functional description
- ✔ comprises at least two domains
- ✔ represents the real twin with constantly high quality
- ✔ is closely coupled to the real twin by communication technology
- ✔ accompanies the real twin its whole life span.

The snapshot twin…
- ✔ freezes the state of a DTiPS at a certain time instant
- ✔ is not coupled with the real twin
- ✔ can be used as a model for simulations
- ✔ is stored close to the DTiPS for documentary reasons.

The linked DTiPS…
- ✔ (hierarchically) connects different DTiPSs
- ✔ couples them by communication technology
- ✔ enables information encapsulation by maintaining full sight onto the real twin.

The term "simulation" commonly refers to the execution of the model. Therefore, we understand it as the possibility to perform investigations vicariously on a model without affecting the real object. Thus, simulations take place decoupled from the real object. While the model describes the anticipated reaction of the real object to inputs or events, e.g., measured values, switching actions, or short circuits, simulation is the process of stimulating the model with these inputs and events. Simulation answers the question of how the real object would have behaved under the same circumstances, given that the model and simulation are sufficiently verified, validated, and accredited for this situation.

Summarizing, modeling and simulation decouple the object of interest and the investigation of its behavior and enable *what-if* analyses and *post-error* analyses. By contrast, the pronounced goal of a DTiPS is to tie the virtual model close to reality and potentially detected real-world stimuli. The connection of the real object with its virtual counterpart (*twin*) is essential for a DTiPS and is usually established as a direct communication interface, either unidirectional or bidirectional.

Discussion of Added Values and Challenges

In the previous sections we outlined our understanding of a DTiPS, which could help with everyday business in the power and energy system industry, delimiting it from the current state of science and technology and providing a clear taxonomy to aid discussion and application in industry. We dedicate

> Each time it is accessed, the user can be sure that this piece of information is valid even under consideration of all other domains and stakeholders.

this section to a discussion of general added values and the challenges, which we find are worthwhile to overcome. We keep the discussion generic and use the next section for a comprehensive example of the most important aspects.

The power and energy system industry is inherently a complex business. It involves several physical and business domains as well as in-house and external stakeholders. Naturally, everyone involved perceives the system a bit differently—in technical terms. They hold different, loosely coupled models and simulations, which potentially lead to contradictory information. Tying them together to an SSOT provides a trustworthy, consistent, actual, and continuous source of knowledge. Each time it is accessed, the user can be sure that this piece of information is valid even under consideration of all other domains and stakeholders. Moreover, an SSOT implies that this knowledge is perpetually curated so that updates of one specific aspect propagate to the rest of the knowledge automatically. Repeated manual and resource-intensive on-demand preparation and validation of data is replaced by an automatism to ensure continuous quality.

Obviously, the transformation from single models to a DTiPS requires some effort. How much effort is needed is dependent mainly on the current state of data management and the structure of processes. Most importantly, data quality assurance plays a major role in the whole life span of a DTiPS, but especially when setting it up the first time—you have to step back and consider the question: "Do we have the right data and are we processing the data right?" The transformation requires knowledge in change management, data engineering, and computer science. Those are fields that typically do not belong to the core business of many companies in the energy and power system industry. Finally, an in-depth knowledge of business and technology is needed to determine the cost-to-benefit ratio of setting up a DTiPS, while still some aspects can only be uncertainly assessed. The benefit of consistent knowledge might only pay off in reducing the risk to take malicious decisions. Still, interlinking all relevant information and relying on an SSOT also makes it a single source of corruption. The design and operation of a DTiPS necessitate cybersecurity, fraud prevention, and data integrity as some of the most important targets.

In the target image, DTiPSs are backed by sophisticated data engineering and computer science solutions. A core requirement is to make the knowledge accessible in an automated and easy fashion. The building of interfaces will become a key concept. What is valuable for company-internal use can also be beneficial for collaboration. The idea of an interconnected DTiPS allows restrictive exposure of trustworthy, consistent, actual, and continuous knowledge to external service providers, regulators, etc. As history of information is preserved, and the DTiPS accompanies an asset or system throughout the whole life span, loss and corruption of data as well as incompatibilities across project phases are reduced to a minimum.

While manageable complexity arises in setting up a DTiPS, we believe that complexity arising in future energy and power system engineering tasks can only be handled by a consistent digital view onto the reality.

Example: Integrated Microgrid and Macrogrid Planning Process

In previous sections we presented in abstract terms the definition of a DTiPS, delimited it from current understanding in academia and industry, and finally discussed challenges and added value. To better understand the different aspects, we provide a grid planning example, where interconnected DTiPSs are utilized.

For a newly planned wind farm, grid reinforcement measures are required in grid operator (GO) A's grid, which also affect the neighboring GO B. Consequently, and iteratively, the following steps need to be taken: cooperative, internal planning of measures by GO A and B, approval by a regulator, and finally, realization of measures. Those tasks involve a variety of stakeholders in house (asset management, operations, etc.) as well as externally (regulator, neighboring GOs, and hardware and service providers). Each one has a differently broad view onto the system. Obviously, exchanged data or simulation models should only cover the level of detailing needed for the individual use case. Access to further data should be restricted to fulfill confidentiality requirements. Figure 3 depicts the different use cases, different interconnected digital twins, and their lifecycles.

Interconnecting the different DTiPSs ensures that any changes at any stakeholder are propagated automatically to all other partners. This reduces the manual effort significantly: neither communication of changes nor manual incorporation into the stakeholders model is needed. If required, the consortium can grant granular access to the regulator, which itself benefits from consistent information. In case of a suggestion for adapted measures, the regulator can spin off a snapshot twin and hand it back to the consortium. The snapshot can be assessed and investigated and eventually merged back into the different digital twins.

Alongside the planning project, different aspects must be taken care of, ranging from systematic restrictions, such as dynamics and stability and power assets to protection device design and parameterization. In this example we will focus on the revision of the protection scheme of a specific switchgear. Figure 4 shows the information exchange along interconnected digital twins with a focus on the later realization stage of the project.

Starting with the DTiPS of the grid, a snapshot twin is spun off to assess the requirements from the system's perspective (expansion measures). These are communicated to the DTiPS of the switchgear (step 1), where also a snapshot twin is spun off. Simulations show the need for a new protective device, which leads to the creation of a third DTiPS for this specific device (step 2). Note that it does not exist physically yet. The DTiPS is handed to a protection device manufacturer, who prepares quotations and enters the properties of the device into the DTiPS. As the switchgear's

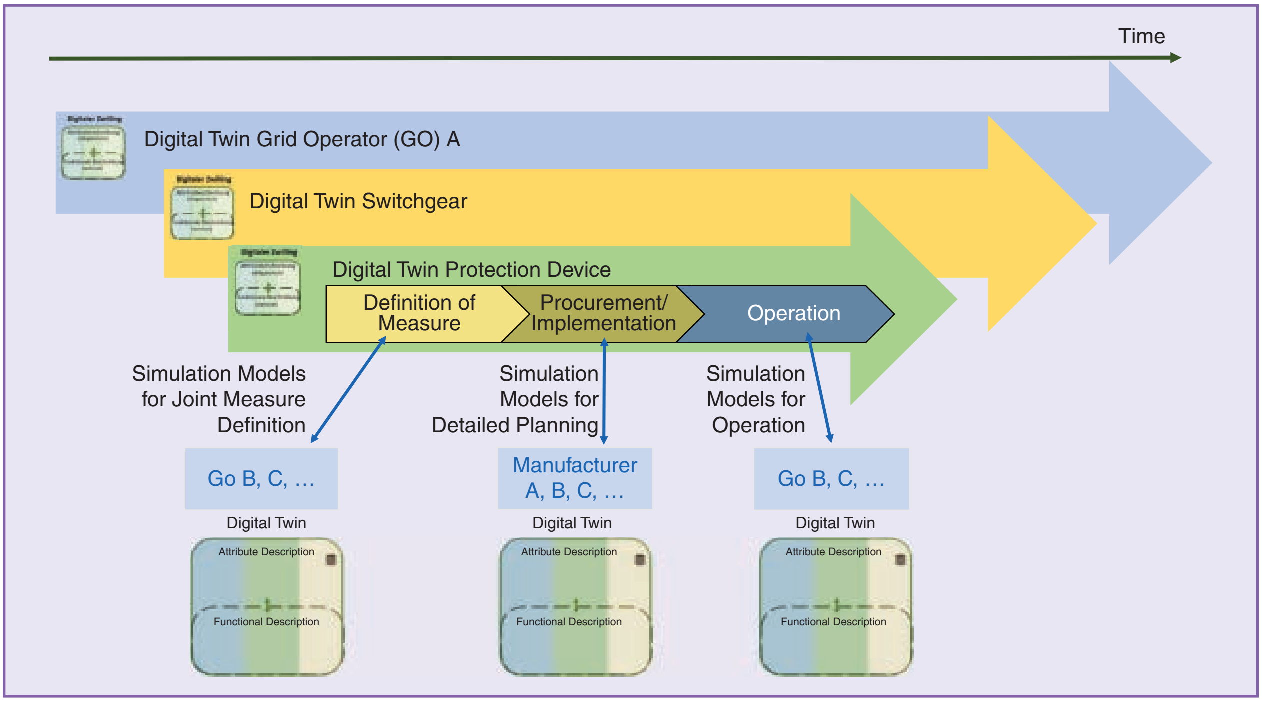

figure 3. Exemplary interaction of several DTiPSs in connection with the installation of a new protection device.

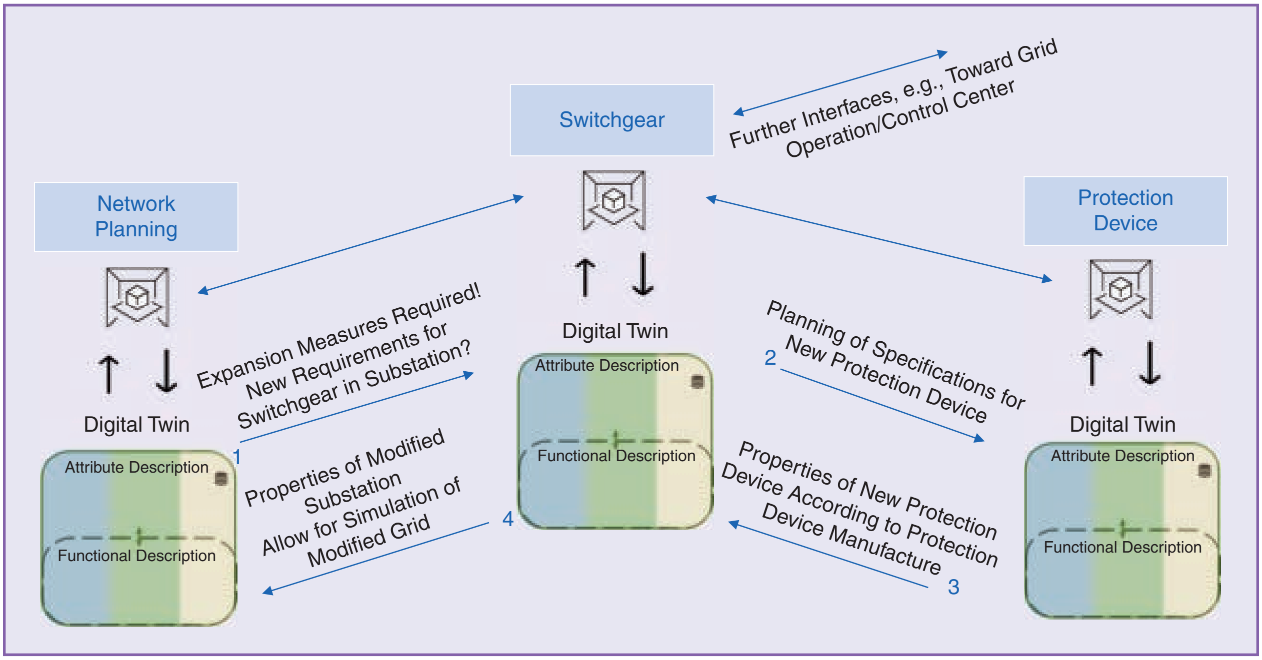

figure 4. An example of the interaction of several DTiPSs.

table 2. Overview of added values in different phases of the project.

Phase	Added Values
Cooperative "internal" planning	Reduced costs due to trustworthy, consistent, actual, and continuous source of knowledge; eased information exchange due to solid interfaces; increased quality of and trust in results; reduced project duration by efficient and effective data handling
Regulatory approval	Eased information exchange due to solid interfaces; consistent feedback by snapshot twins; accelerated approval phase
Commissioning	Eased iterative adaption of hardware specifications and parameters; adaption of plans based on necessary adaptions in execution

DTiPS holds reference to the protection device's DTiPS (step 3), a new snapshot twin can be used to finalize the protection scheme. As the grid's DTiPS also references the switchgear's DTiPS (step 4), the revised protection scheme can be derived from the perspective of the overall grid. Based on the evaluation results, further iterations with the manufacturers of the protection device can take place until all requirements are met and a physical protection device is ordered. Prior to the grid integration, the physical device is tested by hardware in the loop between the digital and the physical twins. The subsequent implementation process and also the transition of the project into regular operation (the next lifecycle phase) require further similar interactions between the DTiPSs.

Table 2 summarizes added values for the different steps of the planning project.

After successful commissioning of all required assets, the operation phase starts. During this phase, measurements, field reports, etc., feed knowledge into the DTiPS, which later helps in maintenance or formulating requirements for replacement assets, when the current ones reach end of life time.

Conclusion

The increasing use of the term *digital twin* and the lack of a specific definition for the term DTiPS have resulted in the establishment of a specific task force on this topic at the VDE. The authors of this article represent members of this task force, and we are proposing a definition for a DTiPS. As described in detail, the DTiPS is a virtual representation of an existing or future real object. A DTiPS constitutes the description of its attributes and functional properties. It comprises at least two domains and is coupled by bidirectional communication with the real object, accompanying it from planning to disposal. This coupling is achieved through digital autonomous communication and information infrastructure, but manual indirect adjustments are allowed as well. A snapshot twin based on the DTiPS can be extracted, which is decoupled from the real twin. The snapshot twin can be used for simulations, and it is stored close to the DTiPS. Also, it is possible that different DTiPSs are connected by communication technology, which enables information encapsulation while maintaining full sight onto the real twin. There are specific requirements to use the digital twin, e.g., timeliness for updating the DTiPS, response time so that a decision can be made by the DTiPS, accuracy of the infeed data, and the updated parameter values being of interest for the application of the DTiPS. Future applications of DTiPSs have to consider the data processing as an SSOT in detail because the data handling requires an accurate DTiPS. In addition, cybersecurity, confidentiality, fraud prevention, and data integrity are of utmost importance. However, if these topics are solved, the DTiPS is a powerful asset to get in-depth knowledge of the corresponding system, which supports planning and maintenance and reduces the costs by trustworthy, consistent, and continuous data handling. The solid interfaces and the data handling lead to consistent feedback, which allows detailed monitoring, automation, and an accelerated approval phase and supports commissioning.

For Further Reading

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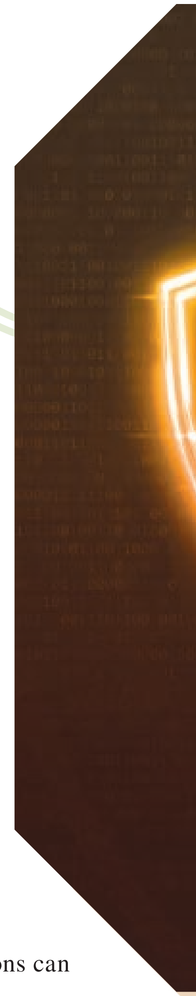
A Fortunate Decision That You Can Trust



Digital Twins as Enablers for the Next Generation of Energy Management Systems and Sophisticated Operator Assistance Systems

POWER SYSTEM OPERATION IS GAINING COMPLEXity due to the changes imposed by the energy transition. Especially, the increased share of intermittent and decentralized renewable generation units in the energy mix, an increased uncertainty regarding the supply of energy, and the predominantly market-driven cross-region and cross-border transport of electricity impose new challenges on the operation of power systems in Europe. In particular, power system operators must facilitate higher utilization of the grid capacity and coordinate more with neighboring transmission system operators (TSOs) and distribution system operators (DSOs). To deal with these new challenges, there is a pressing need to improve the observability and controllability of key system parameters to safeguard the reliability of power systems. Furthermore, the aforementioned developments and challenges go hand in hand with the need to improve the system resilience from the cybersecurity and system stability points of view. In the future, these challenges cannot be met without innovation towards intelligent decision support systems and assistant functions, which allow a look ahead combined with fast response and proactive actions. Here, the rather novel digital twin (DT) concept in combination with data-driven (i.e., machine learning) applications can be purposefully applied.

The DT approach has been identified as a key concept by several industries (e.g., aviation), including the power system domain. In general, the term *digital twin* refers to virtual (via digital modeling) representations of systems, processes, or objects that are able to reflect physical conditions through state abstraction and connect the physical and digital worlds via sensor data streams. The DT concept is promising for applications where future operating conditions must be predicted, or unobservable system states need to be estimated to improve observability. For this reason, the DT is an integral part of recent discussions on road maps for autonomous systems and concepts for achieving a higher degree of automation in the operation of power grids.

This article presents the concept of applying the DT as the core instance in the next generation of energy management systems/distribution management systems (EMSs/DMSs) and discusses the advantages of this prospective novel EMS/DMS architecture. Figure 1 illustrates the evolutionary development in the power system domain from basic DT applications to systems that anticipate automated power system operation. As illustrated here, emerging real-time applications in information technology (IT) and operational technology (OT) enable new opportunities for

Digital Object Identifier 10.1109/MPE.2023.3330120
Date of current version: 12 January 2024

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the increasingly demanding operation of power systems. This trend toward IT/OT convergence is epitomized by the DT concept.

An important prerequisite for the application of DT in EMS is that the simulation engine can process high-fidelity analytical models in order to accurately resolve the discrete states of the physical system. In contrast, data-driven machine learning approaches only mimic the behavior of the observed system. By applying a set of training data (inputs and outputs), these create low-fidelity surrogate models for a certain purpose. However, to improve a DT's applicability, when the original computational model is too time-consuming to provide insights within a required decision interval, surrogate models are perfectly applicable for assistance systems. In turn, a DT based on analytic models can enrich the training data, especially for uncommon operational scenarios.

A Data Federation—The Basis for Efficient DT Creation

The foundation for creating a DT is a data integration approach that allows data to be accessed and queried from multiple disparate sources, such as databases, data warehouses, and cloud storage, as if they were a single unified data source. This approach is often referred to as a *data federation* or a *single source of truth* (*SSoT*). It eliminates the need for data replication, enabling real-time access to distributed data for comfortable analysis and reporting.

By Christoph Brosinsky, Matija Naglič, Sebastian Lehnhoff, Rainer Krebs, and Dirk Westermann

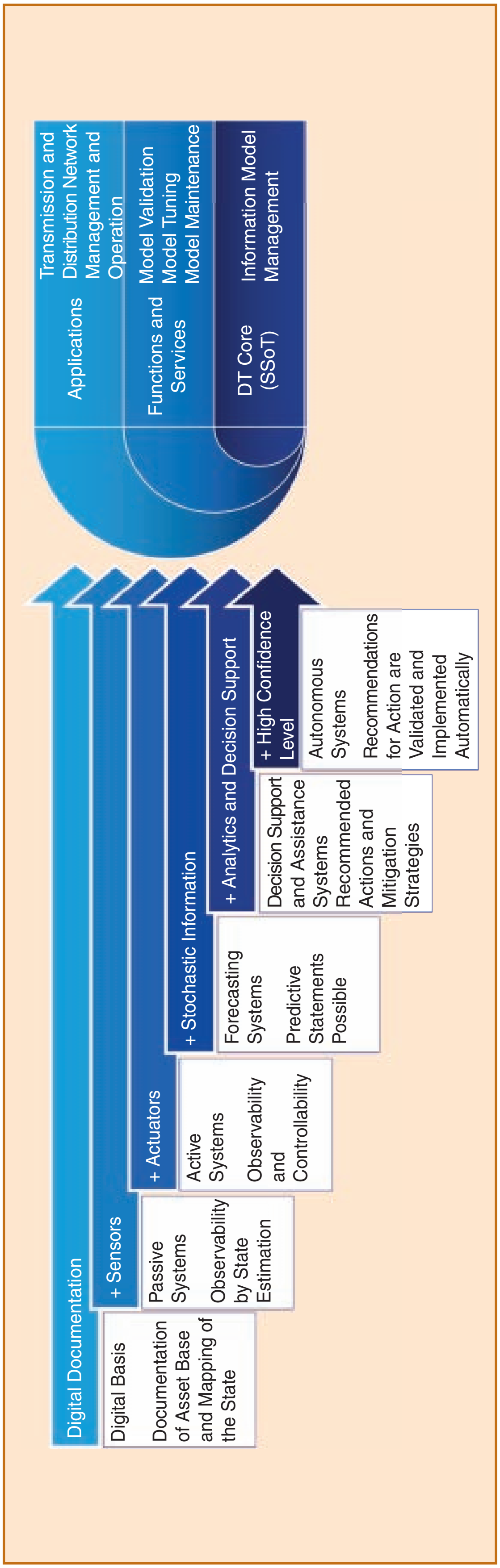

figure 1. The evolutionary development from basic DT applications to systems that enable automated power grid operation. SSoT: single source of truth. (Adapted from an illustration provided by DNV Energy Systems Germany GmbH, 01217 Dresden, Germany; used with permission.)

It is recommended to apply a canonical data model within the data federation to enable seamless integration of information without the need for translation via interfaces among all data sources. To create a data federation of large infrastructures, a data verification engine is an asset to keep the data consistent and maintain integrity.

Today, many TSOs and DSOs still use an isolated (siloed) approach to manage grid and asset data models across the entire business landscape. They maintain different representations or data formats of the physical existing power system in different software tools and data silos. This approach is inefficient and error prone, and it results in fragmented data stored in disparate places, often organized in many-to-many interconnected systems. It increases the risk of data inconsistencies and entails high (manual) effort for the maintenance of duplicate data. Furthermore, such systems are difficult to maintain and to expand. Given the expected increase in grid complexity due to the expansion of renewable generation, this approach is not sustainable in the future. To enable optimal and fast interaction among different tools and applications required for power system planning and operation, proper grid data management and an integrated data governance scheme is mandatory.

Although consolidation across all of the different data silos is very cumbersome, especially in the case of proprietary data models and structures, the effort is rewarded by a significant reduction in effort and sources of error. To harmonize all different data sources of the existing data storages, the remaining data silos connect to the SSoT via a standardized interface or customized adapters. The SSoT creates a business advantage through increased efficiency and flexibility. New data sources can be incorporated in a flexible manner via adapters. In this way, the SSoT becomes the central broker among all applications and data sources in the enterprise. The remaining SSoT representation of the assets within the physical power system is the foundation for maintainable DT applications, and enables adaptability to changing environments by

- ✔ reducing the modeling effort and enabling faster adoption of new technologies
- ✔ supporting effective and profitable market participation
- ✔ improving network reliability through validated and accurate data models.

Figure 2 illustrates the high-level concept of the SSoT. Quality gates during data exchange reduce the effort in data checks and consolidation. The data model quality is assessed by a data verification engine, which leverages the broad knowledge of power system experts to indicate suspicious data in the system representation. In the first development step, the data validation engine can be based on simple rule sets to check the model data for deviations from feasible physical limits, standard values, and typical values from type sheets.

The SSoT comprises a knowledge graph that represents the physical existing grid with entities and relations. The

> The DT concept is promising for applications where future operating conditions must be predicted, or unobservable system states need to be estimated to improve observability.

knowledge graph can capture a broad spectrum of data from structured and unstructured data and is the natural way to represent entities and their relationships. Graphs are manageable very efficiently. The knowledge graph uses a domain-specific ontology stack; this ontology defines the entities and relations based on the electrical infrastructure with different properties.

To address the challenge of creating a power system data SSoT, it is advisable to invest in a robust data integration platform capable of collecting, transforming, and consolidating data from various sources. Ensuring compatibility through the utilization of industry-standard communication protocols and canonical data models is crucial. Furthermore, the accuracy and completeness of data are paramount to preserve the integrity of the SSOT Consequently, this requires the implementation of data quality checks, validation processes, error correction routines and the introduction of data governance practices to sustain data quality over time. This commitment to data quality is essential for upholding the reliability and efficiency of digital processes to manage highly automated power systems.

Notably, the sharing of confidential power system component models among system operators and detailed plant models by equipment manufacturers with third parties is typically restricted due to its criticality or intellectual property concerns. Therefore, stringent security measures, such as encryption, access controls, and continuous monitoring, should be implemented to safeguard the data. Conducting regular security audits and assessments is imperative to remain compliant with pertinent data privacy regulations. The architecture of the data integration platform should align with the objectives of an information security management system, specifically ensuring the confidentiality, availability, and integrity of information. In addition, the development of a comprehensive data governance framework is recommended, which defines the roles, responsibilities and processes required for holistic data management.

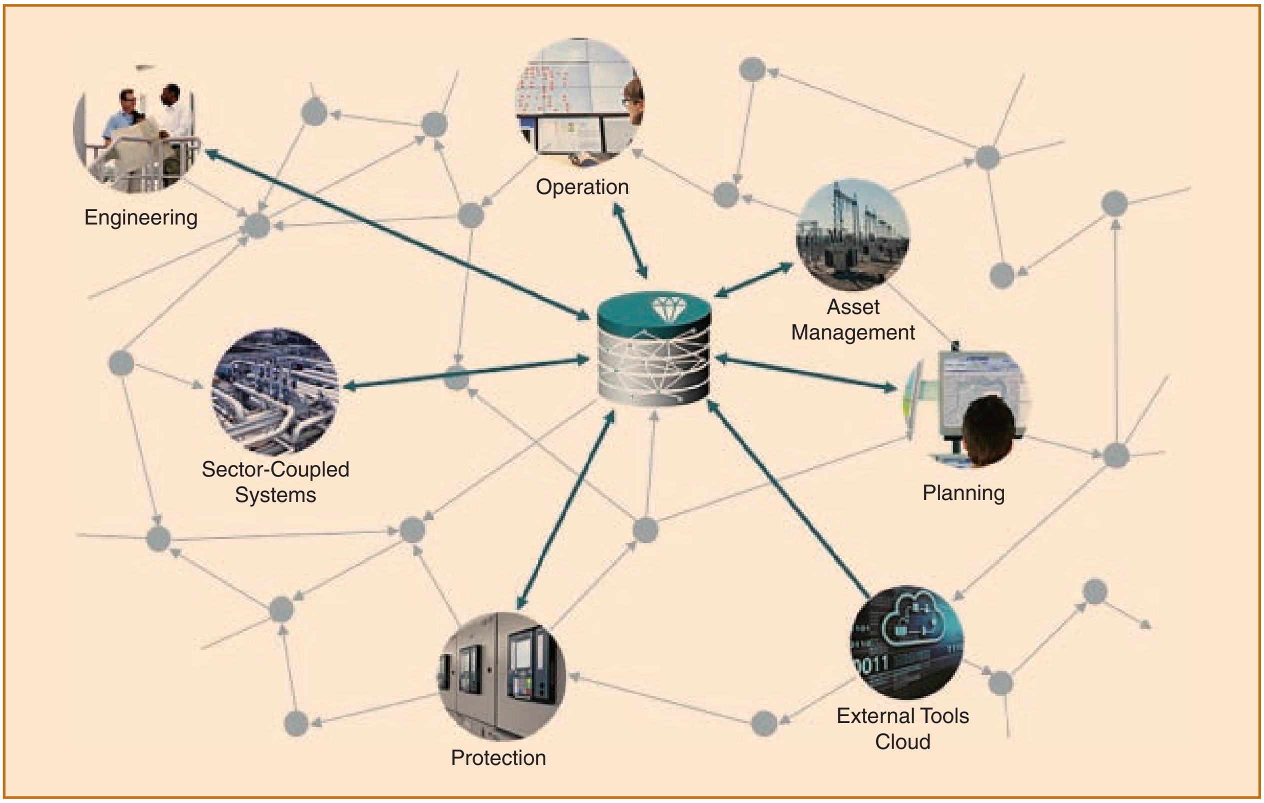

figure 2. A data federation organized as a SSoT.

Vision of DT-Supported EMSs/DMSs Aiming Toward a Higher Level of Process Automation and System Operation

The process of power system operation can be divided into operational planning and system operation. While operational planning comprises all processes to prepare real-time operation, i.e., long-term and medium-term strategies for generation unit and transmission capacity allocation, power system operation focuses on real-time and short-term control actions to ensure stable power system operation and reliable electricity supply.

Today, the operational planning, operation, and control of power systems are primarily model based. Using a model and sensor feedback, state estimation provides real-time observability of the system state. The estimated state is used to subsequently compute optimal control actions, including economic dispatch and security assessment. As the power system operation becomes more complex, a model of high quality and reliability is required to provide the desired degree of observability.

While the quantity and the rate of gathered sensor information in the control room is increasing, the available time to react on critical situations in power systems operation decreases. Therefore, the cognitive capabilities of human control room operators need to be assisted by appropriate tools. To tackle these major challenges, a range of new strategies and novel concepts for future power system operation need to be developed. These include a higher degree of automation and novel system operation strategies considering the planning time frame, that allow automatic adaptation to operational situations, e.g., preventive or curative system operation approaches, the assessment of dynamic security, special protection schemes, and continuous control functions. The novel requirements reveal the key challenge: to set up an appropriate, consistent, and maintainable data model.

A promising approach is to combine traditional power system models and sensor data in a way that allows the creation of a continuously adaptive high-fidelity model of the power system. To reach a higher level of power system automation, an architecture for the next generation of EMSs for the monitoring and control of future electric power systems has been designed. This concept, referred to as a DT-centered EMS, can provide new information for power system operation. The simplified architecture of the proposed DT-centered EMS is illustrated in Figure 3. By applying phasor measurement unit (PMU) data streams with appropriate dynamic state estimation (DSE) and parameter estimation methods, continuous tuning of model parameters is achieved to increase the accuracy of the predicted states and results derived from simulations. Based on a modular framework, the DT-centered EMS enables vendor independent development of advanced decision support applications and assistance functions that support the cognitive capabilities of the human operator.

Considering power system dynamics, the concept enables a wider adoption of synchrophasor data in control rooms since the new type of information provided by the PMU-based wide-area measurement system becomes applicable by many subsequent EMS functions for decision making during real-time operation. The modular EMS architecture aims toward the support and orchestration of applications for different use cases as well as the integration of novel applications and methodologies while keeping legacy system components and applications applicable. The approach furthermore helps to enable the transition toward an integrated data model within energy utilities, which supports actual and future business needs. Through validation by measurement data, human operators gain trust in the validity of the model and, thus, in the implementation of proposed decisions. Instead of taking conservative decisions (considering worst case reserves), actions can be evaluated and secured by simulations. Increasing confidence in the simulation model can help to reduce stress on both human staff and equipment, especially in unexpected situations, and, finally, mitigate the risk of human control room operators making unfortunate decisions.

To address the challenges of future power system operation, next-generation EMSs must provide the following features:

- ✔ an appropriate, consistent, maintainable, exchangeable, and machine-interpretable canonical data model
- ✔ the flexibility to adapt to altering business needs by a modular software architecture
- ✔ support for legacy system components and applications while facilitating the integration of novel applications and methodologies
- ✔ online applications that propose preventive or curative actions to maintain or re-establish a secure system state
- ✔ the ability to relieve human operators of numerous manual interventions to address the increasing number of events and rising response time requirements by a high degree of automated subroutines.

These requirements and functionalities have been considered in the proposed EMS architecture illustrated in Figure 3. It comprises the following novel components:

- ✔ a DT database including a model management platform (SSoT)
- ✔ a modeling engine that can run several model instances in parallel as a sandbox instance for decision support
- ✔ a dynamic digital mirror that continuously validates the master model by measurands
- ✔ a model parameter estimation function that can tune model parameters according to the objective to minimize the model error
- ✔ an automation system that can create scenarios from the validated master model to assess system security and predict future system states.

Concept of Online and Offline Dynamic Security Assessment Utilizing a DT

Maintaining adequate levels of power system stability is regarded as one of the key responsibilities of transmission and distribution power system operations. According to

Kundur et al. (2004), the stability is "the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact."

Nevertheless, the ongoing changes in the energy mix have led to a decrease of system inertia and in an increasing number of partly novel dynamic phenomena in the power system. This, in combination with the higher grid utilization, which results in less available grid capacity to manage power flow changes (for instance, during unexpected events and remedials), can negatively impact the stability of the power system.

To determine whether and at what level a power system is safe against disturbances (contingencies), a security assessment analysis is performed. The classical static security assessment (SSA) is based on a power flow study and aims to validate that the line flows and bus voltages following a defined set of contingencies in a steady state remain within acceptable boundaries. However, SSA neglects all fast-changing transient behavior following a contingency and does not guarantee that a safe postcontingency state can even be reached.

To bridge the gap, a dynamic security assessment (DSA) based on detailed dynamic grid models and performed time-domain simulations validates the ability of a power system to withstand a defined set of contingencies throughout the transient period and reach an acceptable steady-state operating point. Typical DSA analyses include but are not limited to an assessment of critical fault-clearing times; transient stability; voltage stability; loss of synchronism; identification of poorly damped interarea oscillations; and short-term violations of electrical quantities, such as voltages, currents, and angles.

DSA tools can be used to reliably assess the grid security while considering occurrence of potential small-signal, voltage, frequency, converter-driven, and resonance-related stability issues. Depending on the phenomena to be investigated, future DSAs may be root mean square (RMS) or electromagnetic transient (EMT) simulation based or even hybrid by the connection of multiple simulators.

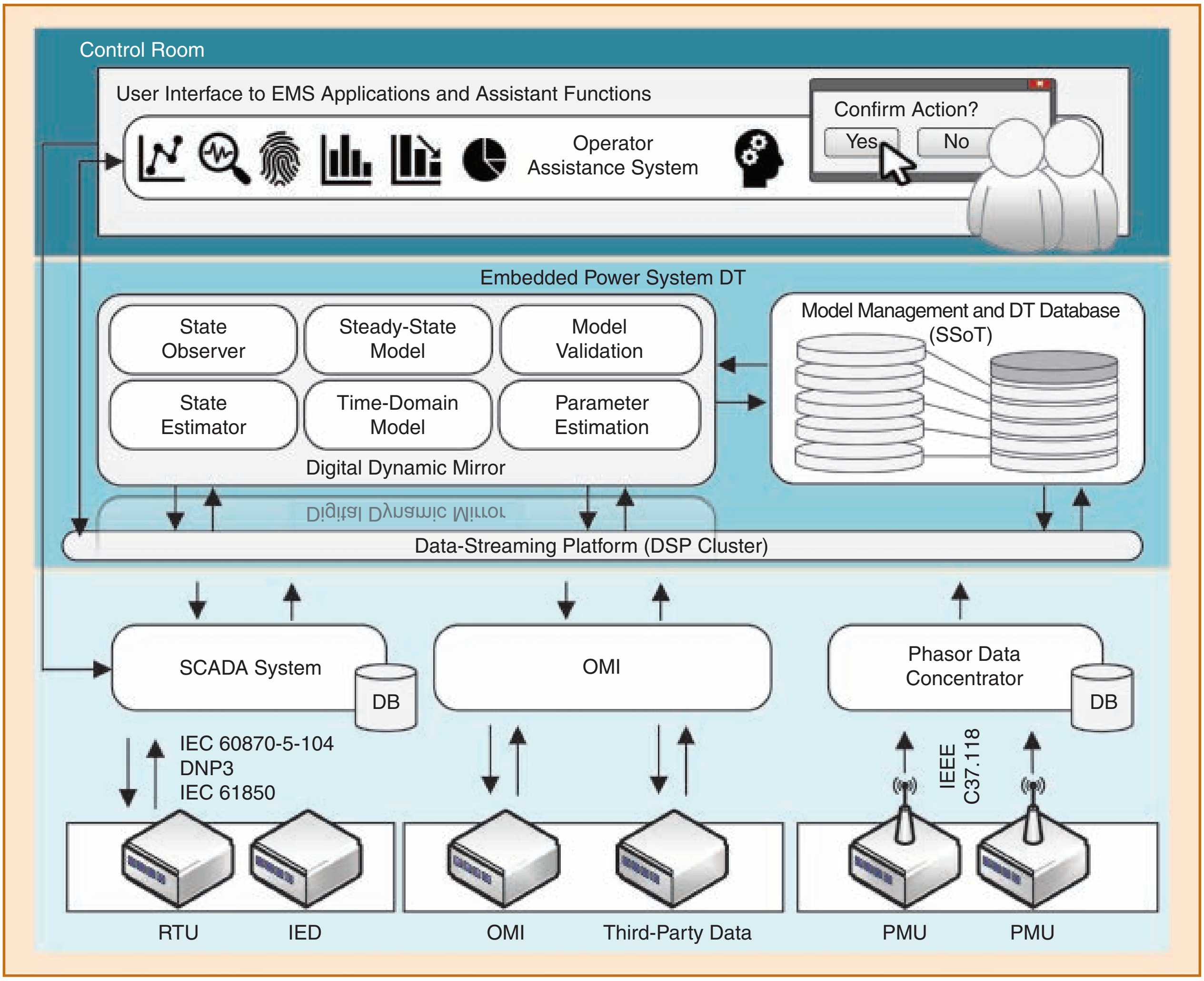

figure 3. The reference architecture illustrating an EMS/DMS with an embedded power system DT. See also Brosinsky (2023). DSP: digital signal processor; OMI: other metering infrastructure; PMU: phasor measurement unit; SCADA: supervisory control and data acquisition. DB: data base; IED: intelligent electronic device; RTU: remote terminal unit.

Figure 4 demonstrates the main functional components of the new concept of online and offline DSA utilizing a DT. As visualized in Figure 4, the concept is twofold and consists of input and output information. We distinguish two processing streams: first, to estimate the present and, second, to predict the future operating conditions. On the one hand, *online* DSA refers to the measured and status data required to estimate the present grid state and perform stability analyses for a limited set of the most credible contingencies. The following two *online* functions are crucial to continuously adapt and match the digital grid model of a DT to reality:

- ✔ In online mode, DSE is used to continuously to estimate the changes of state variables with respect to time and is based on measurements (i.e., PMU) key system parameters. DSE is particularly suitable for estimating the oscillation dynamics of the system, such as power angle, equivalent rotor speed, transient fluxes, and voltages. The DSE algorithm also enables the short term prediction of future network states.
- ✔ Model calibration and parameter estimation is used for the continuous validation and calibration of the grid model parameters to improve the accuracy of DSE estimates. For this purpose, the measurements of actual grid events are compared with the dynamic response of the grid model for the same events. In the case of discrepancies in the model response, the algorithm identifies the best model parameters (of generators, loads, and line parameters to name a few) to be calibrated, including their optimal values to match with reality.

On the other hand, *offline DSA* refers to various forested data and other grid-related information (e.g., switching plans and outages) to predict the typical future grid state. Here, the following functions are key:

- ✔ A grid-scenario builder is used to build the power system models embodying present and future grid scenarios by taking into account the present and future-like grid model as well as to present environmental conditions and their forecasts. For example, it takes into account weather parameters to determine the grid transmission capacity over time, including cross-border capacity. It uses outage planning information, DSE results, and various forecasts (renewable energy sources, the system load, the underlying DSO grid state, and extreme weather) and, finally, stores and makes the grid models

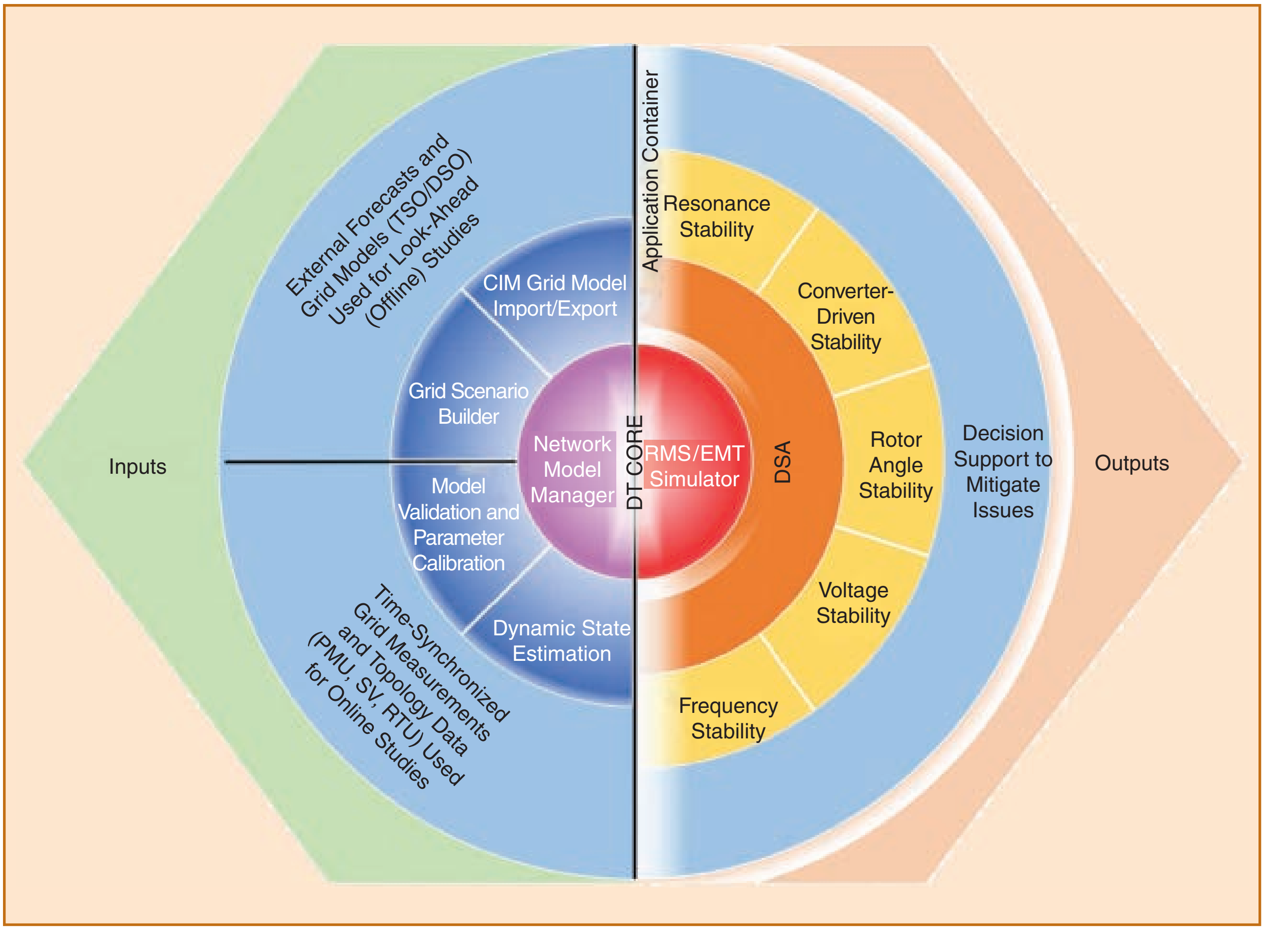

figure 4. The modular approach allows the DT core functionality to be applied multiple times by various applications (like the DSA in this example) being hosted within application containers. CIM: common information model; RTU: remote terminal unit; EMS: electromagnetic transient; RMS: root mean square.

> The network model manager is a centralized solution to manage various versions of the grid model over a changing time horizon (the past, present, and future).

available to the RMS and even more detailed EMT simulator via the network model manager functionality.

- ✔ Standardized grid model import/export, e.g., by the common information model (CIM), is recommended to exchange any changes to the present (i.e., unexpected events) and future (i.e., planned outages) grid model with external stakeholders and vice versa. Industry standards like the canonical CIM-based Common Grid Model Exchange Standard profile can be used to achieve vendor interoperability and to benefit from synergy effects in the power system community.

The key DT functionalities, encompassed into a DT core illustrated in Figure 4, consist of the aforementioned functions, including the following:

- ✔ The network model manager is a centralized solution to manage various versions of the grid model over a changing time horizon (the past, present, and future). The network model manager stores the grid model using the CIM format and makes the grid model data exchange trivial and fully automated via the CIM grid model import/export functionality.
- ✔ The RMS/EMT simulator is used to run multiple time domain simulations of the power grid in parallel. The simulator connects to the grid model manager to obtain the latest validated grid model and obtain the relevant simulation scenarios for analysis.

The output of the conceptual DT consists of applications utilizing the DT core functionality and decision-making information generated by the DT applications for decision support. Similar to the presented DSA, other applications can be hosted within the application container of the conceptual DT illustrated in Figure 4. Of course, multiple application containers could be run in parallel as modules utilizing the DT core. In case of the presented conceptual DT, the DSA application can be seen as the main grid security assessment engine for which functionality shall be improved over time by means of add-ons. Possible future extensions of the aforementioned classical DSA analytical functionality include but is not limited to the following:

- ✔ the continuous assessment of a minimal level of system inertia or short-circuit capacity to maintain adequate level of system stability and security

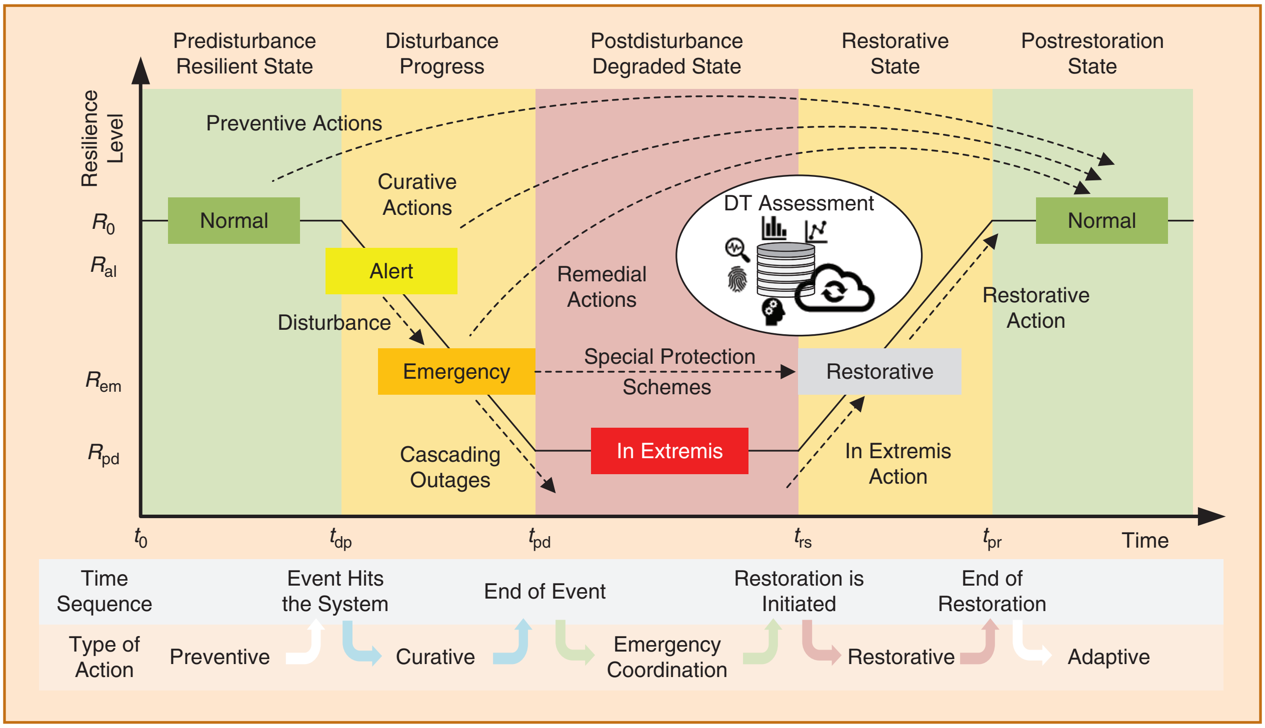

figure 5. The concept of systematic system assessment and automated creation of disturbance mitigation strategies based on Panteli's resiliency trapezoid (Panteli et al., 2017).

- ✔ the assessment of system adequacy in the case of higher power flow gradients due to renewables
- ✔ the validation of special protection schemes based on simulated local (substation) measurements
- ✔ the validation of system integrity protection schemes based on simulated gridwide and centrally collected PMU measurements
- ✔ the (extreme) weather impact on grid assets (e.g., the sufficient cooling of assets in the case of heatwaves or galloping lines due to wind, ice, and snow)
- ✔ optimized decision support to mitigate identified issues with operator feedback learning capabilities
- ✔ the improvement of the online DSA by reinforcement learning to rapidly assess grid security margins without performing a set of numerical simulations of possible contingencies.

As illustrated in Figure 5, the DT-core-based power system assessment in the EMS tries to keep the process parameters of the power system within the required boundaries or mitigate disturbances by providing the ideal or optimized operating trajectory. The assessment is model based and can be achieved through predictive modeling and subsequently applied analytical functions. It should be noted that the DT owner must analyze the field of application and operational requirements, which, in turn, determine the appropriate simulation type and the required modeling details.

A Trust Model to Assess the Coherence and State of DTs

Information and communications technology (ICT) is a key enabler in modern power systems for integrating decentralized actors and coping with increased dynamics of the system, e.g., through the use of DTs on various system levels. However, ICT penetration also increases the overall system complexity and introduces new risks, such as software failures, malfunctions, and cyberattacks. This, in turn, increases the number of factors that affect the state and health of a digitalized power system, i.e., the cyber-physical energy system. In addition to established factors, like functional correctness and safety, other factors, like security, credibility, and usability, need to be considered. Although these aspects may already be considered in certain subsystems (e.g., safety for power lines and IT security for communication networks), they have yet to be systematically integrated into an operational viewpoint of the whole

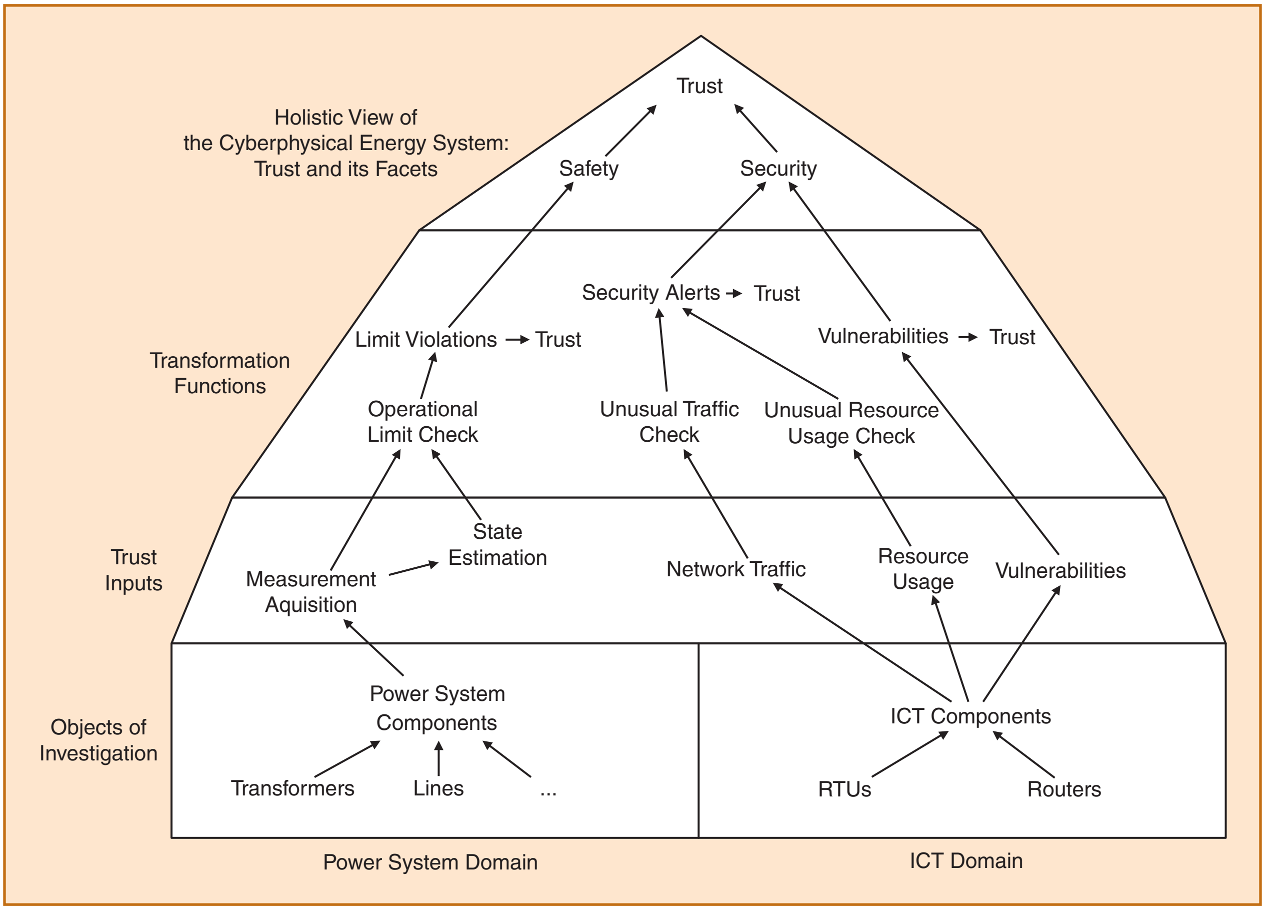

figure 6. An example visualization of trust and its facets. The ellipsis (...) represents all remaining unspecified power system components.

system, i.e., a holistic state and health assessment considering the individual subsystems.

Trust from the domain of organic computing as described by Anders et al. (2011) is one of the first approaches for trust as a holistic perspective on the state of a distributed system with autonomous actors and technical subsystems. It is a subjective, context-dependent, and multifaceted sense about a technical entity with respect to its functional correctness, safety, security, reliability, credibility, and usability. All of these facets can be directly mapped onto the state and health of digitalized energy systems. A trust model on all levels of a digitalized power system, i.e., its DTs, contributes to a coherent state and health assessment, which may then be interpreted by technical subsystems or used by operators in their decision making.

Figure 6 shows how trust facets can be used to get a holistic view of the state and health of a digitalized energy system, considering its components (e.g., transformers and routers) and services (e.g., state estimation or redispatch). Taking a transformer (and its DT) as an example, the six facets shown in Figure 7 can be interpreted as follows:

- ✔ *Functional correctness*: Is the transformer able to perform tap changes?
- ✔ *Safety*: Is the transformer overloaded, or is transformer oil temperature within its limits?
- ✔ *Security*: Are there suspicious cyberactivities targeting the respective remote terminal unit connected to the transformer? Are all measurements available and not manipulated (using ICT health monitoring and intrusion detection systems)?
- ✔ *Reliability*: Can the functional correctness be guaranteed in some future (using reliability metrics, e.g., the mean time between failures)?
- ✔ *Credibility*: In the case of a local or third-party control, is the source of control credible (e.g., through certificate reputation)?
- ✔ *Usability*: In the case of user-interface-based control, is the contextual situation overloaded (i.e., is the situation difficult to interpret by the operator)?

The interpretation of these six facets varies depending on the functionality of the subsystem and its function that is reflected by a DT; e.g., in contrast to a transformer, the safety facet is typically not applicable for a communication network router (which usually cannot be operated outside its operational limits), whereas usability is more complex for supervisory control and data acquisition applications in the control room. Therefore, the trust of the overall system consists of the integrated trust of its individual subsystems, with varying interpretation for facets.

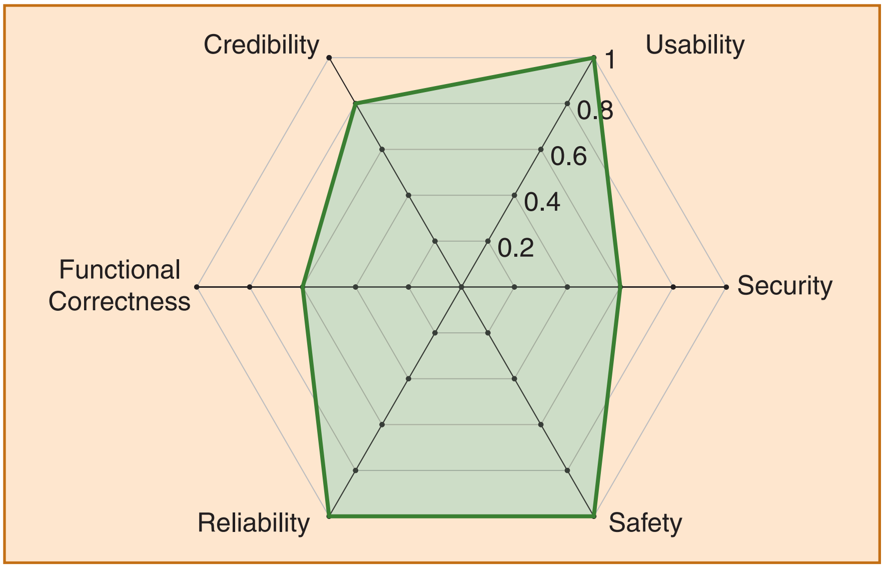

figure 7. The computation of trust.

Conclusion

To avoid the risk of the DT concept being dismissed by engineers and management as hype, this article aims to propagate the understanding of the concept by providing a practical and useful application for power system operation and planning. The concepts and ideas discussed in this article cover a broad spectrum, ranging from those that can be realized with minor adjustments to the state of the art in energy management to those that require significant changes in the EMS and its underlying IT architectures. Future developments and research beyond the state of the art are required in the field of sensor data processing, simulation model tuning, DSE, and many related processes in power system management and operation that are outside the domain of digital technology.

The transformative nature of the concept for power system operators and related enterprises has been highlighted. The overall concept of a DT-supported DT within EMS/DMS environments has been described and substantiated by examples and use cases. It has been outlined that a successful deployment of DTs requires trust in the model, trust in the data, and trust in the algorithms applied for model tuning and system analysis.

Both advanced sensor data processing and reliable modeling are necessary to create the next generation of EMSs. The goal is to reach a higher degree of process automation on the system level that exceeds today's locally realized automatic generation and voltage control in combination with faster feedback controls up to closed-loop control.

As the interaction of IT and OT is combined in the concept of the DT, it can serve as a framework for future EMSs, including novel assistance systems that support human

> A good starting point for creating an applicable DT within an energy utility is to introduce a data federation in the form of an SSoT to consolidate and maintain the available data models.

power system operators in their monitoring and control routines. To provide a validated, high-fidelity, dynamic power system model, time-synchronized phasor measurements of high resolution can be applied for DSE, model validation, and parameter calibration. A model validation routine increases the trust in the underlying power system model as well as the confidence in operational decisions derived from advanced analytic applications, such as online DSA.

Although expert knowledge is required to create the envisioned DT-centric EMS, the deployment is only a matter of computation effort and the deployment of robust model validation and calibration methods. Thus, to create an applicable DT-centric EMS is an interdisciplinary challenge. Here, ingenious in-depth methods from mathematics, computer science, electrical engineering, and cognitive sciences are required. Visionary and dedicated engineers and ICT specialists can improve the proposed concept and use the rich applicability of DTs for power system control and operation.

A good starting point for creating an applicable DT within an energy utility is to introduce a data federation in the form of an SSoT to consolidate and maintain the available data models. Based on standardized interfaces, it can connect all systems and applications producing or subscribing data and be applied for planning, protection, operations, and related areas. Given a validated DT, a trust model comprising all levels of a digitized power system can be created that indicates the state of the power system. Hence, the confidence in decision support functions is high when the system model accuracy is high. The DT, therefore, contributes to coherent system assessment in decision-making processes. The implementation of the concept also influences the role of control room personnel. It will shift toward supervisors of automated processes in the future. By intervening when the automated process is unavailable or exhibits uncertainty or low confidence, they must still be able to maintain the secure operation of the system with manual control. Thus, the human power system operator will remain indispensable in highly automated power systems due to the nature of human intuition when dealing with abnormal situations.

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Digital Twins for Microgrids

Opening a New Dimension in the Power System

THE NEED FOR AFFORDABLE, RELIABLE, SUStainable, and modern energy is now more important than ever because of the climate crisis. Climate change will push up to 130 million people into poverty over the next 10 years and continue to cause more unpredictable natural disasters, such as cyclones, flooding, earthquakes, landslides, tsunamis, and volcanic eruptions. Power outages do not occur only in remote rural areas but also in developed countries, lasting for several hours and even a couple of days, due to the extreme weather in recent years. Microgrids, as a flexible architecture capable of integrating local distributed energy resources (DERs), can satisfy wide-ranging demands via their variable solutions, from off-grid to on-grid applications.

Microgrids have been functioning well for decades within an ecological footprint and provide not only a reliable power supply for rural electrification and critical infrastructure in medical facilities and military bases but also sustainable solutions for communities, buildings, and data centers. To build modern microgrids, it is necessary to enable them to function as a real-time monitoring and controllable unit that is intended to be 1) flexible enough to accommodate advanced digital technologies and digest the uncertainties of the grid edge to form a scalable cyberphysical network;

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Digital Object Identifier 10.1109/MPE.2023.3324296
Date of current version: 12 January 2024

2) resilient enough to run autonomously in islanded mode, with reliable and efficient energy supply to customers in the face of various external or internal disturbances, failures, and disasters; and 3) smart enough to deal with multidisciplinary optimization problems for effective multitype decision support via varying infrastructure and operating conditions in order to achieve a continuous balance of demand and supply.

The digital twin (DT) concept opens a new dimension in the energy system to break down data silos and carry out seamless functional processes in data analysis, modeling, cosimulation, and artificial intelligence (AI)-driven decision making.

To provide a clear vision of DTs and the microgrids of today and tomorrow, this article focuses on DT applications for microgrids in different aspects. Four typical applications of the DT over the lifetime of microgrids, from design to operation and maintenance, are investigated in the following sections:

- ✔ "Application 1: DT for Microgrid Control and Real-Time Energy Management System"
- ✔ "Application 2: DT for Microgrid Protection"
- ✔ "Application 3: DT for Predictive and Prescriptive Maintenance of Microgrids"
- ✔ "Application 4: DT for Real-Time Simulation and Testing of Microgrids."

For each application, key microgrid issues, DT-based solutions, and advanced tools/technologies are presented and discussed.

Application 1: DT for Microgrid Control and Real-Time Energy Management System

The massive integration of DERs at the grid edge brings significant challenges for power system operators in regard to stability, protection, planning, and market operations. Meanwhile, it also offers ample opportunities to provide valuable services to increase overall system flexibility, reduce overall energy costs, and support attaining carbon neutrality targets by 2050. To maximize the DERs' capacity and achieve grid edge reliability, a well-controlled microgrid with two operation modes, islanded and grid connected, is necessary to create a dynamically balanced local energy network. It can achieve wider flexibility through power exchanges with neighboring microgrids and a robust energy transition with the main grid. Modern microgrids have already extended their roles from independent power stations for remote or rural electrification to controllable energy entities with interconnected energy resources, storage systems, and loads that are operated by smart controllers.

Microgrid controls should cover multiple timescales to provide flexibility for future power systems in different aspects: 1) voltage, to ensure power quality and system security, from milliseconds to tens of minutes; 2) power, to balance supply and demand and maintain the system frequency, from seconds to an hour; 3) transfer capacity, to enable power transactions over multilevel energy networks and different active market players, from minutes to several hours; and 4) energy, to integrate advanced power-to-X and vehicle-to-grid techniques for mutual energy balancing over different sectors in medium- and long-term time spans. Behind the control scheme is a massive flood of data from various devices, platforms, and applications through a wide range of communication protocols and with different transmission timescales. Therefore, up-to-date models, accurate data, and automated controls are the foundation to maximize operational excellence. Figure 1 presents an overview of DT solutions for microgrid control. It contains three control levels that support a wide range of services, from the operation of DERs to economic power flow management. This three-level microgrid hierarchical control framework and activities with and without DTs are defined and compared in Table 1.

Application 2: DT for Microgrid Protection

With the complexity of integrated DERs, behind-the-meter activities, and two operational modes, microgrids, as distributed bidirectional energy systems, present unique protection challenges to detect and respond to failures quickly and accurately. The design of the protection scheme for the conventional power system is normally related to the fixed generation limit and distribution topology. However, microgrids are created in varying sizes, topologies, and types; the fault level changes with the operation of each individual microgrid. It is not possible to have a generalized protection scheme that matches any arbitrary microgrid, but it is important to have one that can adaptively detect and respond to faults not only within a microgrid but also in external connections with the main grid or neighboring microgrids. DTs make it possible to reflect the physical conditions of the system and its components with dynamic models and real-time monitoring so that it is easy to access the behavior of the system, recognize anomalies, and then take protective actions autonomously. Figure 2 displays the architecture of DT working principles for a microgrid protection system. In the following section, specific challenges that need to be considered in the microgrid protection system are presented. It is then discussed how DTs can provide effective solutions to resolve these challenges:

- ✔ variable fault current levels
- ✔ disturbances during grid-connected mode
- ✔ faults/events during islanded mode
- ✔ loss of mains (islanding)
- ✔ blinding of protection
- ✔ islanding condition detection
- ✔ resynchronization
- ✔ protection device (PD) selection and interworking
- ✔ bidirectional fault current flow
- ✔ the impacts of the microgrid control strategy on protection.

To mitigate the challenges mentioned above and to provide adaptive protection solutions, a DT can be introduced into a cloud-based digital PD that can be connected to a large virtual protection network for real-time testing, algorithm

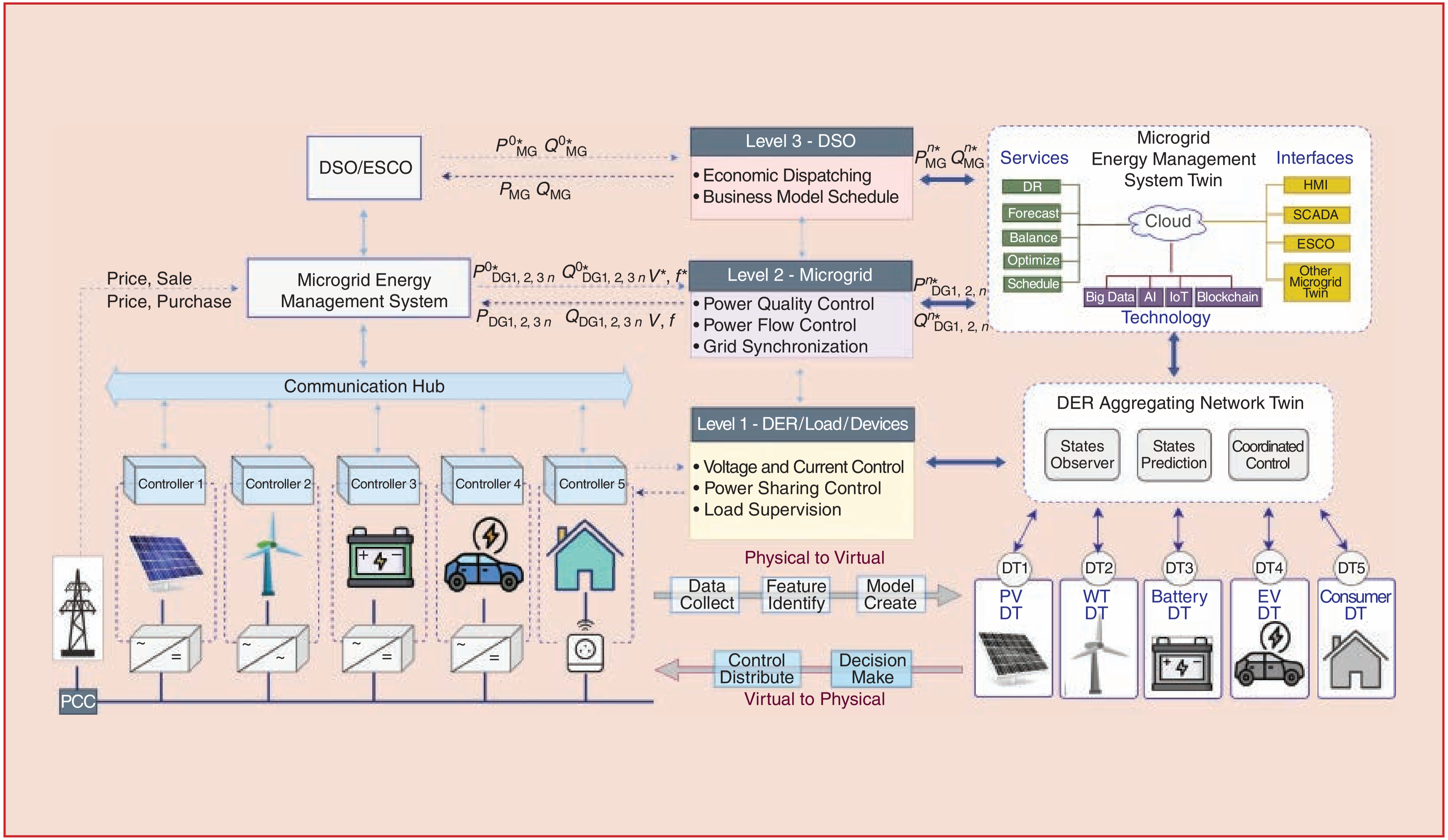

figure 1. DT solutions for microgrid control and energy management systems. PCC: point of common coupling; DR: demand response; HMI: human–machine interface; IoT: Internet of Things; PV: photovoltaic; WT: wind turbine; EV: electric vehicle; P_{MG}: active power of microgrid; Q_{MG}: reactive power of microgrid; P_{DG}: active power of distributed generation; Q_{DG}: reactive power of distributed generation; DSO: dstribution system operator; ESCO: energy service company; SCADA: supervisory control and data acquisition.

optimization, and adaptive function setup over different protection levels. A cloud-based solution for microgrid protection is a pivotal strategy for addressing the multifaceted challenges encountered in modern microgrid systems. Leveraging the scalability and real-time data analysis capabilities of the cloud, it offers dynamic adaptability to variable fault current levels, swift detection and response to faults during grid-connected and islanded modes, and efficient coordination of PDs. Additionally, cloud platforms facilitate data-driven insights, enabling operators to assess the impact of control strategies on protection. This technology also excels in handling bidirectional fault current flow, ensuring accurate fault identification and response. With the cloud-based solution, at the system level, the DT creates a networked context-aware ecosystem that is capable of covering the abstraction of each component and able to construct a map of virtual entities and then capture a real-time operation snapshot to help identify and respond to the correct fault events. For example, the magnitude of fault current depends on the nature of DERs and the integrated location in microgrids. The fault currents contributed by photovoltaics, wind turbines (WTs), electric vehicles (EVs), and batteries are each significantly different since DERs in microgrids are highly dynamic and dependent on the availability and operation of these different resources at any given moment. Further, in grid-connected mode, the fault current level often may be significantly higher than in islanded mode, primarily due to the combined contribution of both the main grid and DERs. However, the actual magnitude of fault current can vary widely depending on factors such as the size, capacity, and configuration of the DERs; the fault location; and the specific characteristics of the microgrid's design and protection system. Therefore, it is necessary to have a clear overview of the system layout, operation mode, and component parameters to accurately predict and take action on fault current. The main blocks and functions of the DT-enabled microgrid protection system in Figure 2 are discussed as follows:

- ✔ *DT for microgrid PD automation*: This refers to a DT at the component level. In the protection system of a microgrid, there are four typical protection zones that need four types of PDs: 1) PD1 for the microgrid point of common coupling, 2) PD2 for DERs, 3) PD3 for low-voltage feeders, and 4) PD4 for load protection. Each physical PD has a digital replica that includes a dynamic model, communication interfaces, and required algorithms. The DTs for PDs, acting as sophisticated computers, can reflect real-time physical conditions/behaviors, identify/predict needs for protection/anomalies, and self-tune to update the data model and, finally, optimize/impact the protection behaviors of physical PDs.
- ✔ *Microgrid and network digital shadow*: This refers to a digital shadow of the microgrid at the system level, which includes a virtual representation of the microgrid and network topology abstraction. Compared with the DT, the digital shadow will not automatically implement control of the physical system. This layer is responsible for representing the detailed dynamic models of the system and its interactions with adjacent systems, enabling real-time system observability and synchronization as well as providing highly compatible communication interfaces to the upper DT processor.
- ✔ *DT processor for algorithm optimization and online testing*: This is the core of the entire architecture, which acts as a high-performance computing engine to aggregate and map the component-level DTs and

table 1. DT-enabled microgrid control functions.

Microgrid Control	Original Activities	DT-Enabled Activities	DT for Services With Various Timescales
Level 1: DER/load/devices	• Voltage and current control • Power sharing control • Load supervision (DR)	• DER DT • Asset monitoring and state prediction • Component-level supply/demand forecasting • Device-to-device coordinated control	Milliseconds~minutes Distributed control/model predictive control: • Data-driven/physical model • IoT/AI • Edge computing
Level 2: microgrid	• Power quality control (voltage/frequency regulation, harmonics mitigation, transient voltage/current control, and so on) • Power flow control • Grid synchronization/island detection	• DER networking DT • Real-time DR • System-level supply/demand forecasting and balancing (individual/neighborhood microgrids) • Local/regional flexibility products	Minutes~days Multiobjective optimization/process scheduling: • Big data analysis • AI/insights • Optimization • Cloud computing
Level 3: distribution system operator/energy services company	• Economic dispatching • Business model schedule	• Business model DT • Coordinated flexibility model • Interface standardization (supervisory control and data acquisition, HMI, other microgrid DTs) • Real-time energy management system with grid/market	Days~weeks Process design/decision making: • Quasi-dynamic simulation data strategy and architecture • Virtualization

system-level digital shadows into a digital world. It provides an environment to integrate advanced data, the Internet of Things (IoT), and AI technologies that can support online simulation and testing. A stress test, with a wide range of protection/fault scenarios, can be deployed using historical data, training algorithms, and anomaly libraries to generate optimized protection algorithms. Finally, the updated data model, PD configuration files, system states, and networked graph can be synchronized with PD DTs for automated protection.

Application 3: DT for Predictive and Prescriptive Maintenance of Microgrids

The ever-increasing complexity of microgrids necessitates advanced operation management and maintenance strategies. Maintenance activities should be scheduled well in advance in order to prevent unexpected failures. To reach high levels of reliability, the condition of individual assets, as well as their impacts on the overall system performance, should be considered. A timely maintenance schedule and execution help to prolong the lifetime of components and reduce lifecycle cost, maintenance cost, and the cost imposed by out-of-service penalties, thus increasing the operational availability of the system as well as reducing the risk of exposure of the crew to life-threatening situations. Safety, service quality, and cost are three important criteria for developing maintenance strategies. Considering the time of execution and the type of required activities, maintenance strategies fall into different categories, as listed in Table 2. There is another category called *prescriptive maintenance*

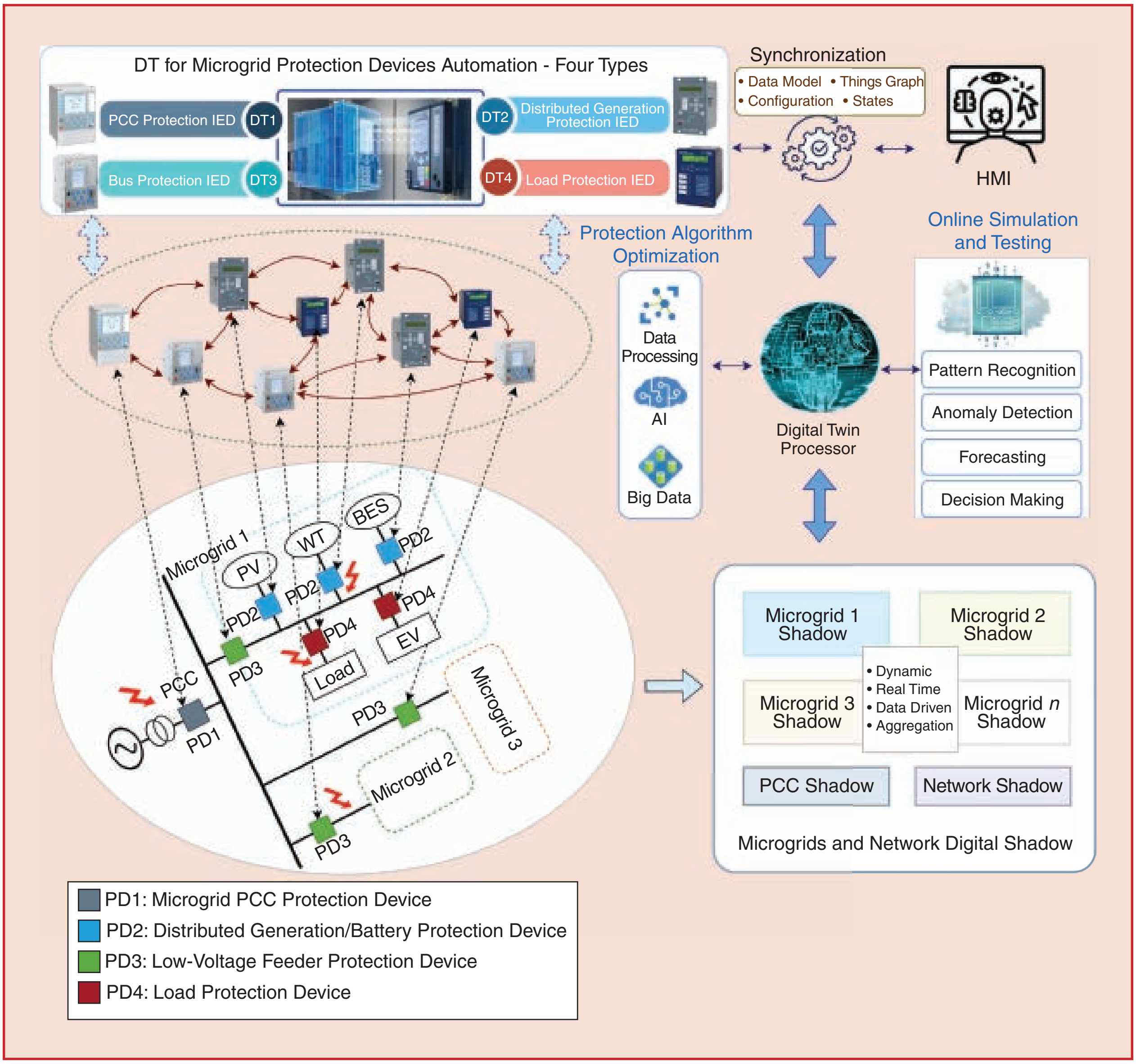

figure 2. The DT framework and working principles for microgrid protection. IED: intelligent electronic device; PD: protection device; BES: battery energy storage.

that, in addition to predicting the condition of components, prescribes an action plan.

Predictive maintenance strategies are used to find the most cost-efficient point to repair or replace assets and estimate their remaining useful life. It is especially attractive in cases where accessing a physical asset would be difficult due to a harsh environment, such as space and marine applications, the aviation industry, or when there is high risk for human lives or environmental pollution. In critical infrastructure, such as a microgrid, predictive maintenance plays a key role in minimizing system downtime. One of the key challenges of predictive maintenance is the lack of large run-to-failure datasets that are required to develop models used to predict system conditions. In this sense, DTs can play a critical role by providing a high-fidelity simulation platform to generate synthetic data from hypothetical failure scenarios, all without compromising the safety of the system. When deploying advanced data analytic tools, real data obtained from the system, as well as accurate synthetic data generated by the DT, are used to develop high-fidelity models for predictive maintenance that facilitate the prediction of an asset's condition and accurate estimation of its remaining useful life. A DT, as a living model of its physical counterpart, will continuously adapt to the changes in the asset's condition and the operating environment using real-time data, thus consistently making available the up-to-date status of the health of system components. Any abnormalities will be detected in a timely manner, warnings will be delivered, and repairs made possible by providing system operators with a ranked maintenance plan, taking into account the severity of potential failures. Figure 3 gives the DT framework for predictive and prescriptive maintenance.

DTs can also be used to validate maintenance activities in the virtual microgrid environment before implementation. In the case of a malfunction or failure in the system, a root cause analysis can be performed to identify and localize the fault, thereby minimizing the crew intervention and workload. This also facilitates the training of maintenance personnel in a low-cost low-risk environment by simulating several adverse operating conditions and then executing different repair actions. DTs provide an efficient tool for keeping track of maintenance records over the lifecycle of components. The DT has been studied for anomaly detection (which can be followed by scheduling maintenance activities) and prognostic health monitoring in electricity systems. An example would be the gradual degradation monitoring of WT components, real-time disturbance detection in distribution networks, and predictive maintenance of power plants and EVs, among others.

Predictive models developed for health monitoring and prognosis can be generally classified into data-driven and physics-based models. Hybrid methodologies, including physics-based and data-driven models, are becoming very attractive, as they can benefit from the advantages of both techniques, where data-driven models can be used for anomaly detection and the cause of defects can be identified with physical models. Depending on the application, both in-house health monitoring systems inside the physical components and remote monitoring systems can be developed using fast and reliable communication systems and cloud platforms.

Application 4: DT for Real-Time Simulation and Testing of Microgrids

With the increasing use of renewable energy, microgrids now have higher requirements for flexibility and intelligence and are becoming more and more complex and heterogeneous. This poses new challenges to the real-time simulation and testing of microgrids in order to enable a more accurate and dynamic design and operation process able to enhance robust control, predictive maintenance, and demand response capabilities. A DT is a powerful tool capable of improving the simulated efficiency of multiple aspects of microgrids with high-performance IoT communication, rich modeling exchanges, and AI-based optimization.

Figure 4 presents an architecture for microgrid real-time simulation and testing with the DT concept by incorporating three key components of the DT: digital shadow, twinning engine, and DT evaluator. A microgrid is a heterogeneous

table 2. An overview of different maintenance strategies.

Maintenance Strategy	Time to Do Maintenance	Advantages	Disadvantages	Potential Role for DT
Reactive maintenance	After component/ system failure	Suitable for low-cost low-risk components with no serious consequences in case of failure	Risk of system failure and unexpected service interruption, safety issues, very high cost	Root cause analysis
Preventive maintenance	At preset times	Clear process that includes expert knowledge	Waste of components' remaining working hours, infant mortality, high cost	Maintenance time setting
Condition-based maintenance	Reaching prespecified condition thresholds	Avoids excess maintenance and waste of assets and cost	Complex, high computational burden, medium cost	State-of-health monitoring
Predictive maintenance	The optimum time	Suitable for critical assets that are difficult to repair and replace	Very complex, very high computational cost, requires run-to-failure data	High-fidelity predictive models

system that integrates multivendor devices. Normally, only black-box models or behavioral models are available for components, so it is necessary to have a standard interface to integrate and exchange dynamic simulation models. A functional mockup interface is introduced in this application, which focuses on the model encapsulation with the functional mockup unit and exchanges black models from different popular electronic and power system software and hardware-in-the-loop platforms. It provides great convenience for system-level DTs. From Figure 4, we can see that a DT can bring new features and capabilities to microgrids:

- ✔ Through complete and accurate modeling, a microgrid DT creates a high-fidelity snapshot of the physical microgrid, which greatly facilitates real-time observation of the system.
- ✔ With high-performance IoT communication, a microgrid DT creates a bridge between the physical microgrid and its digital counterpart. Status information, control commands, and behaviors can be synchronized in real time.
- ✔ With AI, a particle swarm optimization-enabled DT engine, a microgrid DT is a data-driven and self-adaptive framework, which takes the physical models as a baseline and then enhances and continuously tunes the parameters with system real and long-term data to achieve model enhancement learning.
- ✔ A microgrid DT can provide in-depth observation and describe inner component interactions in great detail, which provides the possibility of building complex, low-frequency, and extreme condition simulations.
- ✔ By integrating a system-specific evaluator, a microgrid DT can be situation aware and help to estimate the health state and identify abnormal operations and malfunctions in order to achieve high predictive maintenance capability and sustainable decision making.

Conclusions

Modern microgrids pose many planning, operational, and business challenges for utilities with the big data bang. DTs help to establish a data-centric framework that is capable of cutting across all domains and breaking down data silos, enabling seamless decision making that improves the costs/benefits for end users and different market players. It also provides an open platform with agreed access, interoperable standards, and security protocols to integrate advanced technologies and tools as well as services for microgrids to maximize DER value. As analyzed in this article, DTs are built to support various microgrid applications, providing a data-centric framework that transcends traditional boundaries and dismantles data silos. To embark on the journey toward an advanced microgrid distribution management system, it becomes essential to inherit interactive twins and higher-level twins from these functional twins. This inheritance process evolves in tandem with the maturation of the platform and the proliferation of software-defined

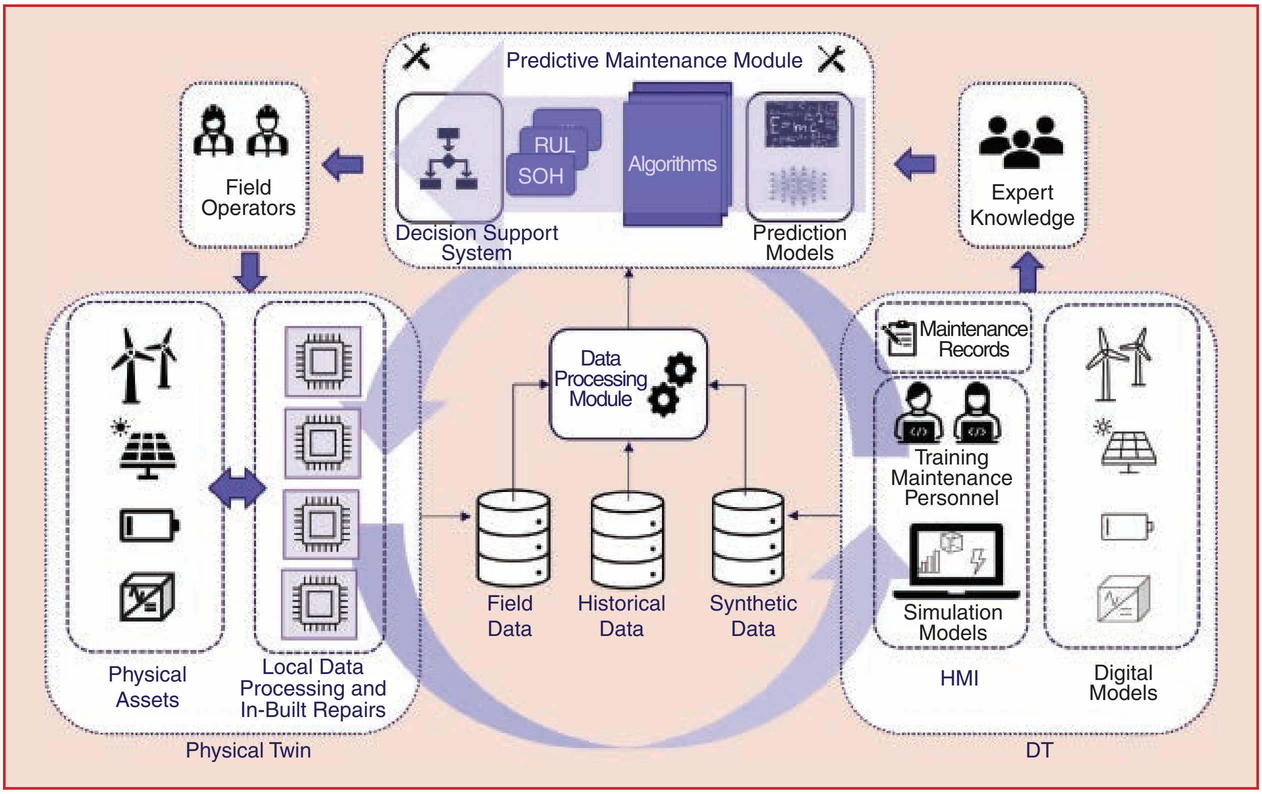

figure 3. The DT framework for microgrid predictive and prescriptive maintenance. RUL: remaining useful life; SOH: state of health.

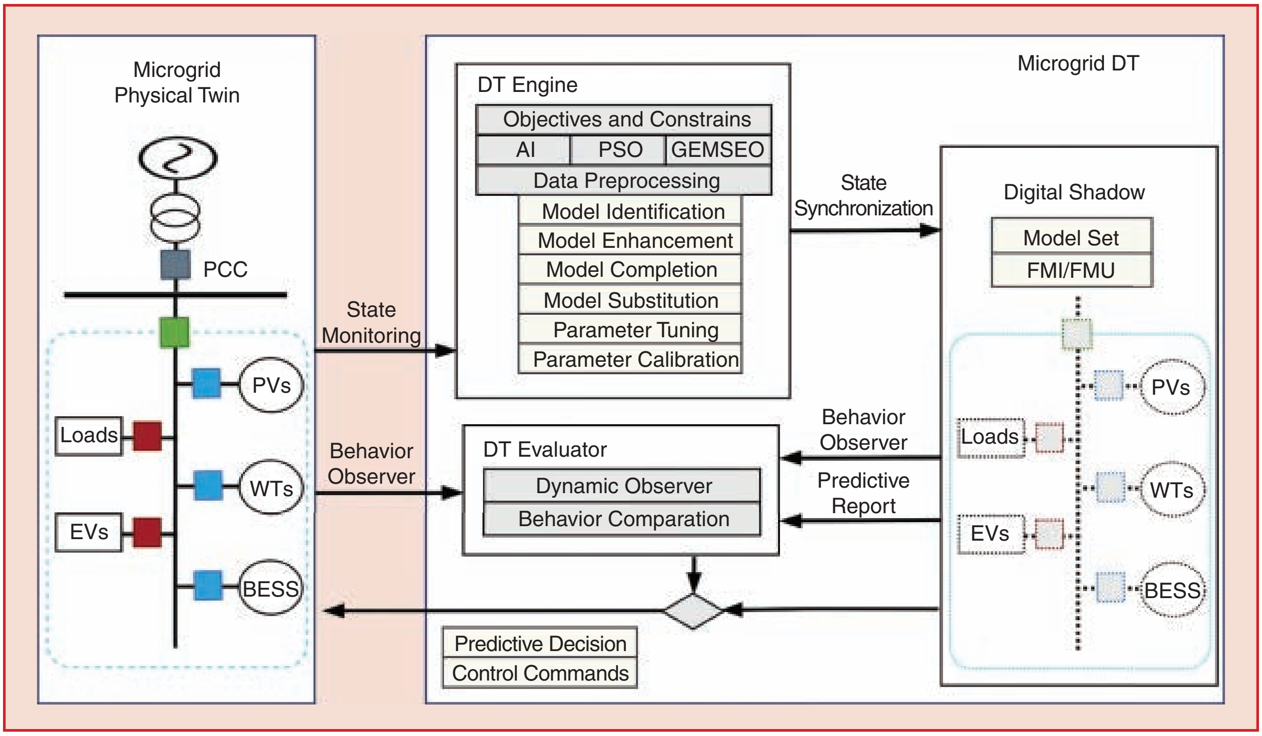

figure 4. An architecture for microgrid real-time simulation and testing with a DT. FMI: functional mockup interface; PSO: particle swarm optimization; FMU: functional mockup unit; BESS: battery energy storage system; GEMSEO: generic engine for multidisciplinary scenarios, exploration, and optimization.

technologies. These encompass software-defined automation, networking, storage, and data center capabilities, which collectively empower microgrid management systems to operate efficiently and effectively in an increasingly dynamic and data-driven landscape.

Acknowledgment

This work was supported by the Villum Foundation, under the Villum Investigator Grant (25920): Center for Research on Microgrids.

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Self-Organization in Cyberphysical Energy Systems

Seven Practical Steps to Agent-Based and Digital Twin-Supported Voltage Control

DUE TO THE ENERGY TRANSITION, ENERGY SYSTEMS need to become more agile, effective, and efficient. More situational awareness and direct responses to changes in the flow of energy are required, especially for electrical energy systems, where demand and supply must be balanced continuously and the power quality must be preserved. This change can be achieved by adding extra sensors, actuators, and information and communication technology (ICT) to collect and analyze data and to make decisions. The addition of ICT results in evolution toward a cyberphysical energy system (CPES), where physical and computational components are integrated to monitor and control physical energy processes.

Currently, the design, construction, operation, and maintenance of these CPESs are a huge challenge, because we, as a society, are not completely sure yet what the future energy system will look like. Much is still unknown about the future value chains and responsibilities in the energy market; especially in the domain of decentral and autonomous

Digital Object Identifier 10.1109/MPE.2023.3327065
Date of current version: 12 January 2024

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 1540-7977/24©2024IEEE

control, we expect rapid successive changes. Also, new technologies are on the rise for more efficient production, storage, and distribution and management of (electrical) energy. If the wrong design choices are made, it will become difficult to optimize CPESs in the future, as earlier decisions cannot be revoked, due to them being "built-in" or "hardcoded."

The key to a successful evolution toward an efficient and flexible CPES is to keep a clear separation of concerns and by not hardcoding market organizations, business roles, and responsibilities into CPESs. The concept of a digital twin (DT) provides a unique opportunity to carry out the separation of concerns (Figure 1). However, to avoid destruction of capital, it is important to design and implement DTs with future (and potentially different) usages in mind.

In this article, we use the example of self-organization in distributed voltage control to demonstrate the separation of concerns between the physical and the cyberparts of CPESs using DTs. We describe an approach to develop DTs that reduces the risk of creating an inflexible CPES that is not able to support the energy value chains of the future (in an efficient, reliable, and affordable way).

figure 1. The electrical (underground) grid connects several objects in this picture taken in the city of Groningen, The Netherlands: a transformer house from 1936, a modern apartment complex from 2008, and public electric bicycles. In the near future, they will all be part of a CPES through connected DTs in cyberspace.

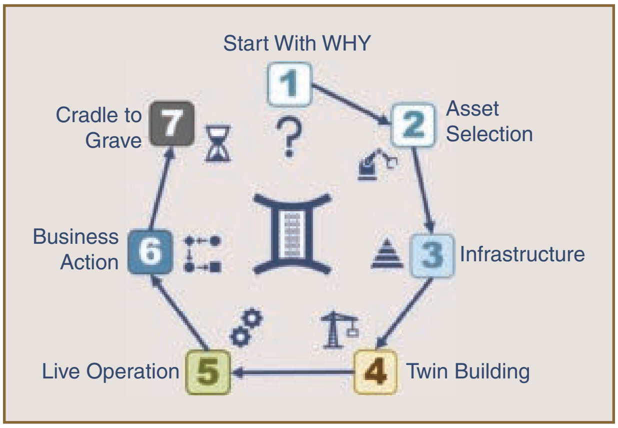

figure 2. The "seven steps to a plan for a DT" strategy, as developed by the TNO.

This approach is based on a seven-step digital twinning approach that was developed for the domain of smart industry by the Netherlands Organization for Applied Scientific Research (TNO). In Figure 2, a depiction of the seven steps can be found.

This article is separated into two parts. The first part is about the need for the digitalization and twinning of the electrical energy system. It describes the challenges in general in terms of objectives that must be met for different stakeholders in the (near) future. It also describes the need for self-organization in distributed voltage control and two approaches for implementation using the "grid edge coordination taxonomy," as introduced last year by Charbonnier et al. in *Applied Energy*. In the second part, relevant aspects of creating DTs to support distributed voltage control are covered. Finally, we provide some conclusions that can be used by parties and stakeholders involved in the evolution of electricity grids to CPESs.

The Need for Digitalization and Twinning

The challenges in the electricity system domain are enormous. The supply of renewable resources and the number of devices connected to the grid is growing, while the topology of feeding in electricity is changing as well. As a result, it is becoming more difficult to avoid congestion and to balance supply and demand, while power quality management is becoming an issue. To make matters even more complicated, the (relative) scarcity of materials and personnel for construction, operation, and maintenance is also increasing. Meanwhile, objectives must be met for multiple stakeholders with sometimes conflicting interests. Next to more insight into the current state of the grid, more control is needed, which in turn drives the need for digitalization and twinning.

Meeting Stakeholder Objectives

There are multiple stakeholders, as well as parties, in the electrical energy system. There are connected customers that want to use the grid (a shared infrastructure) for the transport and distribution of electrical energy. These customers can be electricity producers as well as consumers. The parties trade energy with one another, mostly via energy suppliers and energy traders. There are network owners and system operators that are responsible for the design, construction, operation, or maintenance of the grid. Also, governments exist that have targets for decarbonization. Some of these parties have to comply with regulations that have been set by governments.

For the electrical energy system to function properly (as agreed upon by parties in advance), certain objectives need to be met. In Table 1, we define a sample set of objectives. For each objective, we define an objective beneficiary party (OBP) that will use the result associated with the objective and an objective obligated party (OOP), a party that is committed to produce its associated results. This way of structuring the interest of stakeholders is based on the governance and management pattern from the European Self-Sovereign Identity Framework Lab. The OBP has expectations about the result, and the OOP has matching obligations and vice versa. The parties communicate and negotiate until there is a match between expectations and obligations, which leads to a situation where the objective is met. Results that should be produced by regulated parties, such as an energy supplier or grid operator, can be defined in regulations, which should be seen as a result of this negotiation to match expectations and obligations.

Currently, not all obligations of OOPs in the electricity system are defined in a specific, measurable, assignable, realistic, and time-related way. The lack of such definitions is probably caused by the once natural match between expectations and obligations of parties, especially between grid operators and customers connected to distribution grids. The once oversized capacity of the grid and the single-directional flow of energy from centralized power stations to the edge of the grid did not create a need for such a definition. The natural match is now diminishing due to increased electrification and the distributed feeding in of electricity, which changes the expectations of connected customers and makes the influence of connected customers on the functioning of the grid larger.

Since existing obligations are harder to meet and new expectations arise, renegotiation is required for the uptake of more distributed energy resources (DERs) and electrification. Where the energy transition is happening quickly, it is required that the lines separating concerns can change at the same speed. For example, CPESs should be able to (partially) change from an organizational point of view within one to two years.

In the "Self-Organized Voltage Control" section, we first illustrate how separation of concerns is needed to support rapid evolution in the domain of voltage control. We show why the evolutionary path is difficult to predict, as there are several ways to organize voltage control such that evolving expectations and obligations in the CPES are matched. In the "Cyberagents and DTs for Implementing Self-Organizing (Voltage) Control" section, we explain how the use of DTs can help in implementing this separation of concerns.

Self-Organized Voltage Control

Until recently, grid operators could meet objectives, mainly by good grid design and simple control operations, to

table 1. Objectives in an electricity system and the related expectations and obligations of stakeholders.

Objective	OOP	OBP	Impact of Missing
Access to the grid	Grid operators should realize grid access for new customers. In case of congestion, they might need to refuse a connection request.	Party that wants to become a connected customer so it can consume energy from the grid or feed into the grid	Inability to use (electrical) power, resulting in loss of comfort or money
Decarbonization of energy consumed in the distribution grid	Connected customers together are obliged to produce or consume green energy.	A government with decarbonization goals to fulfill, such as the amount of green energy consumed or produced	Less decarbonization than agreed upon internationally
Manage/avoid congestion	A grid operator is obliged to manage/avoid congestion, if possible, by using market-based options, e.g., asking connected customers to voluntarily provide flexibility to manage congestion. If that is not possible, the operator needs to manage congestion through nonmarket-based means.	Connected customers expect that they can consume from the grid and feed into the grid, which is not possible in the case of congestion.	Inability to use (electrical) power, resulting in loss of comfort, money, or, in extreme cases life In the case of nonmarket-based management, a potential negative impact on the comfort and financial key performance indicators of connected customers
Cost-effective grid reinforcement and flexible usage	A grid operator has a monopoly on connecting customers to the grid and is, thus, directed to be as efficient as possible through governmental oversight.	Connected customers expect affordable prices for using the grid such that they have a certain comfort level or amount of revenue.	Extra and unnecessary costs or an unaffordable grid, in the worst case
Minimizing grid outages	Grid operators have (mostly high) obligations for minimizing grid outages.	Connected customers that want to exchange energy through the grid expect a certain level (mostly high) of grid availability.	Inability to use (electrical) power, resulting in loss of comfort, money, or, in extreme cases, life, and/or other safety risks
Manage voltage in the grid	Grid operators are obliged to try to provide the agreed upon level of voltage, as are parties feeding in like connected customers.	Connected customers have installations that can function only in a limited bandwidth of voltage.	Above or below certain voltages, connected equipment works less effectively, turns off, or (worst case) malfunctions, possibly resulting in safety risks.

OOP: objective obligated party; OBP: objective beneficiary party.

maintain voltage within standards (e.g., International Electrotechnical Commission) and prescribed parameters such that connected customers rarely experienced voltage issues. Now this is more challenging: connected customers are faced with their electric vehicle (EV) charging poles or photovoltaic (PV) inverters stopping consuming or producing power due to under- or overvoltages. In this new situation, existing agreements and understandings about expectations and obligations have to change.

The grid operator has to do more than before to meet the obligations. Grid operators will invest in new options for voltage control, for example, more dynamic (and highly digitalized) voltage control at transformers, and will in some cases choose grid reinforcement, and there will be situations where the grid operator is temporarily out of options. In all those cases, connected customers could become less satisfied (e.g., they do not agree with higher grid costs or are not willing to wait for a solution). In case this happens, both the grid operator and the connected customers will probably look for alternatives and will renegotiate their agreements. A promising alternative is that connected customers contribute more actively to voltage control. This means that obligations will emerge for connected customers, either to the grid operator or directly to other connected customers.

Which new obligations and expectations will emerge cannot be well predicted and will be influenced by cultural, social, economic, organizational, and political contexts, including ad hoc contexts caused by local or global events. New obligations may be defined on a central level (e.g., as a legal obligation for connected customers to deliver voltage control support or the introduction of a real-time auction for voltage support services). It is even possible, within the boundaries of electricity regulation, grid connection, and energy supply contracts, that locally connected customers make bilateral or group agreements to resolve voltage issues. Such new agreements, both the bottom-up and top-down ones, can initially be simple agreements and, over time, evolve to more complex, cost-efficient, and resilient systems of obligations and expectations.

Two example ways of organizing voltage control clearly illustrate the difference in potential evolutionary paths, as they differ significantly from an organizational and information flow perspective. The first way is mediated competition, where coordination of voltage control takes place on a relatively higher level of (physical) abstraction and organization in a CPES. The second way is implicit cooperation, where coordination emerges from the behavior of components in the edges of the grid and no communication to higher levels in an organizational hierarchy takes place. Where in mediated competition, information flows between lower and higher organization layers, information stays at the same level in implicit coordination. In the "Taking Seven Steps Toward DTs for Self-Organized (Voltage) Control" section, an illustration of these methods is provided in more detail while discussing the implementation. Also see "For Further Reading" for more information on coordination of resources at the edge of the electricity grid. The two ways of coordination we use in this article can be found there as well, as part of a larger taxonomy.

Since we do not know in what direction the system will evolve, it might seem as if further development and implementation of the CPESs of the future cannot take place. If a specific organizational structure were defined today and "hardwired" into technical implementations, there would be a high risk of dissatisfied stakeholders in the longer term. For example, due to the arrival of new and/or improved energy technology, artificial intelligence, and/or quantum computing capabilities, stakeholders might want to opt for changes in coordination types to better support the balancing of expectations and responsibilities. This is why, in the following section, we describe an approach using DTs and "cyberagents" that is able to support the expected changes in organizational structures, expectations, and responsibilities. This enables further development in "no regret" evolutionary steps and thus prevents unprofitable investments in technological implementations as much as possible.

Cyberagents and DTs for Implementing Self-Organizing (Voltage) Control

From the example of self-organized voltage control above, we learned that much is yet unknown about the market organization, regulation, and business roles in the future CPES. To reduce the amount of work needed for changing parts of the CPES, it is important to separate concerns while mapping functionality onto technology. In this article, we suggest using the concept of stakeholder objectives, (cyber) agents, and DTs.

Agents are (intelligent) digital components that act on behalf of parties like connected customers and grid operators. They belong to the cyberpart of the CPES. Agents can be seen as systems that can self-organize. They can use information from physical grid components to analyze what to do to meet objectives from stakeholders. This information can be (historical) measurements or forecasts of future behavior based on a model of the physical reality. DTs are useful assets for cyberagents since DTs enable them to use this information to forecast behavior, try new control strategies, and test the system under new circumstances, enabling them to optimize their strategies.

In this article, we define a DT as a virtual representation of a physical object. It contains a model of reality, which can also be composed of cross-domain submodels. There is also a collection of data that contain aspects of (recorded/historic) reality and model output results. Finally, there is a connection between the model/dataset and the outside world: sensors, actuators, (sometimes) a human–machine interface, and/or a communication interface for the exchange of information with cyberagents and DTs. In our view, a country like The Netherlands will have millions of agents in the cyberpart of the CPES representing connected customers and millions of DTs that provide a digital interface for the agents to connect to millions of physical components (e.g., PV installations at homes) of the CPES. Figures 3 and 4 contain a visual representation of the (cyber)agent and DT concepts in terms of the Smart Energy Grid Architecture Model (SGAM).

In the remainder of this article, we zoom in on the information in the "Self-Organized Voltage Control" section, briefly introducing two ways (mediated competition and implicit cooperation) to use agents and DTs to organize voltage control in such a way that stakeholder objectives are met. The TNO seven-step DT planning approach is used to cover all relevant aspects in a structured way.

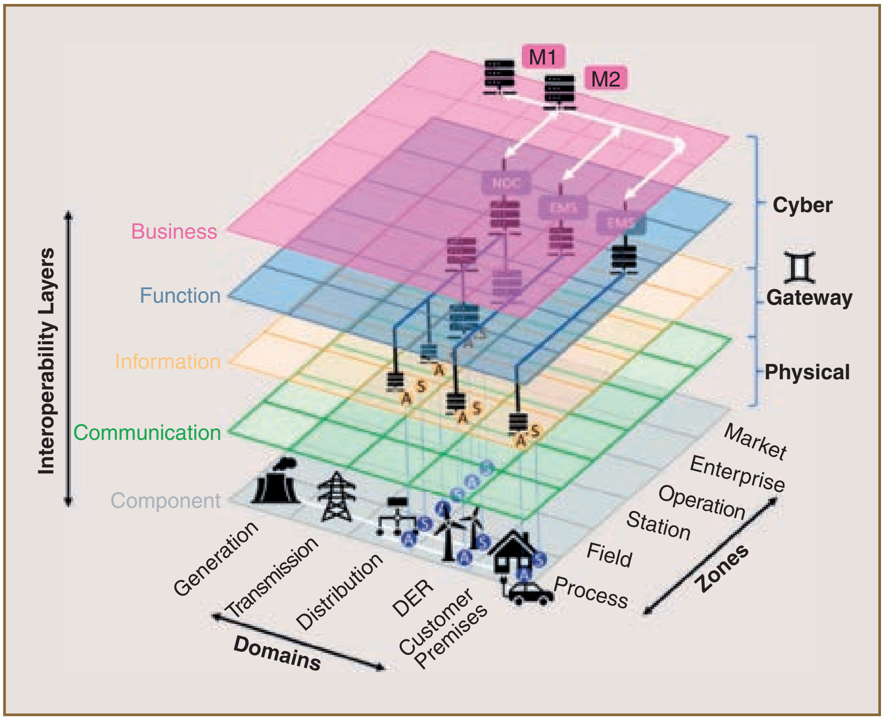

figure 3. The "mediated competition through the market" control strategy in terms of DTs and the Smart Energy Grid Architecture Model. The energy management systems (EMSs) are competing while being mediated by markets (M1 and M2), which the network operating center (NOC) of a distribution system operator can influence (e.g., in case of congestion issues). S: sensor; A: actuator.

Taking Seven Steps Toward DTs for Self-Organized (Voltage) Control

In this section, we introduce a simplified example case to discuss the implementation of self-organized voltage control using DTs. We scope the voltage control area as everything behind a primary substation and assume that two secondary substations are between the grid connections and the primary substation. Furthermore, we assume that there are only two types of assets that consume, produce, store, and convert electricity: PV panels and EV charging points.

In the analysis below, we try to use functionally oriented descriptions of relatively small roles, as we want the reader to be able to see alternative options for organizing CPESs of the future. For example, in a future scenario, professional companies that specialize in operating DTs of grid assets could become responsible for tasks that are traditionally associated with the distribution system operator

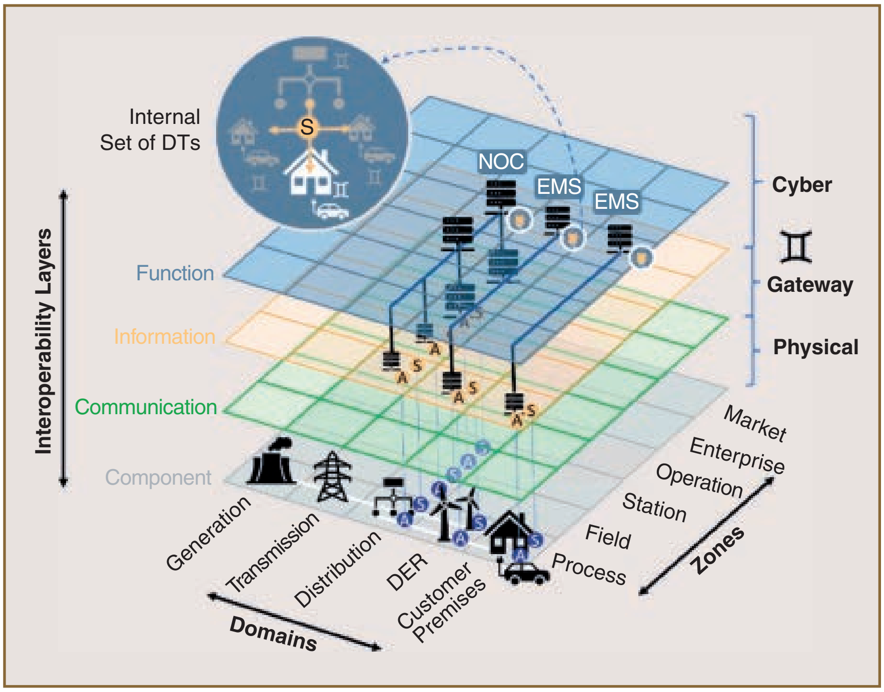

figure 4. The "implicit cooperation" control strategy in terms of DTs and the Smart Energy Grid Architecture Model. The NOC and EMSs do not exchange information but try to create, using sensor information, an estimation of their environment in terms of their own and other DTs' data. They all have an internal set of DTs that they use to make decisions.

(DSO). An example function is providing an estimation of the state of (parts of) the grid.

Steps 1 and 2: Why a DT and What Assets Need to Be Twinned

For brevity and clarity, we combine the first two steps of the "seven steps to a DT" approach. The rationale for a DT ("why," step 1) and "what asset needs to be twinned" ("what," step 2) are strongly intertwined in the case of coordination strategies in a CPES. In the previous sections, we discussed how DTs can support the implementation of coordination strategies for distributed (voltage) control. In this section, we use the two coordination types, as described earlier on, to illustrate that different coordination strategies place different demands on the DT. First, we describe how the two selected strategies can be implemented in a CPES for meeting the objective to keep the voltage within acceptable limits (i.e., "voltage control").

Mediated competition must be carried out by a party that takes up the role of a mediator to support competitive coordination among connected customers. This mediating party is provided (by a supplying party, e.g., a grid operator) with a range of available grid edge resources it may distribute based on a "battle for the best possible deals" between the supplier and the customers. The competition for resources can take place at different areas within the grid, e.g., at the level of a local transformer, a substation, and so on. Different parties have different obligations in providing the objective. In Table 2, we describe what obligations several OOPs have toward the objective "keep the voltage within acceptable limits" in the case of mediated competition. Both the obligations and the expectations of the OBPs are defined in regulations.

We assume, for our example case, that voltage levels are coordinated via a double-sided auction and that every connected customer has an obligation (i.e., by regulation) to coordinate its contribution to the voltage level. Both grid assets and assets connected to the grid can provide voltage support, and so they are both OOPs. Other parties that are seen as OOPs are the voltage market operator that is the mediator that facilitates the coordination and the grid state estimator, also a mediator, the party (e.g., the grid operator) that provides information about the (expected) state of the grid and provides this information (e.g., the outer limits) to the mediator. Note that we assume that for each of the OOPs, it is clear what the consequences are of "not meeting the obligation."

In the case of implicit cooperation, no information is shared among assets in the grid. Decisions are made by the parties themselves (no external mediator), based on locally available information. Operators of grid assets and those connected to the grid cooperate (implicitly) in achieving the objective "keeping the voltage within acceptable and specified limits." Connected customers use models to decide what their actions should be to cater for (cooperative) voltage control. The models are fed with sensor data, and actuators are used to effectuate voltage control. In Table 3, we describe the obligations OOPs have in the case of implicit cooperation. We assume that operators of grid and connected customer assets are responsible (by regulation, social contract, and so on) to contribute to meeting these objectives in the best way possible. In this simplistic example, we also assume that voltage is measured at the location of grid assets and assets connected to the grid and that operators of these assets are aware of what the impact of their control actions on meeting the objective will be.

The conclusion we can draw is that depending on the agency type of the chosen control strategy, there is a significant difference in the need for DTs and what kind of information the DTs should provide to OOPs. In Table 4, the different DTs are mapped to the specific assets from the simplified example described earlier on.

table 2. Obligations of OOPs with respect to the objective "keep voltage within acceptable and specified limits" in a CPES where "mediated competition" has been chosen as a control strategy.

OOP	Obligations of the OOP	Needs a DT
Operator of energy consuming, producing, converting, or storage devices connected to the grid	Must provide timely bids and control grid-connected assets according to the deal that was made (after market clearing)	Yes, to forecast the state of the asset such that it can be translated into bids in the voltage market and to control the asset to meet the obligations that are a result of market clearing
Voltage market operator (has a mediating role)	Must provide a well-functioning auction that ensures the obligation	No, not in a simple market: a double-sided auction suffices.
Grid state estimator (has a mediating role)	Must provide information about the state of the grid and impact of load changes of assets connected to the grid such that this can be used to clear the market while meeting objectives	Yes, to estimate the state of the grid, which is a state that exists on a higher level than single grid assets
Grid asset operator	Must provide timely bids and control assets according to the market clearing	Yes, to forecast the state of the asset such that it can be translated into bids in the voltage market and to control the asset to meet the obligations that are a result of the market clearing

Steps 3 and 4: Using an Infrastructure to Build DTs

We now combine step 3 ("realize an infrastructure for the DT") and step 4 ("build the DT") of the method to describe how to realize the DTs required for supporting the selected control strategies in the CPES. As a means to structure this description, we use the SGAM. As stated on the site of International Electrotechnical Commission standard 63200, "SGAM Basics," "the SGAM is a three-dimensional architectural framework that can be used to model interactions (mostly exchange of information) between different entities located within the smart energy arena." In Figure 3, all three dimensions (domains, zones, and layers) can be seen, next to some other concepts related to DTs that will be explained later on.

The physical part of a CPES can be found at the component layer of the interoperability axis. Different assets can be found in different domains of the business axis: generation, transmission, distribution, DERs, and customer premises. While the components are separated into different domains in the SGAM model, in physical reality, they are connected through the flow of energy carriers.

For the realization of the infrastructure, the perspective of the architectural axis is the most important because it helps us assemble a collection of components in terms of a hierarchical structure at a geographical scale. The first three components are process, field, and station. Physical process components can be identified at the process level. At the field level, these components are controlled using actuators, and data are collected using sensors. At the station level, these data are concentrated, functions are aggregated, and substation automation takes place. This is also where local supervisory control and data acquisition systems are located, and this is also where DTs will be located from a grid perspective. The remaining zones on the architecture axis span a larger geographical area, abstract from (local) physical details, and/or focus on enabling systems that support the primary process. From the perspective of building a DT, the operation zone is highly relevant, as this is where data arrive from different (geographically) distributed components of the CPES and where they are processed and interpreted. The enterprise zone includes commercial and organizational processes. This includes asset management, logistics, workforce management, staff training, billing, and so on. The market zone reflects market interactions on the energy conversion chain, e.g., energy trading and the retail market.

Figure 5 depicts DTs in terms of the SGAM model. In the process zone, at the component layer, there are physical assets at the customer premises, DERs, and distribution domains connected by the physical grid. All these assets have actuators and sensors, which communicate with computing devices at the information layer. At this level, there is information about the state of the sensors and the actuators. This information is also a digital reflection, i.e., a DT, of past

table 3. Obligations in implicit cooperation.

OOP	Obligations of the OOP	Needs a DT
Operator of assets connected to the grid	Sense the state of the objective (implicitly) and be responsive to changes in the signal to maximize the impact on the objective	Yes, 1) to forecast the state of the asset such that it can be translated into a successful cooperative control action ("twinning the asset itself") and 2) for estimating future voltage measurements of the grid when given potential decisions ("twinning the grid from a local perspective")
Grid asset operator	Be responsive to the incentive and coordinate its behavior with other asset operators to maximize the impact on the objective	Yes, 1) to forecast the state of the asset such that it can be translated into a successful cooperative control action ("twinning the grid") and 2) for estimating future voltage measurements when given potential decisions ("twinning the assets from a grid perspective")

table 4. The difference in DTs (functionality) given in the two different coordination strategies.

Asset	Implicit Cooperation DT Requirements	Mediated Competition DT Requirements
Primary substation	DT must provide data of sensors to the operator of this grid asset, including a forecast	DT needs to provide 1) voltage information to the grid state estimator and 2) forecasting information to the operator of the primary substation
Secondary substation	DT must provide data of sensors to the operator of this grid asset, including a forecast	DT needs to provide 1) voltage information to the grid state estimator and 2) forecasting information to the operator of the primary substation
Cables	DT must provide data of sensors to the operator of this grid asset, including a forecast	DT needs to provide 1) voltage information to the grid state estimator and 2) forecasting information to the operator of the primary substation
Asset connected to the grid, e.g., a PV inverter or EV charger	DT must provide data of sensors to the operator of this grid asset, including a forecast	DT needs to provide voltage-related information to the operator of the asset connected to the grid

states and can be used to make estimations of future states. Note that in the distribution domain, there are also sensors and actuators in equipment in the field and station zones. This is because a DSO has more geographically distributed equipment than a customer. The information can be used by CPES elements at the function layer, like a network operating center (NOC) in the distribution domain or an energy management system (EMS) at customer premises. The word "elements" is used to avoid confusion with the concept of "components" in the SGAM model. In Figure 5, the NOC and the EMSs are located in the operation zone, as they are concerned with operating the asset (the grid, the DER equipment, and the customer premises equipment). The CPES elements at the communication and information layer together act as the gateway between the physical part of the CPES and the cyberpart of the CPES. These elements together provide the DTs of the physical assets. This is symbolized with the Gemini symbol.

Depending on the location on the domains axis, DTs might be built on a different technological infrastructure. For example, the DT of a grid asset might be located (in a substation) in the distribution domain, while the DT of a connected customer asset is located in the customer premises domain. The infrastructure in a substation (e.g., industrial computing equipment connected through glass fiber) will probably differ from that at customer premises (e.g., a small computer next to the fuse box). Whatever the difference, both types of infrastructure need to be connected in case of a mediated competition control strategy. Without a connection, it is not possible to inform all components at the right time.

Note that the DTs do not do the decision making that is needed for implementing control strategies. This is done by the agents, as mentioned before. We see the concept of an agent existing at the function layer of the SGAM model. An agent could be located (logically) in an EMS, for example, acting on behalf of a customer.

In Figure 3, an architectural view of the "mediated competition through the market" control strategy is presented in terms of the SGAM. It shows competing EMSs while being mediated by markets (M1 and M2). The NOC of a DSO can influence the markets (e.g., through limitations of capacity to sell in case of congestion issues). In contrast, in Figure 4, a view of the "implicit cooperation" control strategy is provided. There is no exchange of information between EMSs and the DSO NOC at the business (interoperability) layer or on the function layer. Instead, the controlling agents each decide what to do based on information from an (internal) set of DTs, which they construct based on information from their sensors. The DTs of neighboring customers and the distribution grid are "in gray," as they are estimates based on their own sensor information (and not of sensors at neighbors). The DT of the customer itself is "in white," as the controlling agent has more direct sensor information on that.

Depending on what must be digitally twinned, the DT has different requirements for the computational, storage, and communication aspects of its infrastructure. A DT at customer premises will have a smaller topology and geographical scale compared to a DT of a geographically distributed grid. The latter will require an infrastructure that allows for the collection of sensor data across many kilometers. The difference in the temporal scale DTs use also influences the requirements. For example, is an hourly update of the physical component enough, or is new information required each second? In practice, a DT that reflects multiple domains and zones will probably have different update frequencies for different twinned assets, depending on the speed of potential change in modeled aspects. In the case of voltage control, it currently seems that a minute scale seems to be the minimum. Finally, there is the accuracy of measurements, which is related to the temporal scale as well ("accuracy in time"). More accuracy can require more storage. Note that the larger the area of cooperation in the case of an implicit cooperation control strategy, the larger the DT has to be, due to the models involved (see Table 3).

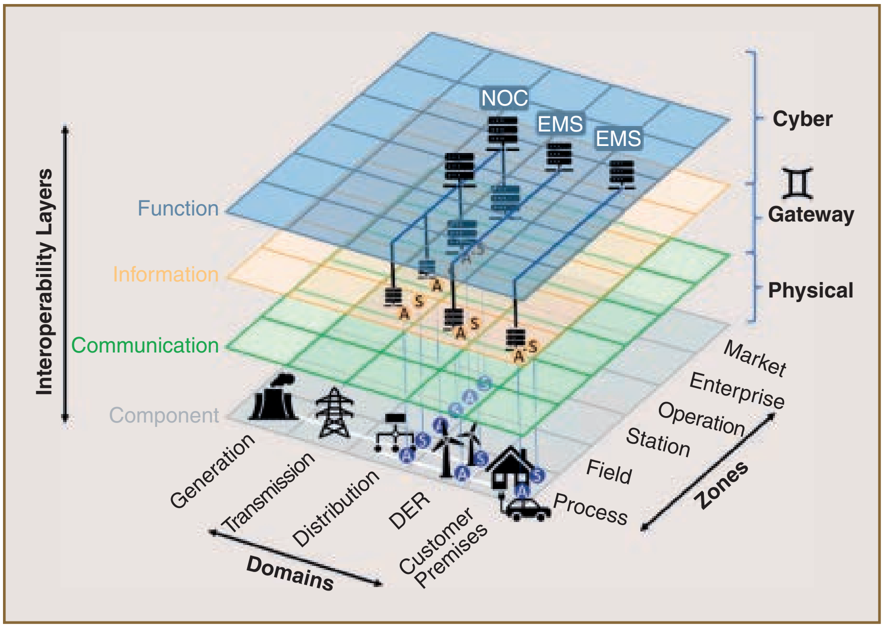

figure 5. DT elements of a CPES in terms of the SGAM. Physical assets at the component layer with sensors and actuators are connected through the communication and information layer to information processing elements at the functional layer.

Steps 5 and 6: DT Live Operation Results in Business Action

After step 4, the DTs have been built, tested, and validated, and components in the cyberpart can make use of them during live operation (step 5 in the method). Since DTs support coordination strategies for voltage control, this is directly related to "business action" (step 6). In the case of "mediated competition," the DTs support the decision making by the digital components in the operation, enterprise, and market zones. The DTs also take care of the effectuation of the decisions by using actuators to control the (grid) assets (the physical components), as the DTs are the gateway from the cyberpart to the physical part of the CPES. Depending on the type of reward that is provided to the parties for fulfilling an obligation, different kinds of exchanges of (financial) value can take place.

Step 7: Cradle to Grave

The last step of the "seven steps to a DT" is lifecycle management. In the previous sections, we have shown that depending on the coordination strategy chosen for voltage control, there are differences with respect to the design and construction of the DTs and their requirements to the infrastructure. This has a significant impact on the lifecycle management as well, which brings us to an important question: If we do not know what coordination strategy will be chosen for the CPES of tomorrow, can we even start with design, construction, operation, and maintenance of DTs? Discussions about expectations and obligations between different parties and stakeholders are only just starting up in some areas.

This is where future research and innovation projects get to play an important role in the development of DTs that are as neutral as possible with respect to market organization, business roles, remuneration, and so on. Involving different potential users of the DTs in the design process will help here, and this might even speed up the discussions about expectations and negotiations. Note that even if DTs are as business neutral as possible, there still might be changes required in DTs. For example, the advancement of improvement in technology does not seem to be over, and thus, new and/or improved physical components will become available, with different capabilities and behavior. This will require new or updated models in a DT that is used for providing measurement data or estimations of future states.

Conclusions

Although the road to the future of the electrical energy system is filled with obstacles (congestion, unexpected behavior, and scarcity in materials and personnel), we can overcome those by the smart application of ICT and letting it evolve in a CPES. For example, flexibility in supply and demand can provide extra capacity, and smart (predictive) maintenance can reduce the load on personnel that have to respond to unexpected failures. The key to a successful evolution toward an efficient and flexible CPES is in managing the system's complexity by means of separation of concerns.

The example of self-organization in distributed voltage control was used to demonstrate how DTs can be used to separate the physical from the digital. We have also shown that the requirements of DTs and the infrastructure depend on coordination strategies to meet objectives agreed upon by stakeholders. Because the energy system is still changing and value streams among parties are not fixed, the DTs need to be designed and constructed as business (process) neutral as possible in order to avoid destruction of capital. To do this, involving multiple stakeholders in the DT design process is advised. Also, the first coordination strategy chosen might not demand much of DTs, but future ones might demand more. Therefore, for the protection of investments in DTs, it is important that the computation, storage, and communication infrastructure for DTs is overdimensioned instead of minimalized.

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Cosimulating Integrated Energy Systems With Heterogeneous Digital Twins

ENERGY SYSTEM INTEGRATION PROMISES IN-CREASED RESILIENCY AND THE UNLOCKING of synergies, while also contributing to our goal of decarbonization. It is enabled by both old and new technologies, glued together with data and digital services. Hydrolyzers, heat pumps, distributed renewable generation, smart buildings, and the digital grid edge are all currently the subject of integration with the power system and the energy sector at large. To plan and operate such a multidisciplinary and multisectoral system properly, insight, tools, and expertise are all needed. This is exactly where the state of the art fails to deliver: tools for integrated energy systems (IESs) are still in their infancy, and many times, even academia treats these sectors separately, producing experts in each of them but not across.

Heterogeneous digital twins (DTs), based on cosimulation, are currently a pragmatic and useful approach to working with such complex and interdisciplinary systems. They can host models and data, coming from entirely different schools of thinking, and bring together what is already connected in the real world.

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Digital Object Identifier 10.1109/MPE.2023.3324886
Date of current version: 12 January 2024

Introduction

Energy systems can be integrated in several directions (Table 1). One dimension is within one sector in a vertical or horizontal way; transmission system and distribution system integration in electricity systems is one example of that. Most of the time, however, we think of cross-sectoral integration where, for instance, heat and electricity are somehow "integrated." This integration can, and in parts should, happen in several phases. Integrated planning ensures that infrastructure supports each other, while integrated operations can unlock synergies when it comes to flexibility. There is integration in terms of automation, by using shared communication channels or information technology, operational technology infrastructure. Even markets can be integrated so that bids may be placed for combined products, such as heat and electricity for combined heat and power (CHP) plants. The effort of producing this increased integration is intended to improve resiliency, flexibility, and/or efficiency.

The operation of the system, however, does not become simpler with higher levels of integration. Previously separated processes (whether in planning or operations, physical assets, or digital workflows) need to be unified or at least made interoperable. Decisions in one domain will have an impact in another that will only surface if the impacted domain is fully analyzed with its own specialized tools and domain experts; performing multidomain analysis one domain at a time and in a serial fashion is likely to be time consuming and inefficient. Interdependent properties (think of sizing infrastructure for a thermoelectric system with multiple crossover points such as heat pumps, CHP plants, etc.) lead to chicken and egg situations that are expensive to solve. Cases with complex, cross-domain dynamics or market

Matching a Connected World

interactions are even more extreme and yet common. Grid operators that run heat and electricity grids, municipalities that want to plan the next decades of energy investments, or utilities that run CHP and sell both products are facing the need for more integrated processes.

The complexity of the problem and the fact that experts from different domains must cooperate on the same integrated problem calls for an integrated model: a DT. Numerical help, DTs, are frequently used when analytical methods face their limits, when systems become too complex to be understood, or when borders of disciplines are crossed. IESs lead to exactly this case. The lack of multidomain tools and methods in the energy sector, combined with the need to integrate domains such as heat, electricity, urban planning, markets, automation, communication networks, and even cybersecurity, is why multidomain DTs are on the rise. They are expected to be one central platform, one central "source of truth," where diverse teams can work on multidomain, multiobjective, and multi-timescale solutions.

DTs for IESs need to be able to

- ✔ represent multiphysics systems (thermal, electric, gas, building physics, etc.)
- ✔ execute different models with heterogeneous data structures and solvers (ordinary differential equations, 3D such as finite elements or computational fluid dynamics, discrete models, and multiagent models), in order to
- ✔ represent multidomain systems (markets, energy, automation, communication, policy, and spatial planning)
- ✔ handle different magnitudes of time (microseconds for power electronics and minutes for heat flow)
- ✔ work with multidomain scenarios in one unified way (e.g., one language to describe all parts of the system).

Further, the model and computation engine need to provide the "usual" features of a DT, such as numerical performance and stability, good scalability, and standardized interfaces. The numerical model of the multidomain DT can either be based on a monolithic solver using a flexible multidomain specification language or combine several models and solvers to a cosimulation.

The DT in this multienergy setting is a platform that hosts models and parameters of all processes involved, takes time series and other environmental/exogenous input data, and then delivers the dynamic behavior of these coupled models within a certain scenario. The workflow is important, as well as how experts interact with the twin: Which interfaces are available? How can the DT system be optimized? How can parameters be estimated or updated? How can uncertainty be represented and traced?

In the case of black box models, one scenario gives one snapshot, and many snapshots are required to see the bigger picture (Figure 1). Without derivatives or other analytical insight into the shape of the problem, though, the location of an optimum (e.g., stability or costs) can only be found via searching.

Sensitivity toward certain parameters or robustness toward others cannot be calculated and, instead, needs to be estimated over a broad range of input parameters. Smart parameter choices and smart sampling with Monte Carlo or Latin Hypercube methods might reduce a potentially astronomical number of interesting cases to a manageable subset, but the fundamental problem stays: the models do not expose details such as derivatives that would allow for smart optimization, and therefore, the solution must be searched for.

If these processes and details were defined in one model (Figure 2), through the use of one language, and executed with one solver, optimization beyond heuristic searching methods would be possible.

Existing languages and tools, however, are not sufficient (in either model coverage or computational power), and legacy models/tools must be integrated, as well. Currently, the standard twin setup for IESs is, therefore, cosimulation-based, whose submodels appear as black box to the simulation master, even if they are white box internally.

Both options are computationally expensive. The cosimulation method requires assets to be shared among simulators (i.e., a power station is part of the thermal model and the electric model), so variables and states need to be shared and exchanged. The monolithic method, however, generates exceptionally large equation systems that must be solved. This does not scale well, either. Still, combined, cross-sectoral models are needed, and both methods are subject to improvement and innovation, as we speak.

Purpose and Modeling Requirements of DTs

When considering the development, design, or adoption of a DT of any system, and particularly of complex IESs, it is

table 1. A nonexhaustive list of examples of dimensions of energy system integration.

Network Type	Carrier	Sector	Policy	Active Assets
	Electricity	Industry	Infrastructure	Storage
Transmission network	Heat	Housing	Markets	Demand Response
Distribution network	Gas	Transport	Resiliency	(Distributed)
Microgrid	Steam	Water	People	Generation

essential to identify its main purpose and from that the DT's key essential features and requirements. For IESs, there are different domains of interest that could be considered, which closely link to the specific application purposes and use cases of a DT (see also the section "Applications"). Some examples are provided below.

Geographical Scale and Resolution

The geographical scale of an IES DT could vary from the national to the regional level, city or town level, industrial hubs such as industry parks, the neighborhood level, and finally, even down to the building level. Accordingly, the relevant use cases could range from the operation and planning of national-level energy infrastructure (electrical and gas networks) to modeling the operation of an individual building. For studies of large-scale network infrastructure, the geographical resolution that is sought is normally at the level of grid supply points and transmission or distribution interface substations. However, hierarchical schemes could also be developed that cosimulate both transmission and distribution networks, again with appropriate levels of details, especially in the context of emerging transmission and distribution technical and market interfaces. This is particularly relevant for the electricity network, especially with more and more distributed energy resources, while less resolution is usually required for gas network studies. At the building level, typical and important IES applications are quantifying and extracting the potential flexibility that could be provided, such as for demand response purposes by smart appliances and virtual storage in the building fabric, while optimally controlling air conditioning plants, etc. Noteworthy DT use cases that are emerging at intermediate levels of the geographical scale and resolution are associated with building DTs of low-voltage networks for fast connection assessment and capacity allocation to distributed energy resources.

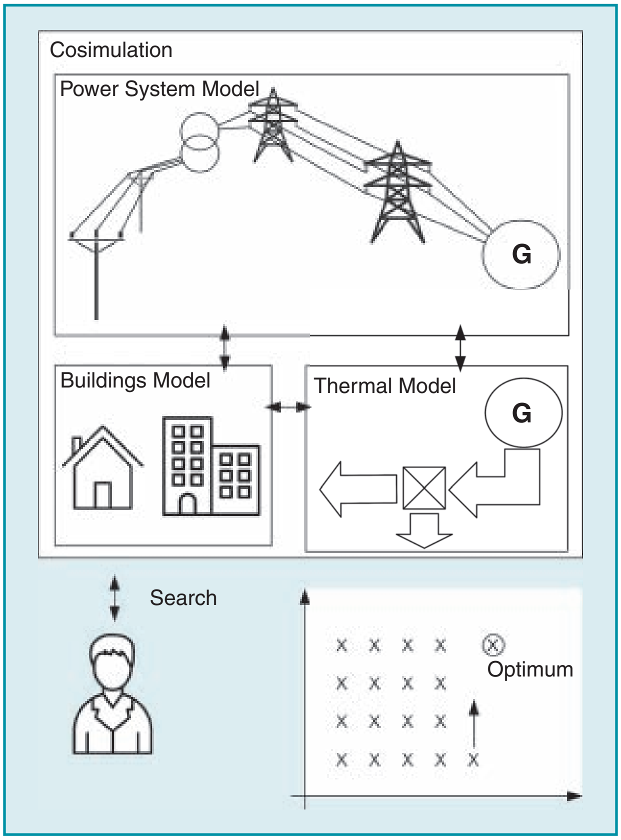

figure 1. The cosimulation (see also the section "Cosimulation as a Tool for DT Implementation") of an IES: a black box needs to be searched.

Temporal Scale and Resolution

In terms of temporal scale and resolution, DT use cases may vary from studies concerning power/energy system and market operation, to long-term, multiyear planning and investment studies (typically between ten and thirty years ahead). For example, typical steady-state problems, such as power flow, contingency analysis, and (for market operation purposes) security-constrained economic dispatch and unit commitment, may typically be run with time resolutions of between five minutes and one hour, with temporal windows of a few time intervals ahead, to day-ahead and week-ahead (e.g., for renewables forecast and pumped hydro scheduling). A much shorter time resolution, down to microseconds, may be needed for power system electromagnetic transient (EMT) studies, which may be simulated over a time

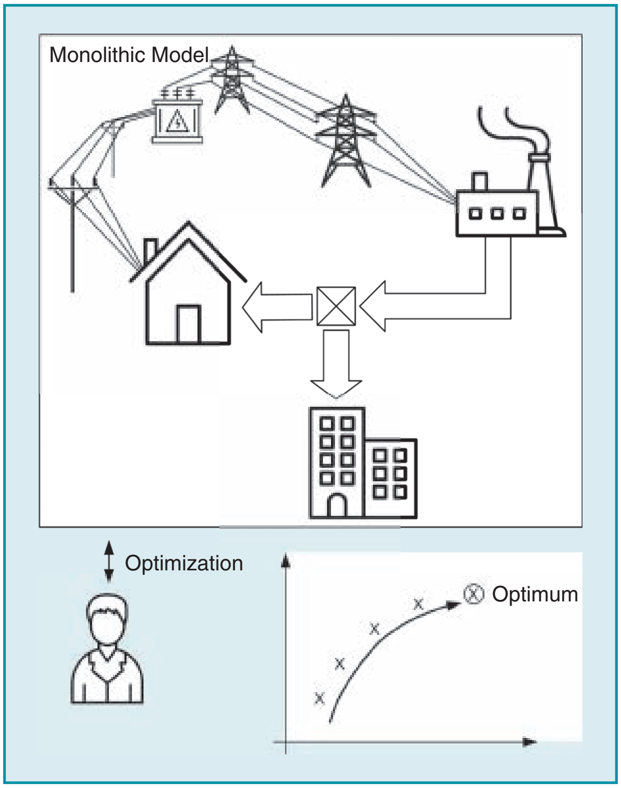

figure 2. A monolithic model that allows for smart optimization.

> An important question that needs to be addressed across all scopes and domains of a DT is that of the functionalities and resolution of the modeling itself.

window of up to a few minutes. On the other hand, hourly or multihourly resolutions are often assumed for DTs that have been built for electricity infrastructure planning studies. In the context of other energy infrastructures, for example, the gas network, the temporal resolution may be associated with both the objective of the study and the geographical scale, given the much higher time constants involved. For example, for planning purposes, a relatively small gas distribution network may be simulated with daily resolution. On the other hand, a large gas transmission network should be simulated with a resolution of down to minutes, if the purpose of the study was to optimize the linepack storage operation in managing gas network flexibility in its interaction with the electricity system.

Sector and Infrastructure Scope

"Sector-coupling" studies are emerging as a key area for IESs, including the use of simulations of sectors such as electricity, heat, gas, hydrogen, water, and transport, as well as the relevant infrastructure. For instance, in the context of decarbonizing future fuels for heating, transport, and other applications, modeling and simulations of integrated electricity–gas–hydrogen systems and networks are being considered to inform strategic industry and policy plans around the world. For example, Figure 3 shows the DT of the integrated electricity and gas transmission network for the east coast of Australia. This has been developed to assess the real-time operational impact of the injection of green hydrogen that is produced from renewables into an increasingly decarbonized gas network. This analysis supports the relevant development of integrated electricity–gas–hydrogen markets, infrastructure planning, and policy development. Different types of IES DT modeling might also be required to study the decarbonization of the transport sector including, for example, models for simulation of the road transport behavior of different types of vehicles or the interaction of these with relevant recharging (electricity) or refueling (hydrogen) stations, along with the upstream infrastructures of said stations. It is clear that such a multisector DT presents a great degree of complexity in terms of the interactions of the different models and modules; the adoption of appropriate geographical, temporal, and modeling resolution; and the availability and efficiency of data exchange across modules, as is discussed in the other sections of this article.

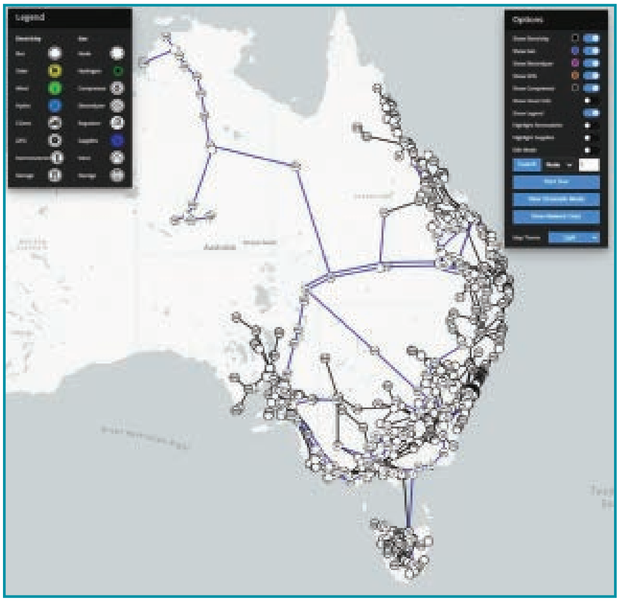

figure 3. The integrated electricity–gas–hydrogen DT of the Australian east coast energy system, under development by the University of Melbourne.

Functional Layers

Different functional layers may be considered in the development of a DT, depending on its purpose. For example, when focusing on the electricity network, a DT of only the physical infrastructure may be appropriate to study problems such as network capacity availability, security, and operational safety margins for different systems and components. A layer of the control infrastructure and architecture could then be added to better identify the potential response of the system to contingencies, such as introducing dynamic system simulations and including the impact of different control systems and layers, on top of steady-state analysis. This is also relevant to a more general incorporation of the information and communication infrastructure and virtual layer on top of the physical energy infrastructure layer, as well as relevant studies pertaining to cybersecurity and the study of cascaded impacts of disturbances across the cyberphysical system. Similarly, an energy market layer could be included to identify the starting point of steady-state and dynamic/control simulations. Again, as in the case of multisectorial integration of different DT modules, the inclusion of different functional layers requires a thorough and careful design of the modeling of each layer and their interactions.

General Modeling Functionalities and Resolution

An important question that needs to be addressed across all scopes and domains of a DT is that of the functionalities and resolution of the modeling itself. For example, a DT of a power system might be developed with different levels of detail for simulation studies that include steady-state power flows or rms or EMT-type dynamic studies that are suitable to study new renewable generation connections. In this regard, the need for performing high-resolution dynamic studies with underlying EMT modeling has recently come to the forefront in several discussions across system operators around the globe, with the aim of quantifying the stability impact of deep penetration of variable renewables interfaced through inverter-based resources, particularly in low-inertia and weak grids.

Most notably, the Australian Energy Market Operator has developed an EMT simulator of the Australian east coast transmission interconnection. Given the computing complexity associated with it, the question, therefore, arises as to when such detailed simulations are *actually* needed and whether an "adaptable" DT of the system should be developed that allows (ideally automatically) for switching among models as needed, shifting from a steady-state to an rms dynamic, and then EMT dynamic details, as required. While such modeling resolution is fundamentally driven by the presence of faster or slower dynamics and the relevant time constants involved in the different technologies and infrastructures, in reality, the choice is also driven by what type of stability and general power system phenomena need to be specifically addressed and under which conditions. In other words, given the tradeoff with computational burden, it may not be desirable to have the highest possible resolution modeling running for any kind of study.

Linked to this is also the issue of data inputs: the more complex the DT of a system is, the more data it will require. It may be that the uncertainty or proprietary nature of many of these data (control schemes of renewable technologies) would produce inaccurate and/or misleading results, thus possibly defeating the purpose of the high-resolution model in the first place. Similar considerations, about both the time constants involved and the purpose of the study, also apply to other infrastructures such as heat and gas systems. For example, EMT modeling might always be required for connection studies of inverter-based resources in weak networks, while a DT should be able to identify the requirements to switch across the level of complexity and possibly down to rms dynamic simulations when making connections to strong networks. For IES, then, five-minute to hourly simulations might be suitable for steady-state power flow or optimal power flow studies, followed by hourly simulations for heat network studies, daily simulations for gas/hydrogen steady-state network studies, and so forth.

As DTs may also be particularly useful in assessing the robustness of IES operation and planning against various degrees of uncertainties, it is important that the appropriate level of modeling complexity is adopted for such studies. In particular, modeling resolutions may be relaxed when, for example, studying sensitivities to different stochastic parameters in steady-state and dynamic system operations. This may include Monte Carlo-based time-ahead scheduling and stochastic simulations, considering different uncertain parameter inputs, or for long-term planning with scenario studies, in order to assess the robustness of investment solutions. In these cases, relatively faster modeling approaches for case screening and sensitivity assessment should be used, and it is desirable that a DT has such flexibility.

Cosimulation as a Tool for DT Implementation

DTs often, but not always, model systems that cross traditional analysis and simulation and domain boundaries. Some DTs can be assembled using a single simulation tool or a set of simulation tools that operate in series with the output of

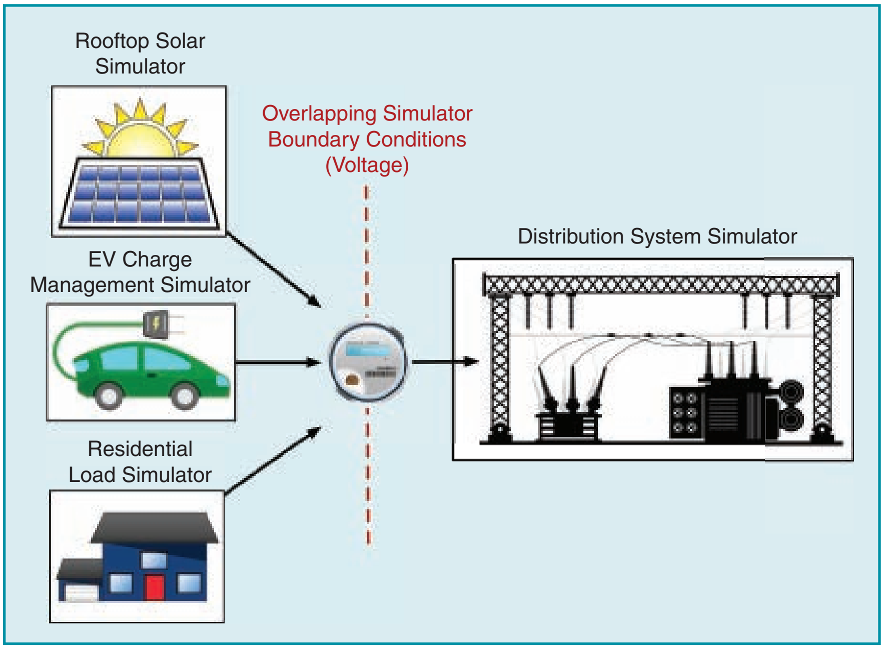

figure 4. The linear DT simulation architecture when no voltage dependency is assumed.

one affecting the input of the next, forming a linear simulation chain. Although this linear data exchange is possible for some DTs, there are others where it is too simplistic or not possible. In such cases, it is common for two or more simulation tools to share system boundaries, with the outputs of one forming the inputs of the other and vice versa. To model these multiple domains, a cosimulation platform is often used to tie the simulators together, providing them the ability to exchange data during runtime and thus influence each other's operation. By providing data dynamically and enabling interaction among the simulation tools, larger and more complex DTs can more quickly be modeled and simulated using existing, best-in-class domain-specific tools without developing and validating a custom, integrated simulation tool.

For example, a DT could be designed to evaluate the impacts of distributed solar generation and an electric vehicle (EV) charge management scheme on total power system demand, as shown in Figure 4. Such a DT could, to decrease model computation and update time, make simplifying assumptions such as constant power residential loads and simple, voltage-independent inverter controls for the EV charger and distributed solar generation. In such a case, the distribution system simulator's power flow solution can be found very quickly because of this voltage independence.

A more realistic DT, though, includes voltage dependency, which creates overlapping boundary conditions between the distribution system simulator and the behind-the-meter assets (Figure 5). The solution of the power flow affects the voltage at the meter, affecting the operating state of the customer assets, which, in turn, affects the solution of the power flow. For these circular dependencies in a DT, a cosimulation platform is helpful in maintaining a consistent state across simulator tools.

Cosimulation platforms generally have two primary, interrelated functions: synchronizing the individual simulation tools in simulated time and facilitating data exchanges at appropriate points of time. Time synchronization is necessary to ensure that the data being exchanged among simulation tools have the correct temporal context. Without regulation of the simulated time, individual tools could send data from the simulated future or past, and the receiving tool would not necessarily handle it appropriately.

Although it is simply stated, managing these two functions can be challenging. Individual simulation tools may have different concepts of time (continuous versus discrete, for example), may be written in different languages and thus have different fundamental data types, and may not save previous model states to allow resolving and iterating at a particular time step. Furthermore, for a given DT, there may be a need to sequence the data exchange among particular software tools in a particular way, run in a wide variety of computing environments from laptops to high-performance computing clusters or even run in a disparate networking environment that includes multiple institutions and/or cloud computing resources. A robust cosimulation platform would be able to facilitate the creation of a DT despite these infrastructure challenges.

There are a number of candidate cosimulation platforms that could be used to create a DT. One of the earliest such platforms is the hierarchical language architecture pioneered by the U.S. Department of Defense and later codified as IEEE Standard 1516 in 2000. Over the past decade or two, the functional mock-up interface has been developed, originally to allow a system integrator to evaluate components from a variety of vendors without exposing propriety details of the modeled components. It has since grown to facilitate more general cosimulation needs. More recently, other generic cosimulation platforms have been developed such as HELICS and Mosaik, both of which were designed with the energy sector in mind but can support a wide variety of simulation tools.

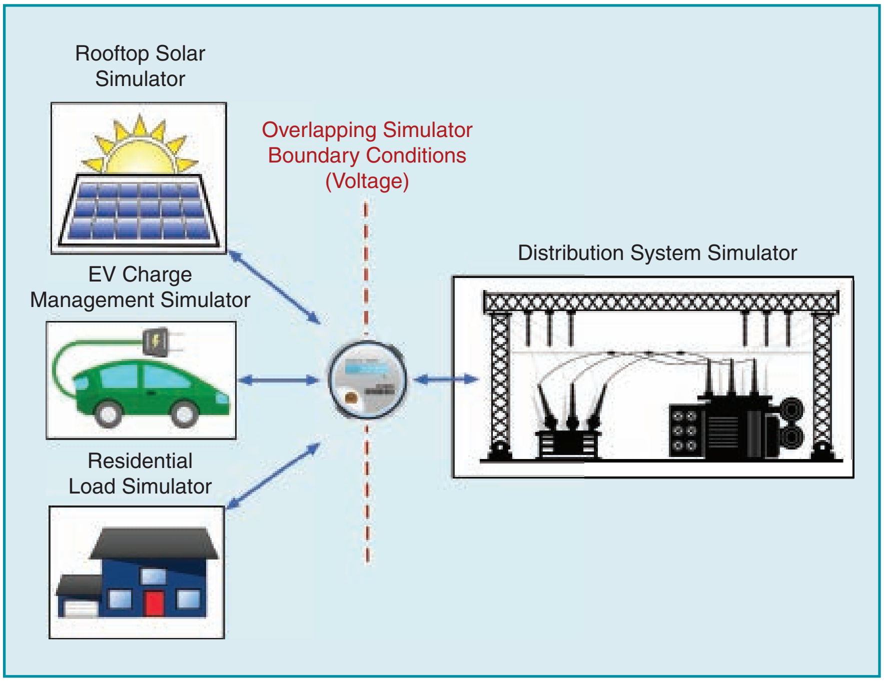

figure 5. The circular DT simulation architecture with voltage-dependent components, where data flow is bidirectional.

Creating integration of an existing simulation tool and a

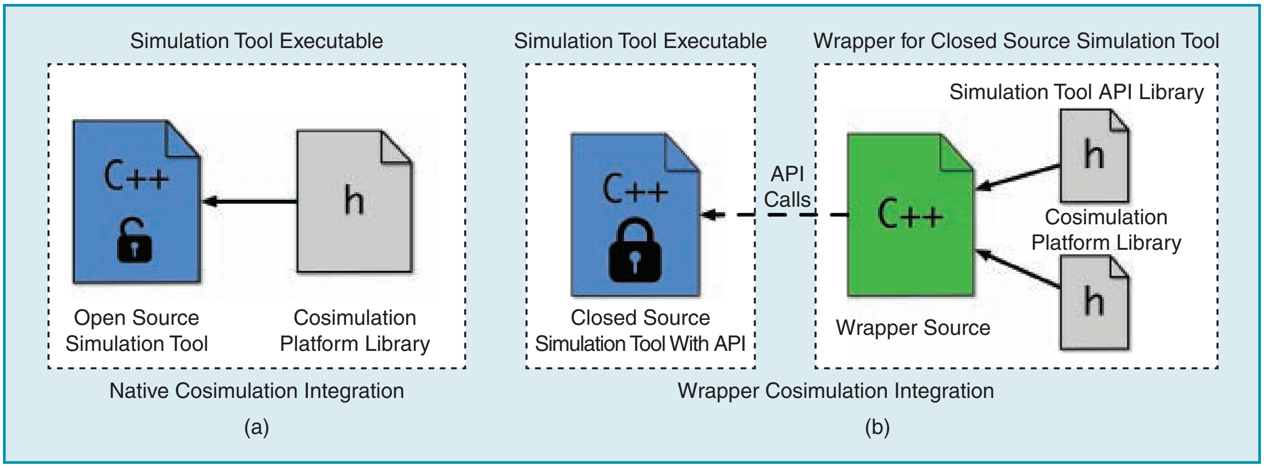

figure 6. The (a) native cosimulation integration and (b) wrapper cosimulation integration.

cosimulation platform typically happens in one of two ways. For open source tools, cosimulation platforms today typically produce a library with the platform's application program interfaces (APIs) in a variety of popular programming languages (i.e., Python, C++, Java, and MATLAB), and the source code of the simulation tool can be edited to include these API calls at the appropriate point in the tool's execution (Figure 6). For commercial tools where the code base is not publicly available or when a tool is not written in a language with support from the cosimulation platform, integration relies on the tool developers producing an appropriately featured API. If such an API exists, a wrapper program written in a language supported by both the tool's API and the cosimulation platform's API can be written. This wrapper coordinates the execution of the tool and the cosimulation platform, utilizing the API calls of both.

Applications

DTs have been in use in various domains of science and technology. The concept first appeared in academia, as a proposal for the information and modeling technology to aid the product life cycle management. The first DT, not yet named as such, contained the full description of a physical product in virtual space, tracking it through its entire life cycle from creation, through operation, to the disposal. The twin was linked by the information flow from and to the physical product, keeping it updated and allowing its decisions to be implemented. The concept of linking a physical system to its exact digital replica was simple yet powerful. NASA was the first to use it in their aircraft design and space exploration missions. The DTs later evolved and deployed in various industries, while their specialization and differentiation became more prominent. Today we have the DT as a service concept or specialized DTs for experimentation, among others.

Across different industries, DTs have found their place in supporting and even taking over many tasks (Figure 7). Planned and predictive maintenance of energy infrastructures and industrial processes have gained traction since DTs provide necessary life cycle tracking and advice to engineers and maintenance crews. The DTs are used within these processes for prognostic health management and, more widely, for the design and operations of industry 4.0 in which the focus of DTs is on improving the performance of industrial processes. Within the automotive industry, DTs have been

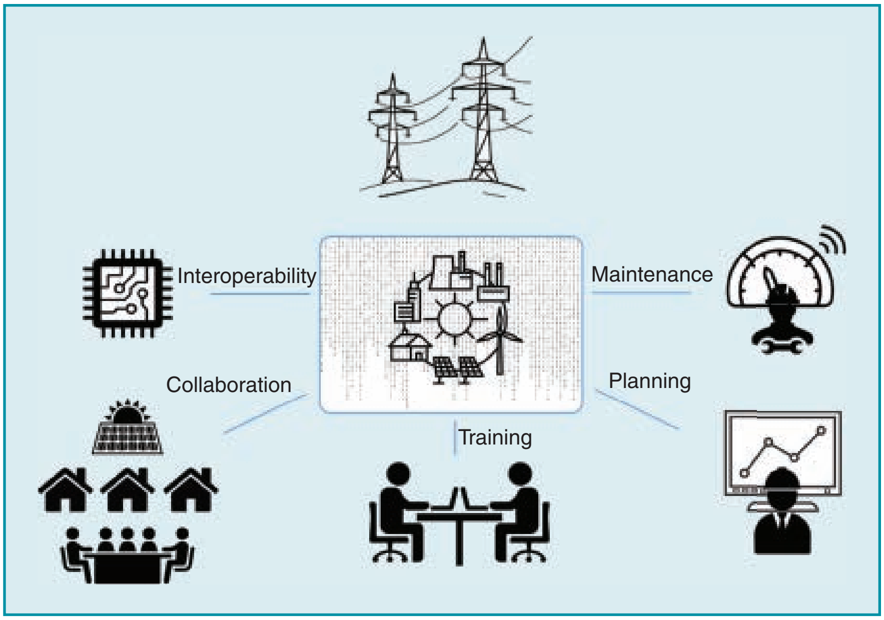

figure 7. The applications of IES DTs.

used in the vehicle design phase and for driving analytics and decision support. In the design phase, they are particularly suitable for cross-checking the suitability, interoperability, and performance of subsystems within vehicles, speeding up the design and validating design choices. Similar is the situation in the aerospace industry. Within the healthcare sector, DTs have found their application in surgical interventions, as well as predicting population behavior. DTs have also been used by governments to aid policy design and to train new world leaders in making relevant policies.

In the field of power and energy systems, DTs can be used for both the design and operation of these systems (see the "For Further Reading" section). In addition to the improvement of the performance and validation of different design options, at the design phase, they could help reduce the search space of the feasible and optimal infrastructure design options. In addition to what has been said about their use for predictive maintenance, they also help visualize the flows of energy and the potential of collective actions by all connected stakeholders. Alternatively, they are valuable for planning and operating the energy consumption sector, helping to devise demand response policies and energy bill management practices necessary for energy cost reduction in households, neighborhoods, office buildings, and business parks.

In the energy infrastructure sector, the DTs have been proposed to augment decision making in the control room, providing necessary support to the grid operators by performing the online grid analysis and suggesting actions for grid reconfiguration (see the "For Further Reading" section). The applications range from real-time power flow monitoring to real-time load shedding support. The advantage of DTs in the control room also includes the possibility to embed trusted third-party and encrypted submodels into decision support systems, leading to higher accuracy of the system, while preserving trade secrets of vendors. Such an approach increases opportunities for verification of control and management algorithms while improving the interoperability of the technologies and leading further to mass deployment. The twins can be used for training and education of the grid and industrial system operators.

Conclusion and Outlook

IESs show all features that usually point toward using DTs: complex behavior, transdisciplinary nature, and being too expensive for experimental mock-ups. The current implementations are usually based on cosimulation, which can suffer from mediocre numerical performance and complex handling of scenarios. There are promising developments with universal modeling languages such as Modelica, but scalability and simulation performance can still be an issue. In addition to the technical limitations, it is mainly the workflow of creating, validating, operating, and updating such twins that requires further attention. Right now, most of the real-world examples in the energy domain are either academic or require intensive support by the platform creator to work with it.

The potential of DTs in IESs is, however, great: synergies and risks that are invisible to the plain eye and can, due to the complexity of the system, also not be identified in an analytical way can be tracked down with a DT. Be it in planning or in operations, such twins are a powerful tool for this complex business. They are a great platform to meet in projects: experts from different domains can join forces, basing their discussion on hard facts coming from a shared transdisciplinary platform, IES DTs. Their success will depend on standardized interfaces, standardized procedures for testing and validation, and (highly likely machine-learning-based) support for model and parameter identification and updating.

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Digital Twins Serving Cybersecurity

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TODAY'S CRITICAL INFRASTRUCTURE SYSTEMS ARE more interconnected and dependent on the electric power grid. This interdependence means that disruptions in one system can have far-reaching consequences across many others. This is particularly evident when a cyberattack in the power grid leads to widespread outages and disrupts essential societal services. To prevent such disasters, it is crucial that proactive actions are taken to secure our power grid control centers and digital substations. This is where digital twins (DTs) play an important role: By creating virtual replicas of cyberphysical assets and processes, DTs allow system operators to anticipate and address potential vulnerabilities in our cybersecurity defenses before they can be exploited. As such, a DT can be considered as a key contributor to safeguard the power system against cyberattacks. This article examines the potential future benefits of DTs in enabling a cybersecure and resilient power grid, explores multiple use cases, and proposes a path forward.

Digital Object Identifier 10.1109/MPE.2023.3325196
Date of current version: 12 January 2024

More Than a Model: Cybersecurity as a Future Benefit of Digital Twins 2

Cybersecurity for a Future Grid Control Center

Cybersecurity concerns arise from complex interdependencies between cyber and power systems. When attackers gain unauthorized access to a system, they can disrupt real-time operations by introducing malicious codes, modifying critical configurations, or launching denial-of-service attacks. These can potentially lead to outages or damage to assets, causing generators to fail, transformers to explode,

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or transmission lines to short circuit. One such example was demonstrated through the Aurora attack at the Idaho National Laboratory, where attacks resulted in a complete generator blowout. Existing state-of-the-art security controls, such as network segmentation of IT–operational technology (OT) systems and the use of firewalls, are deemed inadequate against emerging cyberthreats. To address these challenges, DTs and artificial intelligence (AI) techniques are set to play a crucial role in future grid control centers to enhance cybersecurity and cyberresiliency.

Control Room of the Future

The applications of DTs and AI are expected to substantially grow in the control room of the future to address modern grid operational challenges and cyberresilience. AI-based grid monitoring and control may semiautonomously operate the power grid of the future. In this regard, an analogy can be drawn to modern-day aircraft, where pilots typically handle takeoff and landing, while the autopilot manages the more predictable portions of the flight. Overall, AI-based systems can provide enhanced decision support to human operators working in actual control rooms.

The application of advanced computational and visualization methods in the control room of the future will further enable an effective incident response to identify and contain advanced persistent threats on power grids. The coordinated cybersecurity training of power system operators and computer security incident response teams will improve cyberresilience and enhance the security readiness of the grid operators. Furthermore, the role of threat intelligence in preventive and proactive cybersecurity cannot be overstated. Specifically, information sharing and analysis centers for knowledge exchange among utilities will serve as critical pillars for cyberthreat management. While the energy control center (ECC) will manage the power grid, a network operation center (NOC) or security operation center (SOC) will manage the cyber system supporting the power grid. This can be achieved through dedicated DTs for highly automated and continuous monitoring of potential security incidents and anomalies while providing real-time insights into the system states. AI-based intrusion detection and prevention systems may become the norm by automatically extracting the most relevant and informative features from large and complex cyber power datasets. This can aid in the proactive detection of attacks and defense strategies. Further, adaptive AI may quickly and dynamically adjust to novel threats and attack patterns.

Cyberphysical DTs

Existing state-of-the-art dynamical analysis of large-scale and complex power systems is limited to numerical modeling and simulation. Further, such models cannot describe all operational system states, such as uncertainties, asset lifecycles, and cyberinteractions. To address some of these gaps, DTs have emerged as a promising solution. Cyberphysical DTs are virtual replicas of physical and cyber assets, systems, or processes interfaced with field data and are used to simulate, emulate, and analyze real-world cyberphysical scenarios. They are realized through a combination of numerical models and simulation hardware that represent real cyber interactions and operations, as shown in Figure 1. A DT consists of detailed discrete-time models of OT networks for substation automation and continuous-time models of the power system. The discrete-time systems are used to model and simulate the substation communication networks and processes. Therefore, DTs extend the current modeling, simulation, and analysis capabilities of power system planners from only the physical domain to the integrated cyberphysical domain. DTs also allow the real-time simulation of cyberattacks at the cyber system layer and the impact analysis at the physical layer in an integrated cosimulation environment. Utilizing the advantages of DTs, power system operators can assess and improve the grid operation resilience to cyberattacks and plan the cybersecurity operation of the integrated cyberphysical systems (CPSs).

For real-time cyber power data exchange, a continuous, seamless, and error-free connection is required between the actual system and the DT. The frequency at which the synchronization occurs is termed the *twinning rate* and is crucial for the success of the DTs. With near-real-time synchronization, the cyberphysical DT allows operators to analyze “What if?” scenarios, predict future system states, and conduct scenario-based risk assessments, thus reducing unplanned downtime and maximizing system availability. Overall, DTs enable cyberresilience, which is poised to become an integral part of the control room of the future and should be considered when designing new energy management system applications.

DTs to Enable Cybersecurity Technology Development

To identify vulnerabilities and potential threats in the context of cybersecurity for the power grid, DTs can be used to model the behavior of various components, including generators, transformers, substation automation, and control architecture. By creating a virtual representation of the cyber power grid, analysts can simulate different attack scenarios and test the effectiveness of various defense mechanisms without risking damage to the physical infrastructure. Further, using cyberphysical power grid data generated from the DT, operators can monitor the performance of the CPS in real time and develop early warning systems that indicate possible anomalous behavior or cyberattacks. Advanced AI-based unsupervised or semisupervised algorithms can further aid in this process. By continuously updating the DT with real-time data, power grid operators can stay a few steps ahead of the potential threats and immediately respond to any security incidents that may occur.

The DT at West Virginia University

At West Virginia University (WVU), the physical power system is modeled in a real-time simulator (RTS), while the living digital representation is modeled using power simulator software, as shown in Figure 2. The RTS conducts real-time electromagnetic transient simulations of the power system using a few-microseconds timestamp and is equipped with multiple input–output communication cards for interfacing with external hardware devices. Multiple industry-graded phasor measurement units (PMUs) are connected to the RTS that provide synchronized phasor data in the IEEE Standard C37.118 format at a rate of 30 frames/s. These data are concentrated at local and central phasor data concentrators (PDCs) and subsequently used for the steady-state analysis of the power system. The power simulator software in the DT models the entire one-line diagram of the physical power system network, runs power flows, and updates voltages in near real time within a few milliseconds.

The DT is dynamically updated with data that mirror the true steady-state conditions of the system through a Python-based application programming interface. This allows operators to simulate realistic cyber-induced outages in the DT as it would happen in the real physical system. For example, consider a cyberattack that opens a targeted circuit breaker in the physical system, causing an outage. Once the breaker opens and the line is out, data exchange occurs between the real system and the DT; subsequently, breakers in the DT are opened to mirror the contingency, and alarms in the DT are updated in real time. This allows power system operators to simulate future impacts of the attacks, such as the opening of subsequent breakers in the DT to study emergency operation conditions and simulate different cyberphysical mitigation techniques proactively.

Similarly, the actual cyber system is modeled with software-defined networking (SDN) hardware, while the digital representation is modeled using Network Simulator 3 (NS3). The implementation of SDN has been achieved with a 2740 SDN hardware switch and a 5056 OpenFlow controller. The hardware component 2740S supports the International Electrotechnical Commission (IEC) 61850 network requirements, while the hardware component 5056 allows the SDN switch management and configuration. Hardware 5056 also manages the network consisting of smart sensors, actuators, real-time automation controllers, PMUs, and PDCs. On the other hand, NS3 is utilized as the DT, where nodes are modeled as one-to-one mapping with the substations. To twin real-life SDN scenarios, the layer 3 routing protocol in NS3 is implemented, which uses optimized link state routing, along with the default route with a primary and backup path. Additionally, to create a network requiring less convergence time during failover scenarios, traditional layer 2 networking is avoided, and, instead, proactive flow-based SDN traffic control is implemented. This provides cyberdefense through network rerouting with

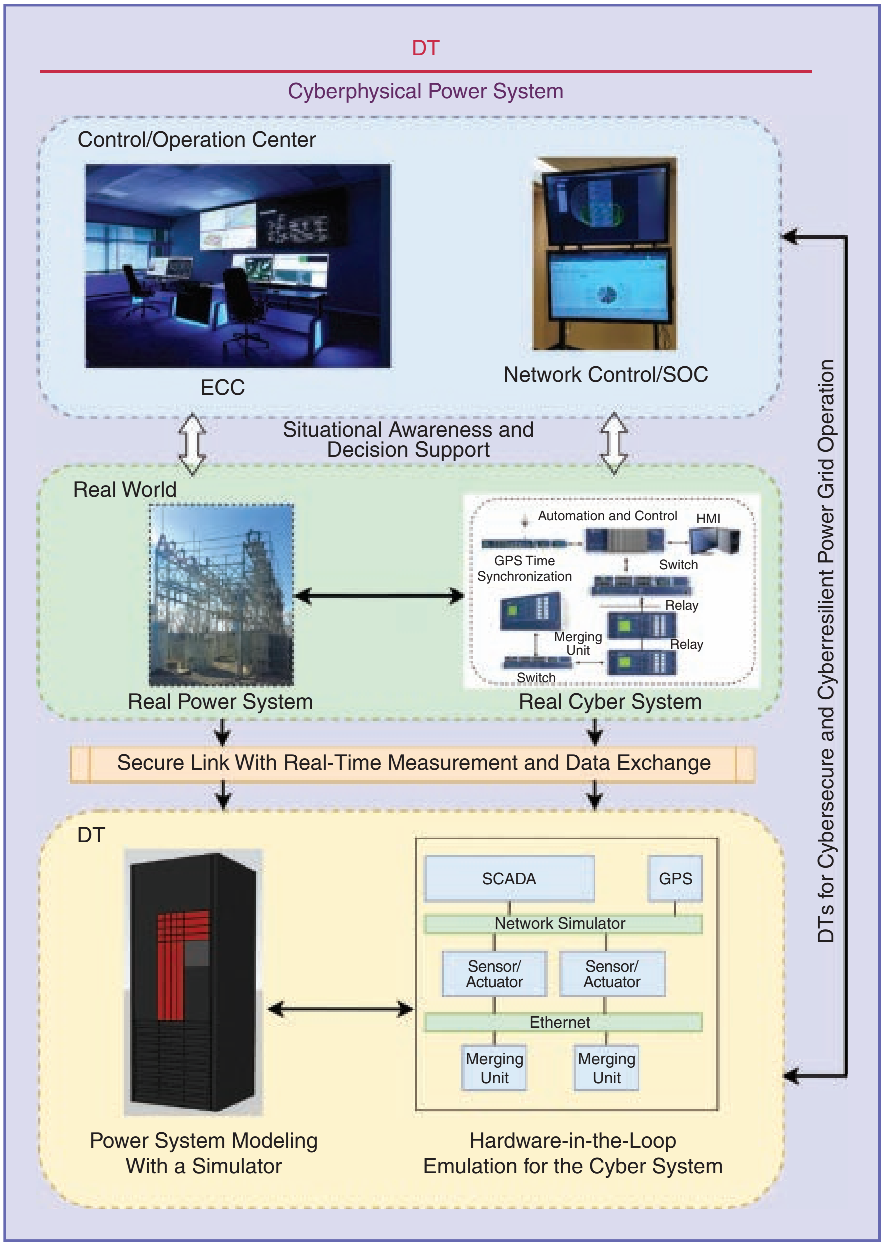

figure 1. The components of a DT for cyber power systems. HMI: human–machine interface; SCADA: supervisory control and data acquisition.

similar timing when compared to the real cyber system modeled via SDN.

AI-Based Intrusion Detection Tool Validation With DTs

The implementation of DTs offers a means of validation of AI tools for cybersecurity and anomaly detection. One such example that can be validated with a DT is an in-house-developed tool that uses field PMU data. This tool aggregates scores from multiple base detectors, such as Chebyshev based, clustering, and regression, and uses a machine learning algorithm to classify anomalies. For example, consider a cyberattack on the actual physical system. This tool, SyncAD, receives actual PMU measurements and concludes whether a set of data is anomalous. When SyncAD detects an anomaly in real PMU data, a flag is triggered, and the corresponding DT data are altered to reflect the new abnormal scenario. To ensure that the AI-based tool performs accurately, reliably, and consistently under an anomaly, additional events can be added to the DT as inputs and then compared against the current anomaly for validation and refinement. In turn, this can be used to monitor accuracy as well as to predict the performance of the AI tool in real time. With this, the use of the DT allows system operators to improve the efficiency of the tool and, therefore, reduce the

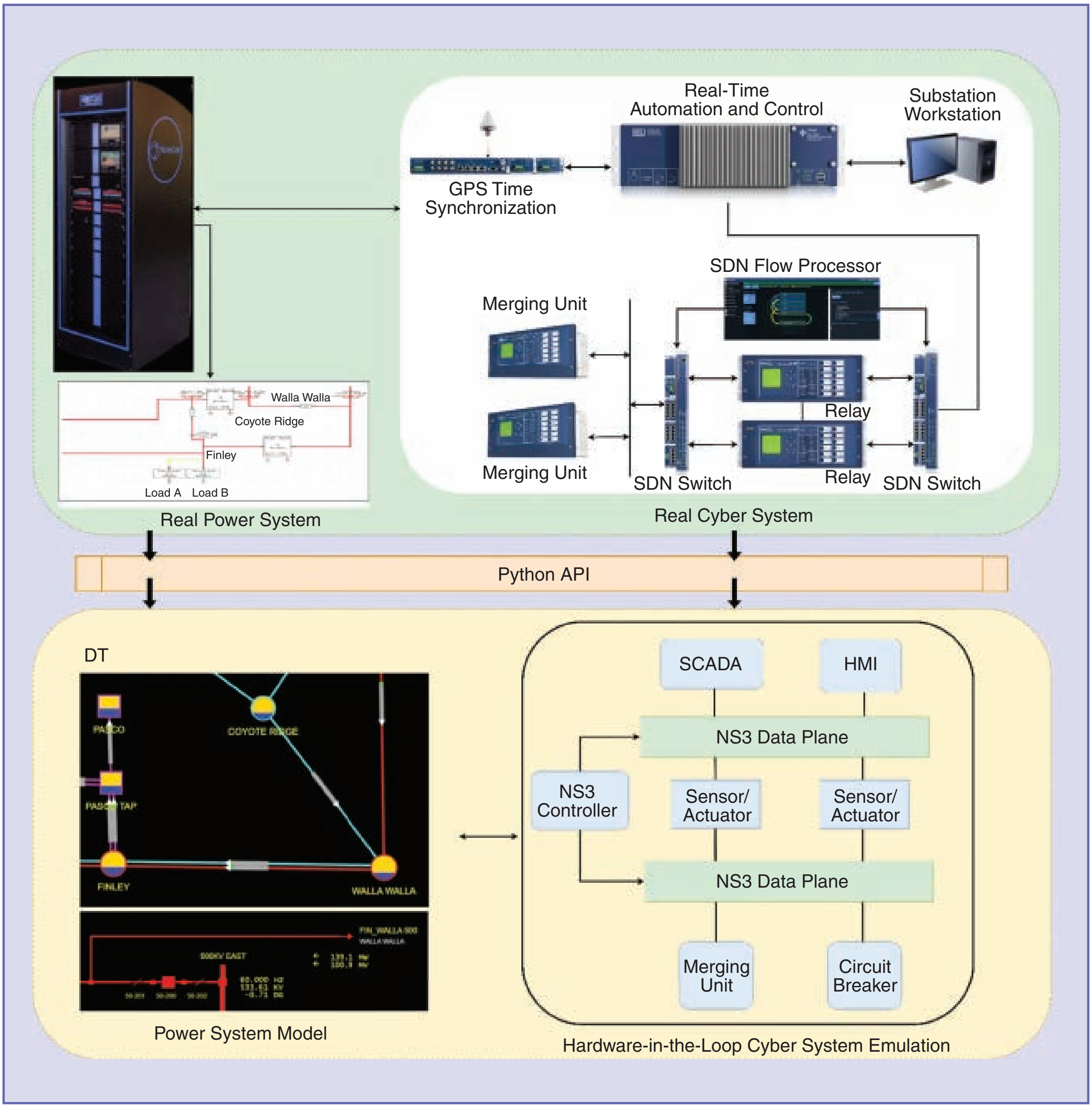

figure 2. The cyber power DT at WVU. API: application programming interface; SCADA: supervisory control and data acquisition; SDN: software-defined networking.

risk of errors, leading to enhanced detection of attacks, proactive control actions, and impact mitigation.

Further, DTs can help maximize the resiliency of the cyber power system through an advanced transmission system resiliency tool. This tool provides a dynamic interface that visualizes substation locations and provides corresponding physical and cyber resiliency scores. These scores are based on the physical network configuration, path redundancy, and transmission availability for the power side and cyber network configuration, communication redundancy, attack paths, and bandwidth availability for the cyber side. First, the field inputs from the physical power system are used to update the DT, and, subsequently, the outputs of the DT are used to assess three resiliency categories: high, medium, and low. By assessing the level of vulnerabilities and corresponding security mechanisms in place, such as authentication, encryption, segmentation, and preparedness, system operators can use the transmission resiliency tool to maximize resiliency on the actual physical system.

SDN-Based Cyberdefense With DTs

To simulate mitigation techniques for probable cyberevents, such as a link failure due to an attack, network reconfiguration is carried out in NS3 to isolate the affected network and prevent further disruption. The action performed in the DT is then mirrored in the real system through SDN, as shown in Figure 3. SDN offers numerous advantages in this case: 1) flexible management of the network architectures and better observability; 2) a centralized controller with programmable interfaces; 3) separation of the control and data planes, making it cost-effective; 4) flow-based control, enabling proactive traffic engineering; and 5) less convergence time in the failover scenario, thus enabling implementation in critical applications. Cyberdefenses can be strengthened by SDN in various ways, including the following:

- ✔ *Better situational awareness*: SDN provides improved situational awareness and simplifies National Electrical Reliability Council Critical Infrastructure Protection (NERC CIP) compliance for data generation and reporting. It gives information on how each device is connected to the network and what traffic is permitted on the network. As a result, malicious changes in the network can immediately be identified.
- ✔ *Deny-by-default security*: SDN classifies network traffic according to application layer services and protocols. This ensures that a network connection, which has been previously configured to only carry C37.118-based PMU traffic or Distributed Network Protocol 3 (DNP3)-based supervisory control and data acquisition traffic, does not carry any other traffic. This feature effectively reduces attack surfaces, making

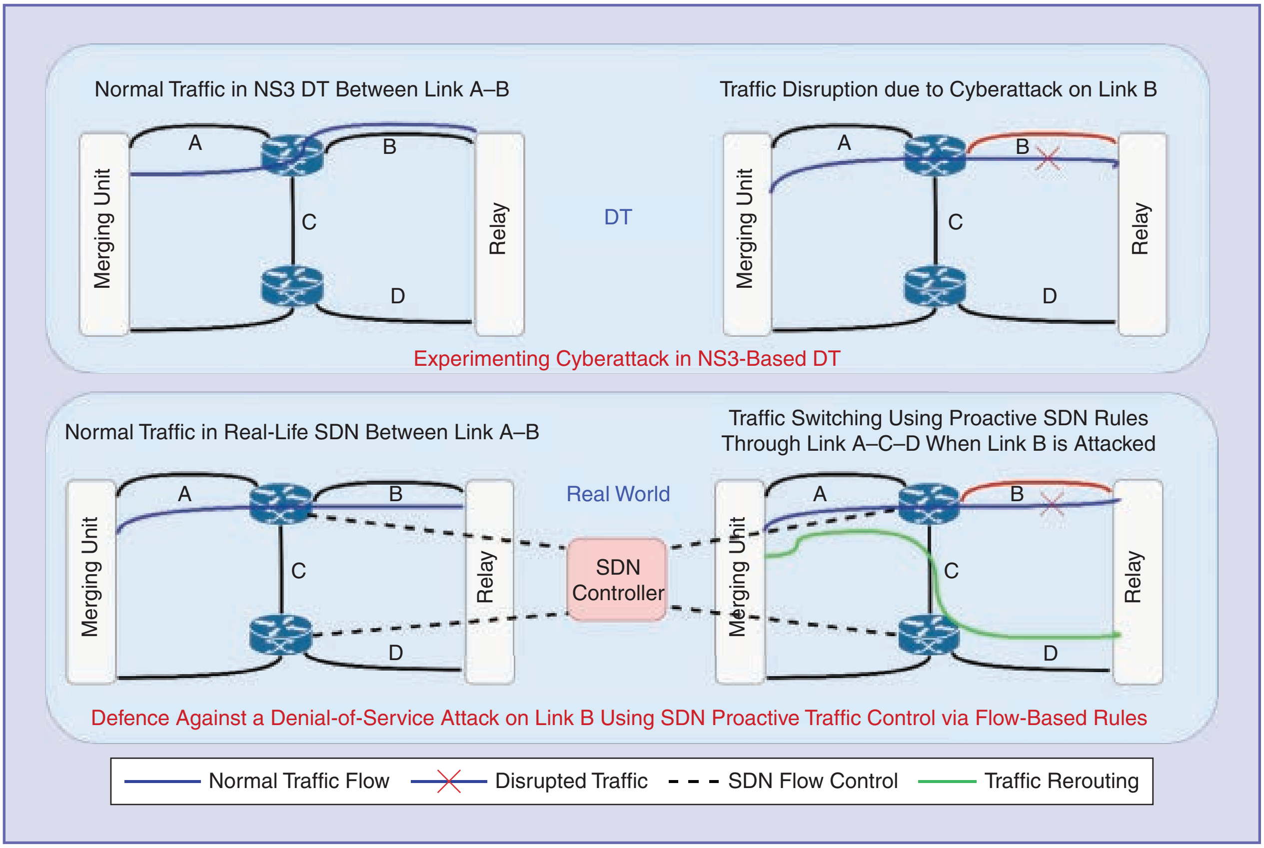

figure 3. An example of SDN-based cyberdefense.

end-to-end communication attributes more rigid. With SDN, granularity in configuration can be achieved, unlike traditional networking, which requires external access control modules.

✔ *Proactive traffic engineering*: This feature enables faster reconfigurability and network reconvergence due to its capability of creating active and backup flows with priority. In traditional networks, the spanning tree protocol calculates both the primary and blocked paths to prevent a layer 2 network loop, making the convergence time after a failover scenario much higher (10 ms to several seconds, depending on the topology). For the testbed at WVU, the flow from the 451 relay to the RTS has been configured as active and backup with the help of the SDN flow controller, thus proactively making the traffic switchover in the case of a failover scenario much faster.

The DT at Virginia Tech

As CPSs, distribution systems are often exposed to multiple threats. Extreme weather events are a leading cause of power outages. It is estimated that more than 80% of outages between 2003 and 2012 were due to weather, and the majority of them affected distribution systems. Physical attacks on the distribution systems cause damages as well. According to the U.S. Department of Energy electric disturbance event report, at least 101 incidents of vandalism, intentional attacks, or threats occurred between January and August 2022. Finally, the ubiquity of information and communications technology devices in the grid has caused an expansion of the attack surface of CPSs. Cyberattacks and cybersecurity breaches have become real threats for the power grids. The resilience enhancement of distribution systems is essential to prevent disruptions of electricity service. Due to their limited generation and energy storage resources to enhance resilience, small utilities and campus distribution systems can be vulnerable to these events. To address these challenges, the DT acts as a comprehensive testbed for resilience planning, cybersecurity testing, and short-term decision support. Operating a distribution system in an islanded mode as a microgrid requires the integration of control, protection, and cybersecurity technologies. Through a collaborative research effort between Virginia Tech Electric Service (VTES) and Virginia Tech's (VT's) Power and Energy Center (PEC), a data link has been established to allow online data to be transferred from VTES's grid assets to PEC's cyber power laboratory. The access to a real-time data stream from the physical distribution system allowed PEC to build a DT of the system.

At VT, the physical part is the VTES campus electricity infrastructure, a 60-MW distribution system that serves the university campus and part of the City of Blacksburg. The DT is modeled in an RTS. The virtual system is a cosimulation of the distribution system and communication networks, as shown in Figure 4. A detailed Electromagnetic Transient (EMT) model of VTES has been constructed within the RTS. The model was created using information about the generation resources, network topology, line parameters, and loading of the system. Power flow analysis was used for the validation of the model. The RTS allows for the study of the transient behavior of the VTES system with inverter-based resources (IBRs) when subjected to disturbances. A cybernetwork of VTES is modeled using the NS3 network simulator. Due to its open source nature as well as its modularity, NS3 can readily be used for other DT projects.

The secure data link implemented at PEC enables access to the real-time data collected by sensors and measurement devices installed in the physical system. The cybersecurity of the data link was a major challenge due to the confidentiality and sensitivity of the transferred data. In collaboration with the VT Office of Export and Secure Research Compliance, several security measures were implemented for the datalink. For instance, a secure room was built with a one-directional communication link from the VTES operating center. Additionally, mandatory cybersecurity training is required for all personnel (student or staff) with access to the DT.

System Planning, Decision Support, and Cybersecurity With DTs

The DT is utilized for studies of system planning (the integration of IBRs and resilience planning), decision support, and cybersecurity monitoring and mitigation. One of the most promising applications of the DT is cybervulnerability assessment. This is carried out by emulating different types of attacks (e.g., denial of service, man in the middle, and false data injection) within the virtual environment. The results of testing are then used to determine improvement recommendations for the real system. As it is not realistic to test cyberdefense algorithms directly on the physical system, the DT is used for the development, initial implementation, and testing of security strategies before their integration into the physical environment. Furthermore, the DT is a physics-based simulation of the full topology of the system, and, therefore, it is used to detect abnormalities in the data received from the physical system. It can constitute an added layer of protection against false data injection and topology attacks. Finally, the deployment of smart grid technologies may necessitate new communication channels. Telecommunication infrastructure can introduce delays or be prone to outages that affect system operations. Those telecommunication methodologies can be tested first on the DT of the cyber power system.

Cyberresilience Planning With DTs

Due to resource constraints, small utilities and campus systems may not have comprehensive intrusion detection and attack mitigation measures. Sophisticated attackers can exploit this vulnerability to conduct direct switching attacks that interrupt the power supply by compromising switching devices. These attacks may be coordinated and aimed at maximizing damage through the deliberate selection of switches and nodes. In the worst case scenario, coordinated cyberattacks on small distribution systems can lead to cascading events and severe outages. Therefore, it is important to create resilience plans that leverage grid assets to sustain the electricity supply to critical loads and accelerate the recovery process after a major cyberattack.

Distributed energy resources (DERs), when managed as part of a microgrid, can help enhance the resilience of a system by ensuring the stable operation of critical services. Microgrids can operate in a grid-connected mode in a normal condition and switch to an islanded or "resilience" mode following cyberattack-induced outages. The deployment of new renewable energy and energy storage resources is required to achieve VT's climate action goal of 100% renewable electricity by 2030. The proposed DERs include a 2-MW photovoltaic (PV) plant that is being developed, a planned 10-MW battery energy storage system, and an existing 5-MW synchronous generator.

A resilience plan with the grid-forming capabilities of power electronics converters is proposed for VTES. VT's DT is used to validate the resilience plan and test different grid-forming control strategies (e.g., the droop control, virtual synchronous generator, or virtual oscillator control). Robust and adaptive microgrid control strategies are needed to ensure proper operation of the microgrid in both the grid-connected and islanded modes. The DERs are designed to comply with IEEE Standard 1547-2018, *Interconnection and Interoperability of Distributed Energy Resources With Associated Electric Power Systems Interfaces*. The standard assigns disturbance ride-through and power quality requirements to avoid cascading events. In an islanded mode, the parallel operation of multiple DERs requires coordinated control to avoid circulating currents between the DERs and ensure adequate power sharing. The DT is used to determine the proper sequence of switching events that ensures stable operation. The implementation of secondary coordinated control and determination of optimal switching actions is validated through controller hardware-in-the-loop simulations using the available microgrid controllers, processing units, and VTES DT.

As a hypothetical scenario, a coordinated direct switching attack is simulated with the VTES DT. In the simulation,

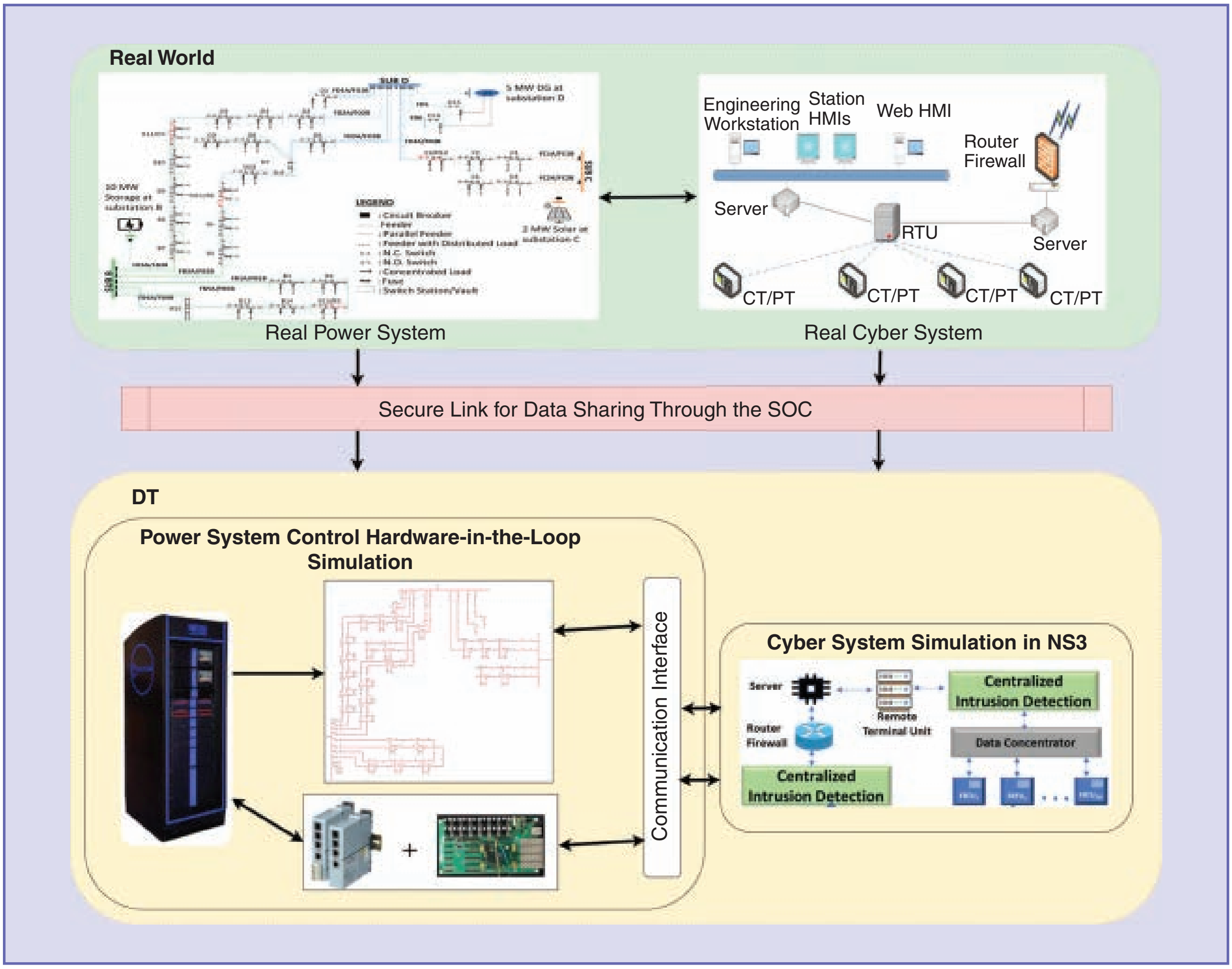

figure 4. The architecture of the VTES DT. RTU: remote terminal unit; FRTU: feeder remote terminal unit; CT: current transformer; PT: potential transformer; HMI: human machine interface; Web HMI: HMI with access to the World Wide Web.

the cyberattack simultaneously opens the breakers that connect the three substations to the distribution feeders. A denial-of-service attack is also used to disable communications to/from the compromised assets. In the absence of a cyberresilience plan, such an attack would cause an extended outage. With the proposed resilience plan, the BESS switches to grid-forming control, synchronizes with the PV plant, and then supplies power to the first set of critical loads (1.5 MW). As shown in Figure 5, the BESS can pick the critical load within a few cycles while avoiding large transients. At the same time, the synchronous generator picks up the second set of critical loads (1.5 MW). The two electrical islands are then interconnected to form a larger system. A novel algorithm that can predict the motives of an attacker in real time is being developed in the DT environment. The algorithm is implemented by distributed agents and can detect an attack and extract relevant parameters used to learn from the attacker's behavior. Following this, appropriate mitigation strategies at the communication network level are implemented.

The DT at Delft University of Technology

At Delft University of Technology, the DT broadly consists of three blocks, as shown in Figure 6: two of them are for modeling the power system, and one is to emulate the communication network. An RTS is used to interface with a realistic digital substation setup. The digital substation consists of various substation protection and automation equipment, such as bay-level intelligent electronic devices (IEDs) and network switches, among others. The IEDs include protection relays from major vendors. This

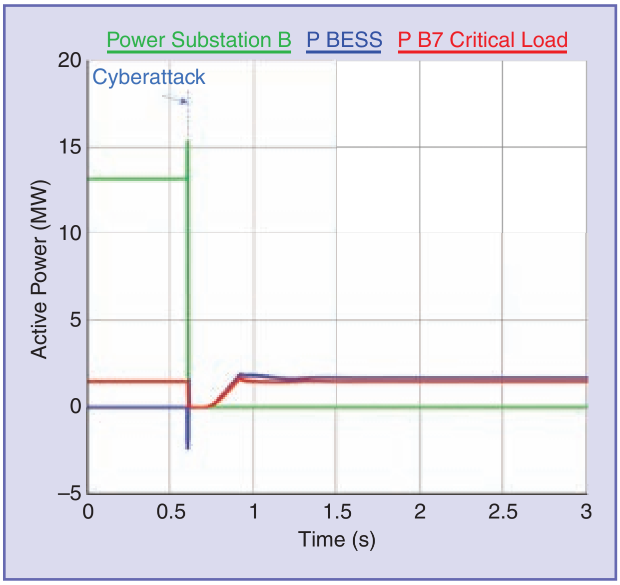

figure 5. The results from a cyberattack simulation in the DT. Substations are disconnected from the system, but the BESS can quickly restore service to critical loads. P_BESS: active power from BESS; P_B7: Active power supplied to Critical Load B7.

combination represents the real-world reference for the DT implemented, using a power system simulator and network emulator. The power grid is modeled on the RTS, and the physical devices are interfaced via the hardware-in-the-loop paradigm for cybersecurity analysis. With this architecture, the operators can analyze the impact of replay attacks on the substation communication infrastructure. The DT of the communication network is modeled in Mininet, an operating system-level network emulator. This includes substation controllers, hosts, switches, and also the wide-area network.

Assessing Cyber-Induced Cascading Failures With DTs

DTs can be used for cyberresilience analysis to study the impact of cybereffects on the power system. The modeled power system in the DT consists of multiple coordinated protection schemes, such as interface protection for generators, distance, and overload protection of lines and load shedding, to simulate cascading failure chains. The impact of various attack vectors, such as packet sniffing, replay, and denial-of-service, can be investigated on the power system. Once a suitable attack vector is established, multiple scenarios are analyzed in depth through the DT. Consider the example where a cyberattack disconnects three transmission lines, for example, lines 05-06, 04-05, and 05-08, in a single substation at $t = 5$ s simulation time. Consequently, due to the sudden $N–k$ contingency, the grid becomes heavily stressed. In the event of no remedial actions (such as load shedding or generator rejection), multiple lines in the vicinity of the attack location are disconnected by distance protection. This sets off a chain of cascading events, also known as the *domino effect*.

This can be better visualized through Figure 7(a) and (b), which depict the heatmaps of voltage angles over the course of the cascading failure propagation for the physical power system. In Figure 7(b), the unstable areas of the grid can be seen in purple and dark blue. These areas suffer severe power swings with voltage angle deviations in excess of 30° or more. Eventually, multiple generators lose synchronism or are disconnected by frequency protection schemes. As a result, the cyberattack results in a blackout with a total loss of load of 3,000 MW. Using the DT, such simulation studies are performed in a safe sandbox environment and with no effect on the real power grid.

Insights from this research can help to identify critical substations or lines that must be secured. Furthermore, a shift toward moving-target defense strategies can be analyzed. For example, in case of an actual cyberattack, the CP-DT enables the following analysis: how to respond in the most effective manner and which parts of the grid must be isolated to minimize both the spread and impact of the attack. The results of applying these methods can also be studied to prepare suitable incident and rapid situational response strategies.

The Path Forward for Enabling a Cybersecure and Cyberresilient Grid

The DT provides state-of-the-art capabilities to enable the development and validation of AI-based intrusion detection tools, SDN-based cyberdefense, an assessment of cyber-induced cascading failures impact, the improvement of system resiliency planning, and decision support. This can enable grid operators to carry out hypothetical cyberphysical contingency and attack analyses in addition to existing physical reliability studies. However, the proper working of the DT technology relies on a number of aspects, and, if any of these inputs are inaccurate, incomplete, or unreliable, the DT may not work properly. These include the following requirements:

- ✔ accurate models of the communication infrastructure to simulate cyberthreats and the associated impacts
- ✔ operational parameters, such as loading and generation
- ✔ reliable connectivity to receive data from the actual system in real time to minimize lost or delayed data
- ✔ accurate data collection
- ✔ reducing missing and noisy data.

With these requirements met, the DT will then be able to accurately predict the behavior of the real-world system it is simulating. Additional limitations of DTs are driven by the modeling capability, data, and application needs. Nevertheless, the future of DT technology holds great promise for cybersecurity and resiliency analysis for power grids.

CP-DT as a Sandbox for Analyzing Cybervulnerability and Cyberdefense

The CP-DT can be effectively used to model cyber-physical threats and analyze their impact on the power grid infrastructure. One crucial application area is that of cybersecurity posture enhancement through a cyber range, such as a sandboxed facility used to launch various types of cyberattacks and analyze their impact on

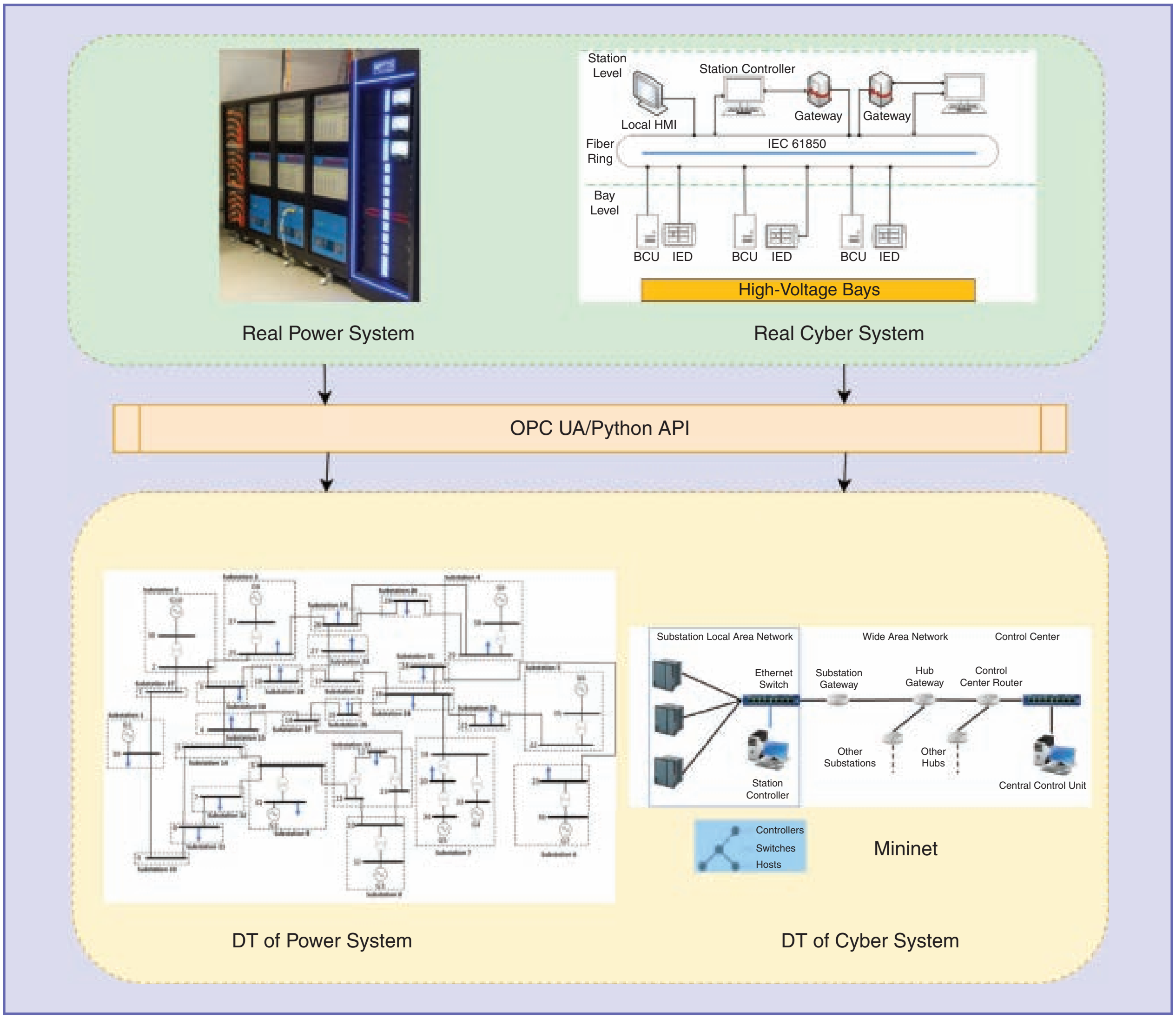

figure 6. The CPS DT cosimulation setup at Delft University of Technology. IED: intelligent electronic device. BCU: bay control unit; OPC UA: open platform communications unified architecture.

the physical power system. The cyber range can provide the following capabilities:

- ✔ *Simulation environment*: A cyber range provides a simulated environment that emulates a real-world cyberattack scenario. The environment is designed to reflect networks and systems found in an organization's infrastructure.
- ✔ *Multiple attack scenarios*: Cyber ranges offer a wide range of attack scenarios, including ransomware attacks, phishing attacks, distributed denial-of-service attacks, and spoofing, among others. This allows security teams to test their response capabilities against a wide range of threats.
- ✔ *Honeypots*: Cyber ranges often include honeypots, which are decoy systems designed to attract and trap potential attackers. Hence, they provide invaluable intelligence on the tactics, techniques, and procedures used by attackers. Therefore, suitable defense strategies can be developed. A dedicated cyber range is an essential tool for operators to test their incident response capabilities on the DT and improve their overall cybersecurity posture.

Routing an Active Cyberattack to CP-DT as a System-of-Systems Honeypot

CP-DT can serve as a honeypot for routing an active cyberattack in a safe and controlled environment for security testing and attack analysis. Furthermore, the use of CP-DT allows for the analysis of attacker behavior and interaction, as the CP-DT is designed to resemble a real system, making it difficult for attackers to distinguish between the two.

Bridging the Gap Between the NOC/SOC and ECC

To bridge the gap between the NOC/SOC and the ECC for future grid operations, it is crucial that coordinated training is provided to both network and operations staff. This includes identifying the specific technical and cybersecurity skills needed, providing technical training, and fostering an overall cybersecurity culture. For training operators on cyberdefense, it is important that ECC operators also have a holistic understanding of secure network design, the existing firewall configuration, the overall communication network topology, and other cyber details. In the same way, NOC/SOC operators need to become familiar with the grid topology and physics, available system components and their operations, system operations, type of data being received, discrimination between normal and abnormal data, practice troubleshooting, and understanding how ECC operators respond to system events. Such cross-domain training will provide hands-on experience in dealing with cyberattacks and can assist operators in developing their incident response skills. Further, red and blue team exercises can be carried out in a safe environment. A centralized monitoring system for both the NOC and ECC will further aid in bridging the gap for future grid control centers.

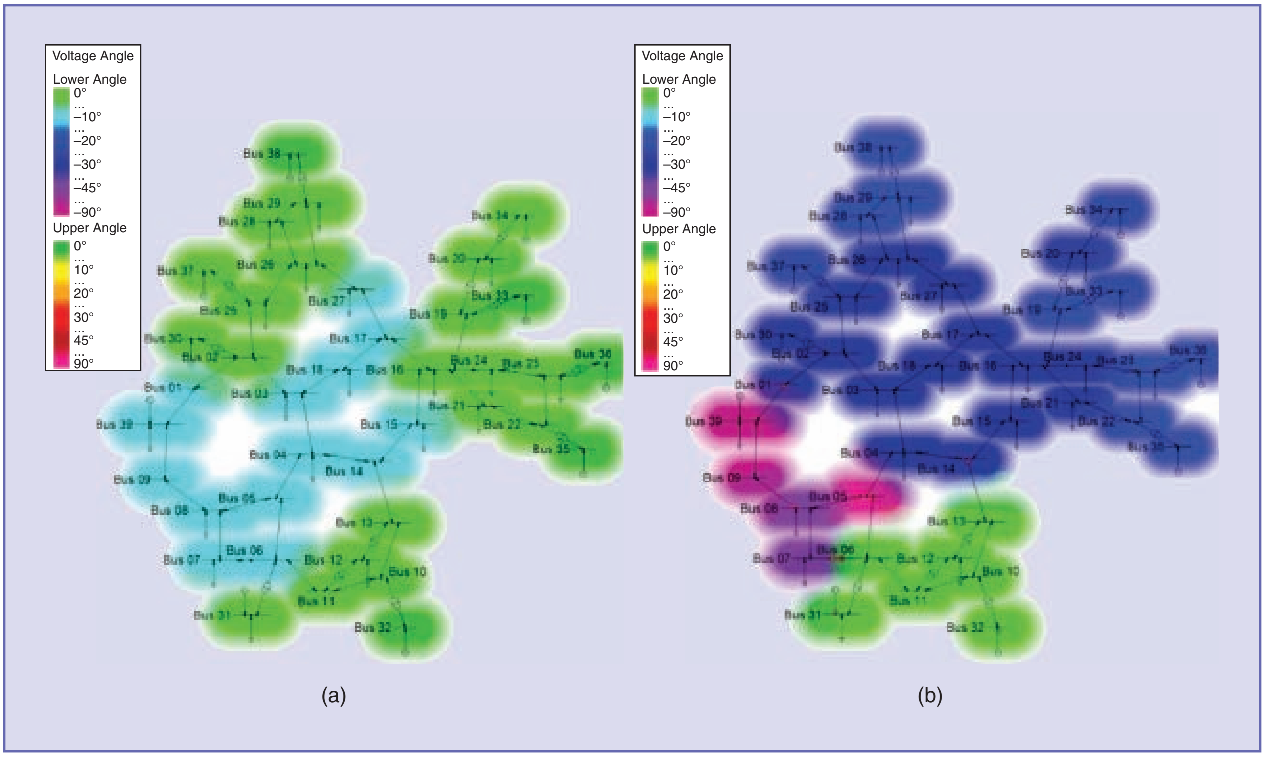

figure 7. Heatmaps of the voltage angles, depicting the propagation of cascading outages. (a) The system at 0 s simulation time, while (b) shows the system at 30 s simulation time.

Cyberphysical–Human Training for Operators and Engineers Using DTs

DTs will facilitate human-in-the-loop for incidence training in a realistic setting including scenarios such as normal cyberphysical operations, abnormal situations, and emergencies. DTs can provide real-time feedback on operator actions, allowing operators to understand the impact of their decisions and/or actions on the system and enable further skill development.

Generating Synthetic Data to Spur Tool Development

The DT generates synthetic data by simulating the behavior of the power system by considering different input conditions and scenarios. The data generated from the DT can be used to enhance situational awareness. Advanced persistent threats on CPSs are difficult to detect and isolate. Such attack patterns are consistent with real-world attack scenarios, such as the Ukraine attacks, where the adversaries performed stealthy network reconnaissance and lateral movement over a period of six months. Hence, keeping in line with the cyber kill chain concept, early-stage attack detection is essential. The proposed DT can be employed to generate datasets used to train advanced deep learning or AI models for attack detection. This can be in the form of visual cues and attack graph maps. Such models can then be deployed in substations to quickly detect anomalous traffic patterns, well before action on the objectives results in a physical impact.

DTs for the Cyberphysical Validation of New Operational Tools

The data generated through the use of DTs can additionally be employed for validating advanced tools, offering insights into areas where existing tools are considered inadequate. With the data generated, operators can identify patterns and gaps in the available tools and use this information to improve new tools.

Validating Alternative Cyberphysical Control Actions With DTs Before Implementation

Multiple control actions can be simulated to determine the best course of action in uncertain cyberattack situations. The DT can aid in the decision-making process by considering all available options before choosing the optimal solution for implementation on the actual system.

Cyberevent-Driven, Short-Term Planning for Cyberresiliency Using DTs

DTs will enable operators and planners to develop and implement short-term planning studies to mitigate unexpected cyberthreats and incidents. Operators can focus on addressing immediate risks and challenges and develop flexible responses to the ongoing cyberthreats. An example of this would be to analyze potential paths of attack propagation and determine which substation communication channels should remain connected and which should be isolated in prevent further spread.

Acknowledgment

The authors would like to thank the National Science Foundation and U.S. Department of Energy for partially supporting this work. They would also like to thank the Virginia Commonwealth Cyber Initiative and Dominion Energy for supporting part of this work. They acknowledge support from Schweitzer Engineering Laboratories (SEL), Real Time Digital Simulator (RTDS), and DigSilent for helping with testbed development.

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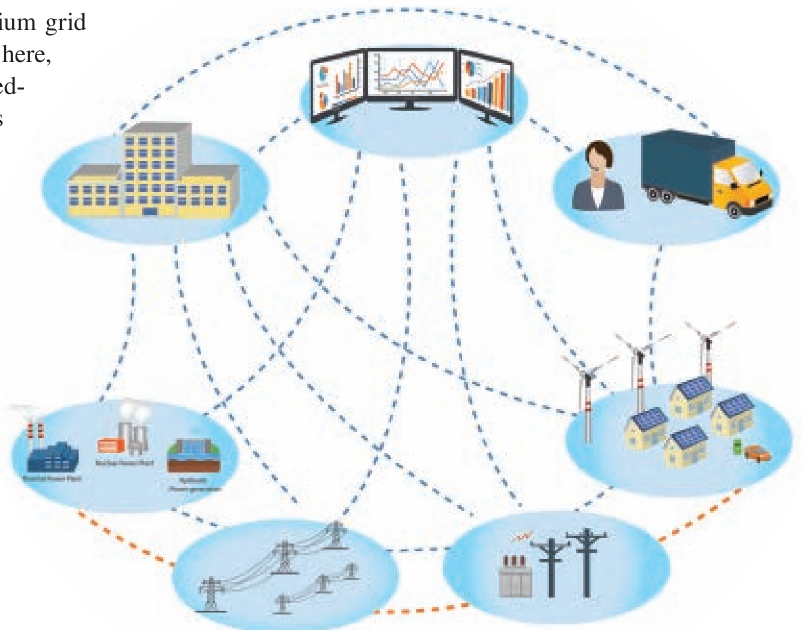
Cloud-Based Digital Twin for Distribution Grids

What Is Already Available Today

THE INCREASE IN DECENTRALIZED FLUCTUATING feed-in at low-, medium-, and high-voltage levels associated with the expansion of renewable energies and the emergence of new volatile loads and storage systems is increasingly influencing the overall system behavior of the energy supply and therefore requires a more proactive role for the distribution system operator (DSO). Low and medium grid voltage levels in particular have a pivotal role here, as a significant part of renewable energy feed-in, and almost any new volatile loads, such as heat pumps and electric vehicles, are connected on these levels. Thus far, especially on the low-voltage level, most grid operators encounter a lack of transparency and controllability. It is essential for the integration of renewable energies and volatile loads to have information on power flows and power quality. Hence, massive investments in grid, measurement, and telecontrol infrastructure would be necessary. Using intelligent software technology for grid management can significantly decrease these necessary investments.



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Digital Object Identifier 10.1109/MPE.2023.3336255
Date of current version: 12 January 2024

By Christian Köhler, René Kersten, and Michael Schöpf

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> Distribution grids are becoming increasingly important, as they play a crucial role in integrating renewable energy sources into the energy system.

In this article, we present an exemplary solution: a cloud-based digital twin approach that can be used for low- and medium-voltage grid management with no new infrastructure investments by the distribution grid operators. Instead of relying on measurements for each part of the grid and each asset, the digital twin that we present in this article uses modeling where measurement data are not available or not delivered in real time. Based on machine learning technologies, any grid part or any connected asset is continuously simulated. These simulated real-time data are then used for a continuous power flow calculation that gives a continuous state estimation in each part of the low- and medium-voltage grid. Comparison with available measurements enables continuous training of the models over time until they become a highly accurate representation of reality. A cloud-based approach ensures complete horizontal scalability, enabling fast computation of large meshed grids and the subsequent training of models. High interoperability with a contemporary DSO software system ensures interaction and control with any asset in the grid. In combination with given workflows for grid automation, the cloud-based digital twin makes it possible to utilize flexibilities at the low- and medium-voltage grid level in a highly automated and efficient way. In this article, we guide the reader through the steps necessary and the benefits of the cloud-based digital twin.

The Changing Role of Distribution Grids and Use of Digital Technologies

The traditional process of energy supply involved the use of large power plants, such as coal, gas, or nuclear power plants, that generated electricity at a central location and then transmitted it over long distances to consumers via the transmission grid. These power plants typically were operated in a way that matched the demand of the consumers. The demand of the consumers was determined based on standard load profiles, which were the only information necessary to determine the needed power and the current state of the grid.

The distribution grid's only role was, then, to connect different consumers to the transmission grid. As a result, the role of the distribution grid was a simple top-down transformation of electricity, to get the power to the location of the consumers.

The energy transition has led to a significant shift in the role of distribution grids. As more renewable energy sources, such as solar and wind power, are integrated into the grid, the distribution grid must adapt to accommodate the variability and uncertainty of these sources. This includes implementing technologies, such as energy storage and demand response, to balance supply and demand. Additionally, distribution grids are becoming more decentralized as more distributed energy resources, such as solar and electric vehicles, are connected. This requires a shift from traditional centralized grid management to a more decentralized and distributed approach. Thus, distribution grids are becoming increasingly important, as they play a crucial role in integrating renewable energy sources into the energy system. Switching from pure transmission and distribution of electricity in a top-down manner, distribution grid operators must now handle electricity flows between any grid levels and more complex information flows.

By using digital technology to optimize electrical power generation, delivery, and use, conventional grids can be transformed into smart grids. Therefore, grid operators are in need of digital solutions that give transparency to these complex power and information flows to optimize power usage and transform the conventional grid into a smart grid.

The most obvious digital solution for the transformation of the grid into a smart grid is the extension of supervisory control and data acquisition (SCADA) systems to lower-voltage grid levels. SCADA systems have evolved significantly over the last few decades in the distribution grid. A typical SCADA system for grid operation generally requires a variety of dedicated hardware components to function properly. Originally, SCADA systems were primarily used for the monitoring and control of large power generators and transmission lines. However, with advances in technology and the increasing need for greater visibility and control of distribution grid operations, SCADA systems have been adapted for use in the distribution grid.

One major change has been the integration of advanced metering infrastructure into SCADA systems. This allows for real-time monitoring of electricity consumption at individual customer locations and enables utilities to detect and respond to issues, such as power outages and voltage fluctuations, more quickly. Moreover, distributed energy resources, such as solar panels and electric vehicles, have been integrated into SCADA systems.

Still, just by extending SCADA systems to integrate more and more grid levels with more and more devices, grid operators might face increasing challenges. Decentralized devices that are connected to the Internet [Internet of Things (IoT) devices] deliver massive amounts of data in nearly real time. To capture the value of the data requires a great deal of effort.

> Not only is the grid itself modeled as a digital twin but the prosumers and other dedicated components, such as voltage-regulated transformers, are as well.

Central control by a SCADA system may be not sufficient to enable a smart grid; instead, to adequately deliver and administer the products and services made possible by the smart grid, intelligence and control might need to exist along the entire supply chain. Hence, decentralized software systems are necessary due to the magnitude of the devices and data collection and computation, which precludes a centralized data collection solution. With the increasing size of smart grids, electricity companies face challenges in keeping the SCADA system constantly updated and upgraded.

Moreover, SCADA also creates several additional security issues, as the electrical power network is a critical infrastructure. Without Internet connectivity, SCADA already contends with security issues, and additional methods of penetration via the Internet make it more vulnerable. As a result, there is a need for new solutions that go beyond the scope of classical SCADA systems.

To cope with these issues, a potential solution would be to complement central SCADA system architectures with high security and redundancy requirements with powerful cloud-based solutions that are able to deal with high amounts of data on lower voltage levels.

Cloud-based digital twin technologies allow systems to be developed that can create a virtual representation of an existing or future real object to fill this gap in digital technologies for the smart grid (see "Digital Twins in Power Systems: A Proposal for a Definition" in this special issue). Moreover, these technologies are capable of shifting the technoeconomic optimum of necessary measurement infrastructure, as elaborated in the next section.

Technoeconomic Optimization of Measurement Infrastructure Installations in the Grid

Based on the historical evolution of power systems and the evolution of SCADA systems, visibility and controllability in the transmission grid (i.e., at the level of high and extra high voltage) is at a sophisticated level. This goes to an extent of mathematically overdetermined systems, where measurement infrastructure is installed for redundancy to ensure highly reliable and transparent electricity transmission.

In medium voltage, the proportion of grid areas measured in real time is already significantly lower than in high-voltage grid levels, while in low voltage, visibility is virtually nonexistent. Visibility at the level of the distribution grid was practically unnecessary until the energy transition since the loads at the customer level were rather predictable and the generation took place exclusively at higher grid levels. Accordingly, there is currently no precise knowledge of the real-time status in the majority of distribution grids.

The first obvious way to create the necessary transparency in the network would be a comprehensive rollout of measurement technology. Due to the highly heterogeneous structures in the distribution grid, this would require a very large number of measurement devices, as a large grid area would have to be covered. The costs of such a rollout would be considerable and would be significantly higher than the expected savings in grid expansion. The path to more transparency in the distribution grid, therefore, cannot be accomplished through a massive introduction of measurement technologies.

Taking a closer look at the specific requirements for grid transparency and controllability on different levels is the key to economic investment decisions on infrastructure. This also involves an integrated risk assessment, differentiated among the different grid levels.

On the high and extra high voltage levels, transmission system operators are responsible for the reliable operation of the overall electricity system. Gigawatts of electrical power are transmitted via transmission lines with several hundred thousand volts. This also involves system balancing and redispatch measures performed in near real time to keep the grid frequency stable. The requirements regarding the safety and redundancy of measurement and control infrastructure are very strict on these levels. Additionally, due to the high energy amounts transported on these grid scales, the investment costs for measurement hardware allocated on each kilowatt hour are comparably low. At the opposite end of the grid, on the low-voltage level, relatively high investment costs per kilowatt hour would have to be allocated. Moreover, requirements for redundancy and safety are not as high as on the high and extra high voltage levels. A potential failure, which is still unlikely on that level, would affect a much smaller number of electricity consumers and would be limited to a small area. As described in the previous section, the classic architecture of SCADA systems is difficult to combine with the scattered data that exist at low-voltage levels. While future IoT devices may generate massive amounts of potentially useful data for certain grid-connected assets, information on other areas of this grid level may still be very sparse because of slow digitization progress, long processes for information transmission, or data privacy reasons.

Due to this lack of real-time data and the necessary use of pseudomeasurements like historic load data, state estimation of the power grid on the distribution level has been associated with quite high noise levels up to 50%. Using new data sources like smart meter data can significantly increase the accuracy of state estimation. The following section gives insights into the capabilities of state-of-the-art digital twins for state estimation and, further, data-driven use cases for the improvement of distribution grid transparency.

Realizing the Digital Twin

The digital twin system can be seen as an integrated solution for network calculation, grid state estimation, and network simulation, including the integration of the economic side, with the aim of overall system optimization. The system's modules can handle use cases such as power flow simulations/optimization/management, short circuit calculations, feed-in/congestion management, and simulation and optimization of different switch states. Furthermore, the system can have integrated permanent data storage for real and generated pseudomeasured values or be coupled to them.

Extended modeling for consumers and generators, as well as the resulting forecasting functionality and grid state estimation function, form the core of such a system. In this area, advanced statistical and learning-based methods can be used, some of which are based on large amounts of data.

Depending on the application, different systems benefit from the data deliveries:

- ✔ *Advanced distribution management system/SCADA*: can be supplied with pseudomeasured values that cover nonmeasured areas
- ✔ *Advanced distribution management system/SCADA*: can receive notifications on current and future grid situations (feed-in/congestion management and use of flexibility in the grid)
- ✔ *Asset management*: can be supplied with generated load data of equipment; alternatively, an estimated condition value for a resource can also be transmitted directly
- ✔ *Geographic information system*: can receive network topology changes from semiautomated network optimization functions.

Figure 1 shows the integration of the different data sources for a continuous improvement of data quality. The crucial point is that not only is the grid itself modeled as a digital twin but the prosumers and other dedicated components, such as voltage-regulated transformers, are as well. The overall digital twin consists of several interacting digital twins on different levels of abstraction. In addition, real-time data sources can be integrated for better estimation and forecasts.

We describe characteristics of such already available systems in the following section.

Advanced Modeling of Consumers, Producers, and Grid Assets

A central pillar of the digital twin is the modeling of all assets that either set up or are connected to the grid.

The first step involves extended profiling for end customers via their own load profiles. In this method, measurement data are combined with socioeconomic data to generate data protection-compliant load profiles based on the characteristics of prosumer groups. These profiles can then be projected onto the grid connection point, with only a subset of real measurements required to create a model with high accuracy.

The same logic applies for generators like photovoltaic panels, combined heat and power plants, or small wind turbines. By knowing the location and the peak power output

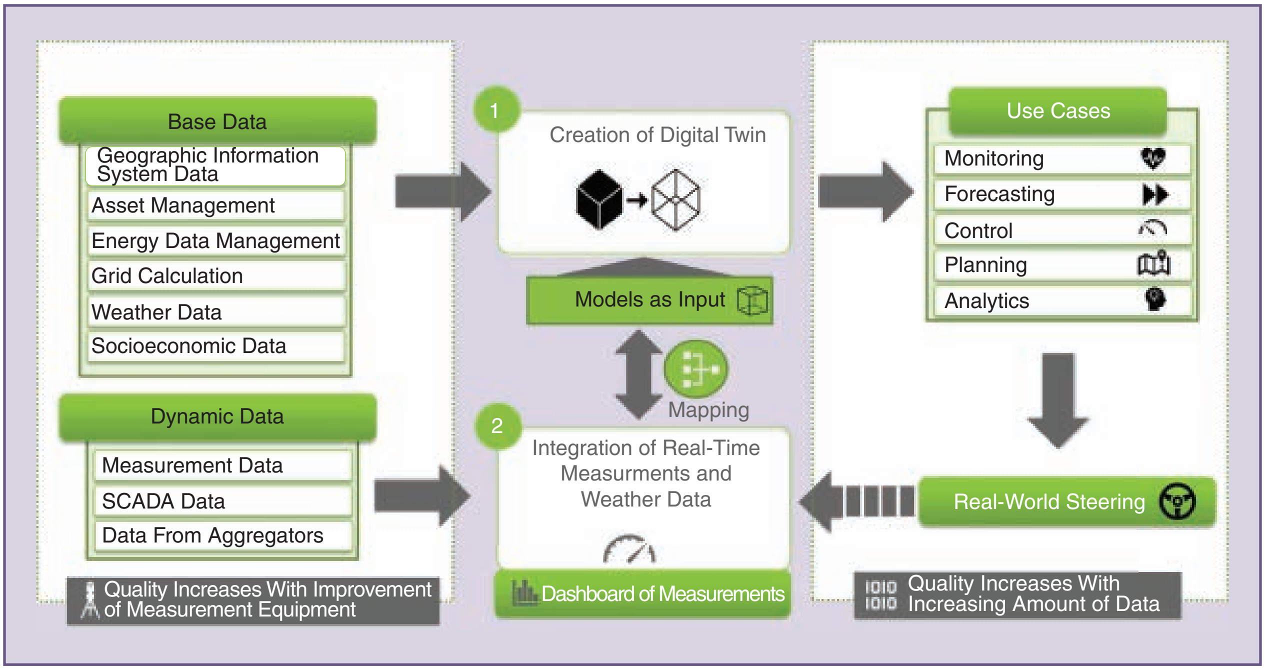

figure 1. The matching scheme for a continuous improvement of data quality.

and then combining this information with weather data, it is possible to generate not only real-time information on the feed-in but accurate generation forecasts as well.

In addition, load profiles can be generated for network nodes and cable routes as a preliminary stage for power flow models. This can be achieved via simple statistical evaluations based on load profiles. Statistical or machine learning models can also be developed for measured network nodes or network areas, such as cable routes, considering not just time information and training load measurements but also external environmental data, such as temperature, or short-term measurements of electrical quantities. The accuracy of such forecasts can be quite impressive, typically falling within a few percentage points of the actual results.

Finally, it is important to note that model updates are essential and typically carried out every six to 12 months. These updates involve reviewing and recalibrating the models based on recent history to ensure the ongoing accuracy and usefulness of the models.

Generally, the digital twin can process and analyze diverse data sources:

1) geographic information system data/network topology data, including current switching states
2) master data of producers and consumers in the network
3) equipment data (asset management data)
4) measurement data from the SCADA/advanced distribution management system
5) measurement data from the energy data area (billing data, load profiles, feed-in profiles, "smart meter data," and IoT devices)
6) forecasts of external service providers, such as weather data and electricity price data
7) socioeconomic data of end customers on the network ("geomarketing data").

The modeling can be done with various exemplary approaches:

1) *Extended profiling for end customers via own load profiles*: Measurement data are blended with socioeconomic data in such a way that data protection-compliant load profiles are generated based on the characteristics of prosumer groups. A prosumer group can be projected onto the grid connection point. Only a subset of real measurements is required. Practical experience shows that between 10% and 30% coverage of real measurements is sufficient to get an adequate accuracy of the grid status.
2) *Extended load profiles for network nodes and cable routes*: As a preliminary stage for powerful models, load profiles of measured network nodes and cable routes can be generated via simple statistical evaluations. In the simplest case, these are based on the load profiles.
3) *Statistical or machine learning models of measured nodes or network areas, such as cable routes*: In addition to pure time information and training load measurements (conventional load profiles), more extensive modeling takes into account further input data, such as external environmental data (temperature) or short-term measurements (see Figure 2). The accuracy of the results of such forecasts is within the range of a few percentage points.
4) *Model updates*: Reviews and recalibrations based on recent history are carried out on average every six to 12 months.

In many cases, the provision of measured values to train the models or to form their own load profiles takes place with a longer time delay of one year or more. Here, knowledge of the switching state at the respective measuring times is essential. The process can also take place on this basis and represent added value for ongoing operations. In future systems, a

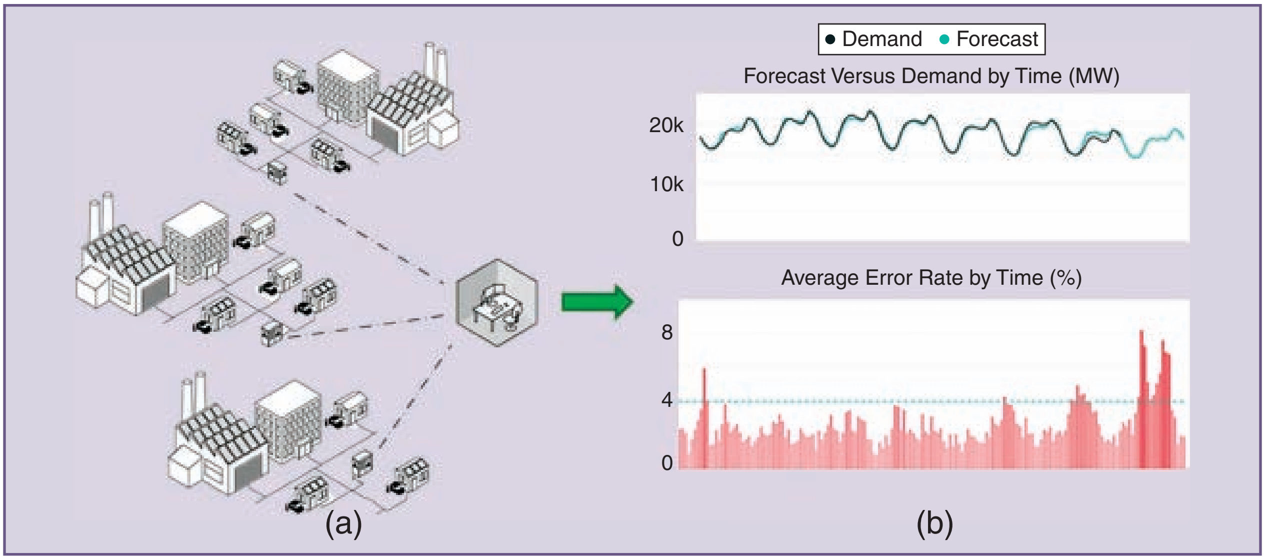

figure 2. The basic structure of the predictive models. (a) Input data from the digital twin. (b) Exemplary model results from the prediction models.

reduction of the interval should be sought to reduce deviations. Pure modeling does not require a live data stream (see the model update cycle information earlier in this section). However, the use of higher-quality models with deviations in the single-digit percentage range requires near-real-time data provision, e.g., the provision of a 24-h measurement time series every 24 h.

In real use, the recommendation is to ensure the timely provision of data with expanding measurement and telecontrol technology. However, measurements without remote reading can already be used today and contribute to a better recording of the network situation.

Grid State Estimation and the Digital Twin

A grid state estimate typically includes real measured values and, if necessary, pseudomeasured values from models. In the distribution network, the estimation is based on a mathematically underdetermined system wherein fewer measured values are available than nodes and edges in the network. Accordingly, grid state estimation requires real-time data transmission.

Grid state estimation can be carried out according to the following scheme. The problem can be stated as follows:

1) Power flows P_{ij} and Q_{ij} over the branches are usually not recorded at all.
2) There are not enough measured values for P_i, Q_i, and U at available nodes.
3) The system is underdetermined.

The approach to execute state estimation contains these steps:

1) Load models are created for consumers and generation. The data can be derived from, e.g., smart meter measurements, billing data, (weather) forecasts, or other sources.
2) Based on the combination of measured values and pseudomeasured values, a load flow calculation for the determination of power flows P_{ij} and Q_{ij} is performed.
3) Measured values are incorporated with a higher relevance than estimated data from the models.
4) Finally, the state estimation finds a probable grid state, with uncertainty for each state variable.

Automation

The challenges of the smart grid will lead to a higher number of interventions. On the other hand, though, many distribution grid operators face the challenge of staff shortages due to problems of demographic change.

Adapted from the stages of autonomous vehicle driving, one can distinguish six stages of grid automation:

- ✔ *Level 0*: There is no automation, and system management acts manually based on reporting and measurement information. While system management can monitor and remotely influence the grid's status, there is no automated background function.
- ✔ *Level 1*—Assistance: This involves a background function that carries out grid calculations supported by information. This background function provides proposals for action, and the system management decides and intervenes manually.
- ✔ *Level 2—Partial automation*: This includes a background function that is manually enabled or disabled by the grid control system operator. Once enabled, the background function controls the system automatically without further release.
- ✔ *Level 3—Conditional automation*: This level includes a background function that is automatically activated or deactivated through a triggering condition. Once activated, the background function automatically controls the system without further release.
- ✔ *Level 4—Highly automated*: This involves the implementation of many triggering conditions, resulting in automated grid operation during normal operation. At this level, the grid control system operator becomes active only in the event of rare or exceptional fault events.
- ✔ *Level 5—Complete automation*: This level involves the system guide setting parameters and rules, then starting up the machine. Grid operation runs fully automatically, with no human intervention required.

Properties of an Available Digital Twin System

As an example of an available system in practice, we developed a modern digital twin system that offers several important properties. One of the most notable features is its exposed modern application programming interface (API), such as a Representational State Transfer API, which conforms to OpenAPI (www.openapis.org) specifications. This allows for seamless integration with other systems and easy communication with the digital twin. It allows several digital twins to connect while remaining under the control of their respective owners (site operators), ensuring data privacy and the sharing of needed information at the same time.

In addition to the Representational State Transfer API, the digital twin system also includes a complementary streaming API or message bus system support like MQTT or Advanced Message Queuing Protocol. This is especially useful for data collection in the field and allows for continuous data stream analysis using stream analytics engines.

The developers have taken a microservice-oriented architecture approach in their digital twin system. This means that there are no monolithic programs; instead, there are independent services that communicate with one another via defined APIs. The modules are stateless, making it easier to scale and update the system as needed.

The data storage system in the digital twin is also highly scalable and modern. Often, specialized not Structured Query Language storage, such as key value storage and graph databases, is used, among others. This ensures that the system can handle large amounts of data efficiently and effectively.

For such a modern digital twin system, state-of-the-art IT approaches should be used. This involves continuous development, deployment, and updates as top priorities. The developed system includes so-called continuous integration and continuous delivery pipelines, allowing for a smooth and streamlined process to update and deploy new features.

Finally, this digital twin system offers horizontal scalability, ensuring that the system can handle increasing data volumes and traffic loads without any significant issues, making it a reliable and sustainable solution for businesses and organizations that require a modern and efficient digital twin system.

Human-Machine Interface: Visualization of Grid Topology and Grid State

In the rapidly evolving landscape of IT technologies, modern web user interfaces have emerged as the cornerstone of user engagement and satisfaction. These interfaces are more than just the visual part of a website; they encompass a complex blend of technology, design principles, and user-centered thinking to become complex applications. These web applications are not limited to single devices or device types. So-called responsive designs make them available on personal computers, smartphones, and tablets. In addition, local storage enables persistence and offline execution, so the difference from classical desktop applications is further reduced, but flexibility is still provided.

The web-based visualization allows the user to display a variety of grid resources and power generators as well as consumers (households, industry, and so on) connected to the grid in a map view. The interface delivers a condensed view of the information so that the user can easily assess situations. Also, the user can easily dive into data details.

The interactive map (Figure 3) gives a fast overview of the real-time grid state. Critical areas can be easily identified by, e.g., heat maps or traffic light colorization. All elements are automatically updated if the data in the back end change.

All data can be interactively explored (see Figures 4 and 5). That includes grid or station statistics based on real-time measurement data, statical data, or estimations. Key performance indicators in particular are easily accessible for information-driven decision making.

Application Examples of the Digital Twin Platform

Municipal Utility EWZ: Greencity

Starting in 2018, during the Greencity pilot with EWZ in Zurich, Switzerland, it was demonstrated that model-based real-time monitoring and control of the low-voltage grid is applicable in real-world applications. Every 5 min, power flow calculations are used to estimate the grid status based on a digital representation of the physical power grid, measurements made in the field, machine learning-based load models, and specified grid constraints. Grid congestion is handled in an automated way by the digital twin platform. Loading infrastructure is actively controlled by the digital twin to avoid grid congestion.

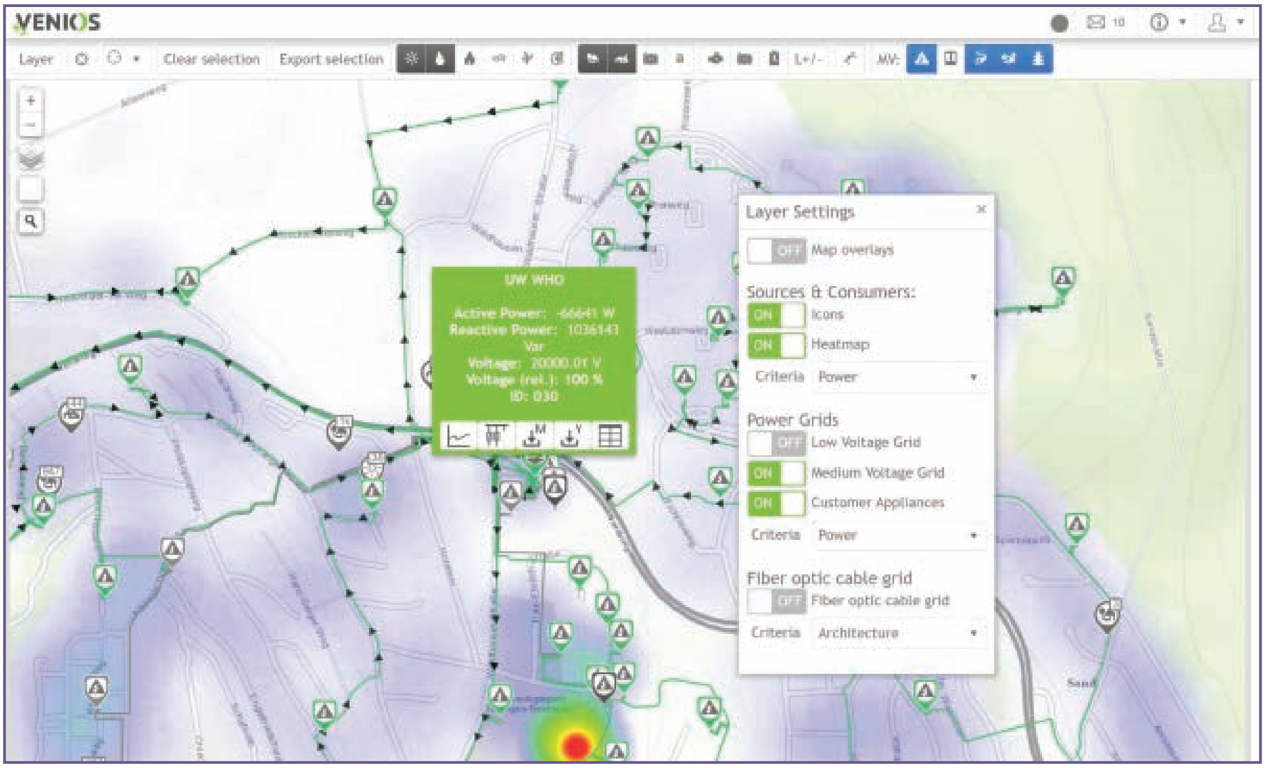

figure 3. An interactive map gives a fast overview of the real-time grid state.

The digital twin platform implementation within the cloud environment receives streamed measurement data from the field. The low-voltage grid's specified measurement points and parameters are addressed by the fundamental monitoring concept. An expandable cloud environment that meets IT security requirements has been demonstrated by experience in IT architecture. The installation will be expanded to the whole grid.

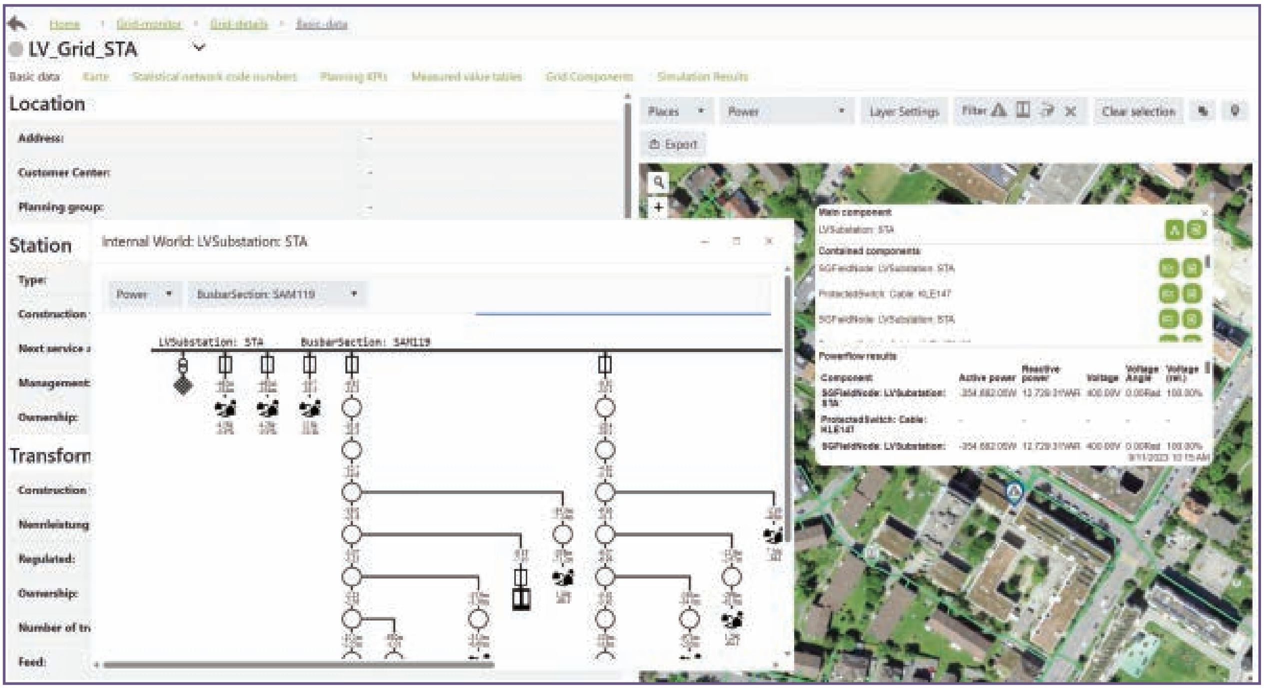

figure 4. Outer and inner world views are available and completely linked. The grid topology can be explored and changed during runtime. All users see changes in real time.

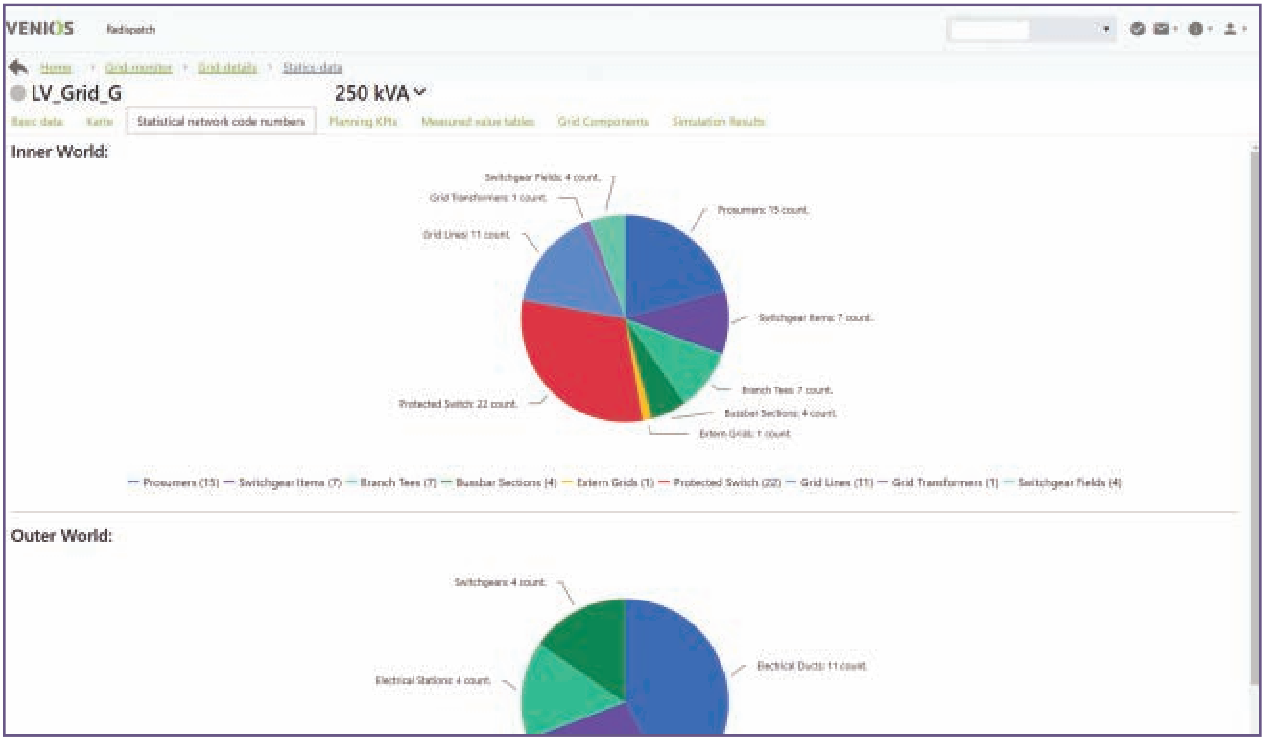

figure 5. Diverse statistics and key performance indicators are available. All numbers are automatically derived from base datasets, measurements, or continuously running grid state estimations.

As more renewable energy sources are integrated into the grid and electrification increases, there will be a greater need for a transparent and efficient grid.

Municipal Utility Schwäbisch Hall

The municipal utility Schwäbisch Hall uses the digital twin platform for the monitoring and planning of its own low- and medium-voltage grid. In addition, the municipal utility provides grid management and planning services to other DSOs that are not performing these processes themselves for resource and/or cost efficiency reasons. Since these services sometimes must be provided far from company headquarters, Schwäbisch Hall relies on an efficient combination of the implemented digital twin platform for network condition monitoring and planning in the low- and medium-voltage range and a conventional SCADA system for network management within the framework of an interconnected control center.

Summary and Outlook

This article presented the idea of a cloud-based digital twin as a practical solution for providing transparency in distribution grids without requiring high infrastructure investments. This innovative solution utilizes machine learning technologies to continuously simulate every grid part and connected asset in real time, resulting in a continuous power flow calculation that provides state estimation for every part of the low- and medium-voltage grid.

The cloud-based digital twin goes beyond simple simulation by incorporating field measurements and continuously comparing simulated data with them, thus enabling continuous training of the models over time until they become highly accurate representations of reality. This ensures that the digital twin can adapt to changes in the grid and maintain its accuracy over time.

One of the key benefits of this technology is its complete horizontal scalability, which allows for the fast computation of large meshed grids and subsequent training of models. Additionally, high interoperability ensures interaction and control with any asset in the grid, making it possible to utilize flexibilities on the low- and medium-voltage grid level in a highly automated and efficient way when combined with workflows for grid automation.

Currently, this digital twin is being used in multiple distribution grids, but its full potential has yet to be realized. As more renewable energy sources are integrated into the grid and electrification increases, there will be a greater need for a transparent and efficient grid. The cloud-based digital twin can be instrumental in meeting this need by enabling connection to flexibility markets. It can automatically determine the need for flexibility, determine the value of different types of flexibility for grid congestion relief, and be used to determine reference profiles (baselines) for flexibility providers. In the future, the digital twin could potentially automate more and more functions of grid operation, up to entirely automated grid operation.

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READERS ARE ENCOURAGED TO share their views on issues affecting the electric power and energy profession. Send your letters to the editor-in-chief at pem-eic@ieee.org. Letters may be edited for publication.

The Availability of Data

The September/October issue of *IEEE Power & Energy Magazine*, with its emphasis on grid communications, recently ended up in my mailbox, and it is a fascinating commentary on the ability we have to gather data and to communicate those data to the users. I got involved with the application of process control computers for substations (actually converter stations) in 1968. We got serial numbers 2 and 3 of GE's new real-time process control computers. This was among the first applications of sequence of events (SOE) recorders imbedded in power system control computers. We also had a couple of Hathaway-built fault recorders with about 1.5-kHz bandwidth. The U.S. Army Corps of Engineers had the first of these installed in the John Day Dam in Oregon. I made sure that SOE recorders were included in the digital relaying system developments sponsored by EPRI beginning in 1979 with an additional feature, which was to save a data file around the time the relays produced trip outputs to be used as an audit trail for diagnostic analysis.

Digital Object Identifier 10.1109/MPE.2023.3331470
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What I learned from working with the electric utilities is that no one has time to analyze SOE and fault recorder data unless there is a serious event or suspect trip operations. The digital relays can and do collect information that can be used to detect numerous performance issues with substation equipment, but again, no one has time to analyze the data. So, just because you can collect and use data for process control functions, there must be real cost benefits for it to be done. This side of the "equation" is missing in the magazine.

For instance, if you have millions of sensors capturing data with microsecond time resolution, consider the number of sensor failures that will have to be addressed. Each component failure might cost hundreds of dollars to fix since a crew has to be dispatched with a new module, the new module must be installed and tested, and then the old module recycled. This is after having spent potentially billions for the initial investment. If the useful life of the modules is 15 years, then there will be millions of modules to replace at the end of the module life. Will the costs be justified?

Massive amounts of collected data have no value unless they are useful. Collecting diagnostic data has limited use unless the data can be used to prevent failures of equipment or to avoid blackouts. Will the data be available even after a major storm-related outage? A major hurricane impacted Florida a couple of decades ago. The restoration crews could not use utility phone lines or radios because the antennas were damaged and the fiberoptic links were on the ground. But they could use a pocket full of quarters and pay phones to call the dispatchers. That would not be possible today. Every utility has a website that tells the customers to go to their website to get information about outages and restoration of the power system. Good luck with that when the power is out. However, most people have car radios that can be used for messaging, but this is an unused option. We have been enamored by high tech to the point that we are ignoring the system weaknesses.

Consider also the weaknesses of 5G, which is likely to become inoperable during inclement weather, such as snow or heavy rain/fog. Millimeter waves do not travel very far if the path is obstructed. This is one unavoidable issue with wireless systems. In addition, before you should use a datum with microsecond time resolution, you need to know the characteristics of the measuring device and any past processing of the datum that is possible by means of a digital or an analog filter. The effects of noise present in the data need to be understood. Some of this was addressed in the following Cigre technical brochure: e-cigre > Publication > Overall impact of digital techniques for transmission systems (Substation control).

—Stig Nilsson

Robert D. Barnett

the universal power system

an evolution

IN THE THIRD DECADE OF THE 21st century, electrical power is taken for granted. We plug a hand drill into an outlet, just as confident that the system will supply power at the correct voltage and frequency as the electrician who hooks up a 500-hp dc motor. We don't expect to have to hook up to a different system for every class of power that we need. This is a universal system, similar in concept to that of the open architecture computer bus, both of which we now take for granted—but of course, this was not always the case. In North America, the development of the power system can be seen as occurring in four stages.

In this issue's "History" pages, we explore the evolution of the universal power system. In this article, the author takes us through the evolutionary stages from the age of the steam engine, to early dc systems, through the stage of a need for greater transmission distances, and then to the universal polyphase ac system.

We welcome back Robert D. Barnett for an eighth time to the "History" pages of our *Power & Energy Magazine*. A Life Senior Member of IEEE, Robert graduated from the University of Waterloo and Niagara College. In 1982 he formed the Niagara Society for Industrial History as a support group for a proposed museum in a former Niagara Falls power plant, and he has written on the history of the topic.

John Paserba
Associate Editor, "History"

Stage 1: Power Transmission in the Age of the Steam Engine

From the beginning of the industrial revolution to well into the early 20th century, the reciprocating stream engine (Figure 1) and, to a lesser extent, the hydraulic turbine were the prime movers for manufacturing machinery. It is not commonly recognized that, in addition to traditional applications, such as locomotives and textile mills, steam engines were used to power steel rolling mills, blast furnace blowers, and swing bridges, to name just a few applications. For the most part, where power was needed, the steam engine was used.

As the manufacture of small and complex items, such as watches, hand tools, railway apparatus, etc., began to dominate the industrial scene, it became impractical to site these prime movers at the machines they drove.

Steam engines were too large to be used to drive small machine tools—a single milling machine or drill press, for instance. Economies of scale dictated the use of large engines or water wheels in a centralized location. As a result, a means of transmitting this power to the machines that needed it was developed. These transmission systems more often than not took the form of mechanical line shafts, belts, and pulleys with a power takeoff at the machine itself.

The line shaft transmission of power for general manufacturing was practical only to distances of fewer than 100 m (Figure 2). Other mechanical means, such as compressed air and the pumping of hydraulic fluids, were tried, but they were limited to the same order of magnitude as the line shaft. Both space and the practicality of maintaining these complicated systems were limiting factors, as were the losses often incurred in bearings, belts, clutches, and fluid turbulence.

A system was needed that was easy to install and maintain and was also more energy efficient.

Stage 2: The Electrical Coupling—The Early DC System

Any electrical transmission line can be thought of as an electrical "line shaft" that links two mechanical devices. At one end of the line is a hydraulic turbine driving a generator, and, at the other end, connected by electrical conductors, is some load—a pump, for instance—driven by an electric motor.

For most of the 19th century, dc had been in use in one form or another

Digital Object Identifier 10.1109/MPE.2023.3331170
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because it could be provided by batteries. Some of the first generators powered arc lamps to provide light for important buildings and streets (Figure 3).

By the last quarter of the 19th century, dc generators were being used to supply both arc and incandescent lamp systems. These early generators were designed before the factors governing magnetic circuits were well understood by the average engineer. It was a natural step, then, to use these same dc lighting systems as a power supply for motors (Figure 4).

By 1890, dc motors were beginning to be used for industrial purposes, although they didn't resemble modern motors. A fairly large and well-understood dc power system was becoming entrenched. Small motors, as low as 1 hp, could now be easily located near the machines that needed them (Figure 5). Large systems of shafts and pulleys were being replaced by dc motors.

Power could now be generated in a central station with electrical conductors replacing the much larger system of shafts and pulleys. Generator design also began to improve as the understanding of magnetic circuits advanced, and, by the end of the 19th century, the dc system of distribution was well established.

The economic ramifications of the new system were obvious. Now, manufacturing plants could expand, unhampered by the necessity to provide space for dozens of steam engines. Steam engines would be installed in a central station that was owned by a company specializing in power generation and distribution.

Even while all of this was happening, a problem with dc was lurking in the background. DC machines were only capable of generating low voltages, on the order of 1,000 V (Figure 6). This was due primarily to the flashover limitations of their commutators. There was no simple equivalent to the ac transformer. As a result, power could be transmitted only over distances on the order of only a few miles. By the late 1890s, the dc system that had, for a time, solved the problem of mechanical transmission

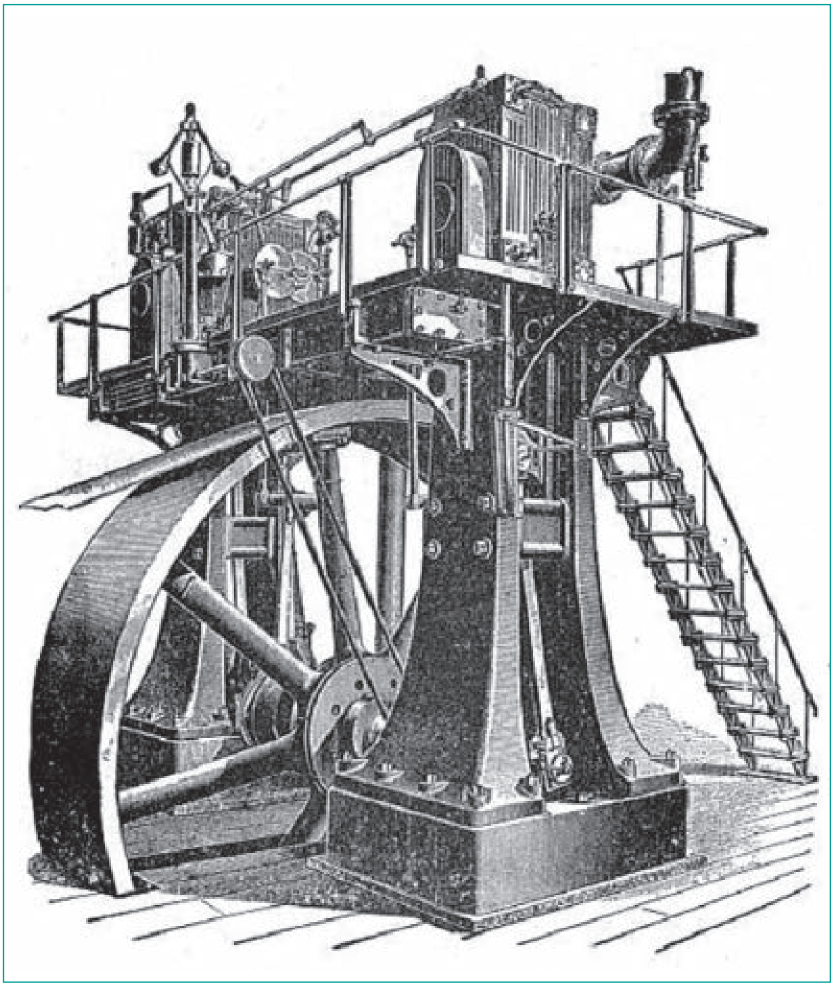

figure 1. A large, vertical, cross-compound Philadelphia Corliss steam engine. (Source: N. Hawkins, *New Catechism of the Steam Engine*, Theo. Audel & Co., New York, 1897.)

figure 2. Belts and pulleys—mechanical power transmission in the age of steam. (Source: http://ifsa.my/articles/mechanical-power-transmission-part-i-an-overview; in the public domain.)

energy losses was itself becoming limited by its own losses.

Stage 3: The Need for Greater Transmission Distances

As outlined in *Electrical Engineering* (Christie, 1925), several attempts were made to increase dc voltage. Because the Thury system had some success in Europe, it was, for a time, considered for use in the United States. It was a constant-current system, and, because of this, so were the transmission losses. The voltage was varied as the load changed. Several dc generators were placed in series and brought in or out of the circuit as the load dictated.

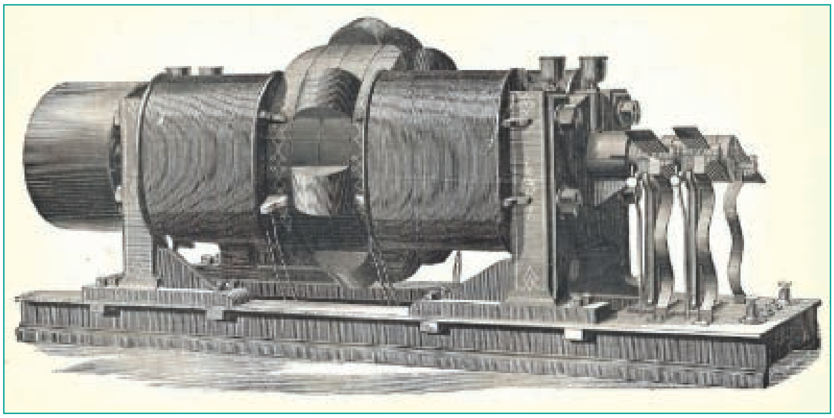

figure 3. An 1880s dynamo, rated for 25 arc lights, manufactured by the Brush Electric Manufacturing Co., Cleveland, OH, USA. (Source: Silvanus P. Thompson, *Dynamo-Electric Machinery*, E. & F. N. Spon, London, 1888; in the public domain.)

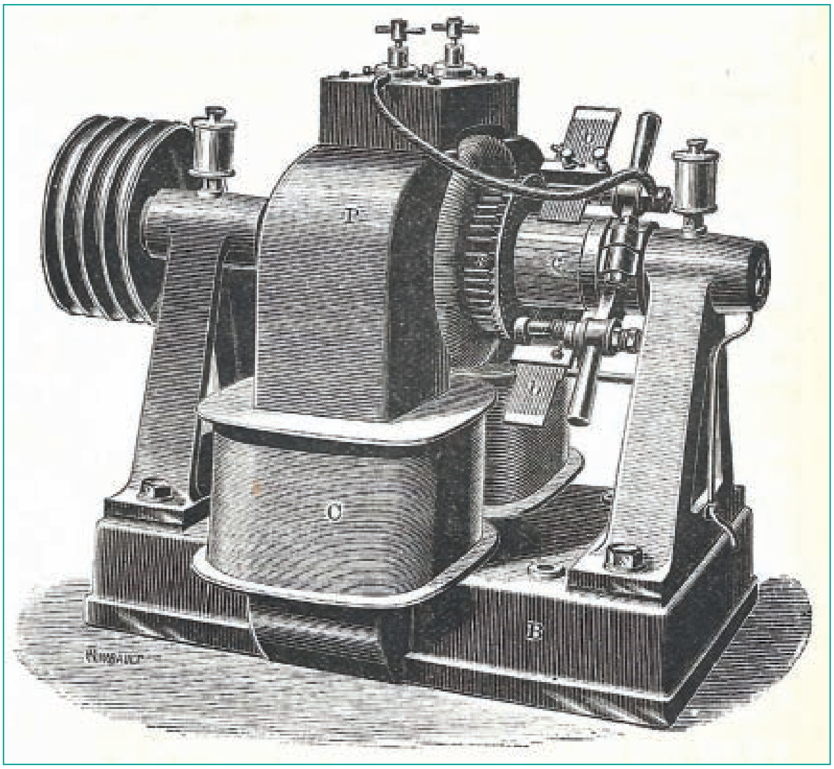

figure 4. An 1880s dc generator intended for general lighting service. It could deliver 180 A at 105 V. (Source: R. Mullineux Walmsley, *The Electric Current*, W. J. Johnston Co., London, 1894; in the public domain.)

This was accomplished by means of an automatic regulator, which moved the brushes and varied the resistance in a rheostat or diverter, shunting part of the field winding. In some cases, the speed of the prime mover was varied as well.

The various generating units were not required to be in a single station and could be located at any point along the transmission line. This was useful for long-distance transmission because a number of small generating stations could be located at intermediate towns close to a source of energy. This system was tried in the mountainous regions of Switzerland and Italy.

Figure 7 shows the layout of a 60,000-V, 150-A Thury system. During periods of light load, any generator could be taken out of service by disconnecting the regulator, moving the brushes over to the position of zero voltage, and then closing the short-circuiting switch. To put it in service again, it was brought up to speed, with the short-circuiting switch operated and the regulator set for the required current.

The motors had to drive through insulating couplings and were put into operation by opening a short-circuiting switch and then moving the brushes to the proper position. The regulator was then connected in to take care of the speed. In the majority of terminal stations, the power, which was transmitted by dc, was converted into ac for local distribution, with the series motors driving ac generators.

There were several problems with this system, however. Load sharing was an issue that resulted from the fact that the generator field was in series with the armature and not in parallel, as with the vast majority of dc machines. This meant that, unlike the shunt generator, the excitation current of a series generator varied with the load. If not controlled, this would cause that machine to take on more than its share of the load, particularly when combining this with the Christmas tree effect—where, if one machine had an open circuit failure, so did the whole series string. For general power transmission, the series system did not have much to offer.

By 1890, it was well understood that ac could solve this transmission distance problem once a workable transformer became available. AC allowed transmission potentials of more than several tens of thousands of volts to be obtained from a relatively low-voltage generator. Since higher voltages reduced the amount of current required to transmit a given block of power, this lower current meant that power could be transmitted to greater distances without prohibitive losses.

However, there were still several challenging problems. Little was understood about ac reactance and the problems it caused in transmission and equipment operation. In many cases, there was an impedance to the flow of current in ac circuits that was greater than the resistance of the circuit alone would indicate. It would take no less of a genius than Charles Steinmetz to explain what was happening and provide an analytical method for circuit calculations, but the most important shortcoming was the lack of a reliable, self-starting ac motor.

At the beginning of the last decade of the 19th century, the patents for an ac induction motor were sold by Tesla to Westinghouse. These patents, however, were for a rudimentary version of the induction motor. Much work would be required to bring it to a commercially viable state. An example of the problem was encountered in 1891 by Westinghouse at the Gold King Mine in Telluride, CO, USA. It was well known that, in both the dc and ac systems, a generator could be used as a motor. This was, in fact, done at Telluride, where a synchronous motor was used to drive mill equipment. Being a synch motor, it was not self-starting, so a small Tesla pony motor was used to bring it up to speed before it could be put on the line. This Tesla motor didn't perform very well, but that's another story. As we have seen, the dc system did not suffer from these problems.

There was a great deal of interest in financial circles for implementing the ac system, and all of the ingredients were in place, though financial backers were reluctant to invest in an unproven system. They were only waiting for someone to commit to the ac system—for the right catalyst to be added to the mix—and that would happen at Niagara Falls.

Stage 4: The Universal Polyphase AC System

For years, the power of the falls at Niagara was known throughout the world. Their location on the border of the Niagara Frontier in the United States and the Niagara Peninsula in Canada, though, put them at a great distance from any large manufacturing loads. Even at the end of the 19th century, at which time the Great

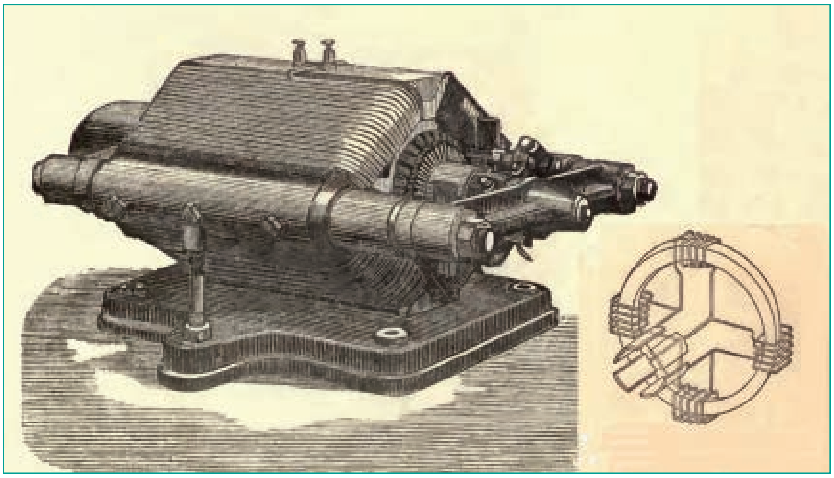

figure 5. This De Meritens motor employed a ring armature, show in the inset. It weighed 72 lb and had an efficiency of 50%. The typical power output was fewer than 10 hp. (Source: S. P. Thompson, *Dynamo-Electric Machinery*, E. & F. N. Spon, London, 1886; in the public domain.)

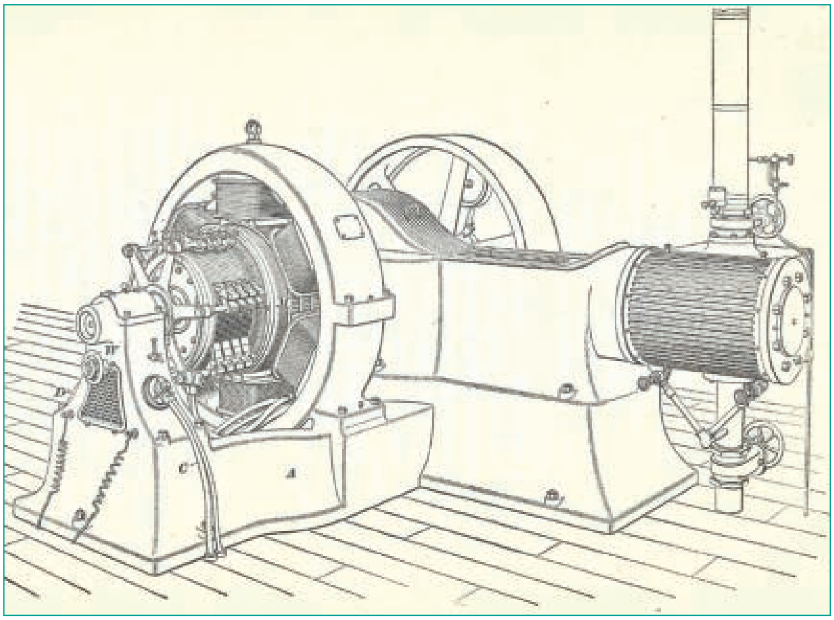

figure 6. A dc generator driven by a steam engine was the most common source of electrical power in the late 19th century. (Source: The International Library of Technology, Section 12, "Dynamo Design," ICS Scranton, 1905; in the public domain.)

Lakes port city of Buffalo, NY, USA, was fast becoming a large manufacturing center, the transmission distance of 30 km from Niagara Falls was not within the capabilities of any system then in use.

In 1892, the Niagara Power Company decided to develop the vast potential of Niagara Falls and transmit its power to Buffalo; there was no clear-cut system of choice, but many were proposed. In addition to the conventional ac and dc proposals with some not-so-conventional twists, there were proposals for shafts and belts; pulleys and ropes; compressed air; hydraulic power; and, last but not least, the polyphase ac system of George Westinghouse.

Before a decision was made as to what form the power transmission would take, the power company owners, headed by Edward Dean Adams, began construction on the mechanical equipment for the powerhouse. This was to take the form of 10 turbines that were each rated at 5,000 hp; these were the largest for their day and required only a scale-up of conventional practices. What the turbines would be driving, however, remained in doubt.

Even while all of this was happening, a problem with dc was lurking in the background.

In the late 19th century, the two major electrical loads were street lighting and dc street railways, with the latter being the largest motor loads. Because of this, it was inconceivable that any system used to transmit power for motor use would be anything but dc. Adams was not convinced, though, and, after several unsuitable proposals, he made the courageous decision to adopt the Westinghouse polyphase system. This decision was the catalyst that accelerated the arrival of the electrical age.

The alternators that Westinghouse built in 1895 were of an unheard-of size: 5,000 electrical hp. They were only vaguely reminiscent of modern hydro alternators, though. The alternators were two-phase machines with rotating armatures, and they generated 25 Hz. The frequency was dictated by the speed of the turbines, which, by the time the Westinghouse contract had been let, were long since fixed at 250 r/min.

Within 10 years of first power at Adams Plant No. 1, a sister station, Plant No. 2, and the Rankine plant of the Canadian Niagara Power Company were online and delivering power. With the exception of its 25-Hz frequency and the fact that the Adams plants were two phase, this power system was identical in concept to that in use today.

Why is this such a big deal? To fully appreciate the impact of the Adams plants, we need to look at another contemporary generating station.

The *Niagara Falls Electrical Handbook*, written in 1904, provided the following information. In 1895, the Niagara Falls Hydraulic Power and Manufacturing Company (Figure 8) began the erection of it second powerhouse. It was located just a few kilometers down the river from the Adams plant at the present-day location of the dock of the *Maid of the Mist* riverboat tour. In terms of the early 20th century, this generating station was large, but, more importantly, it was representative of the generating station design philosophy of the time. In this station, there were 15 turbines in operation, the capacity of which ranged from 1,600 to 3,500 hp. The combined output capacity was about 34,000 hp. It's not clear from the text why the numbering begins at Turbine No. 4; perhaps the first three turbines were old and taken out of service. The handbook gives a fairly detailed description of the loads supplied as well as the power requirements and voltage level. Some loads required dc and others, ac. Note that each turbine typically had several classes of load

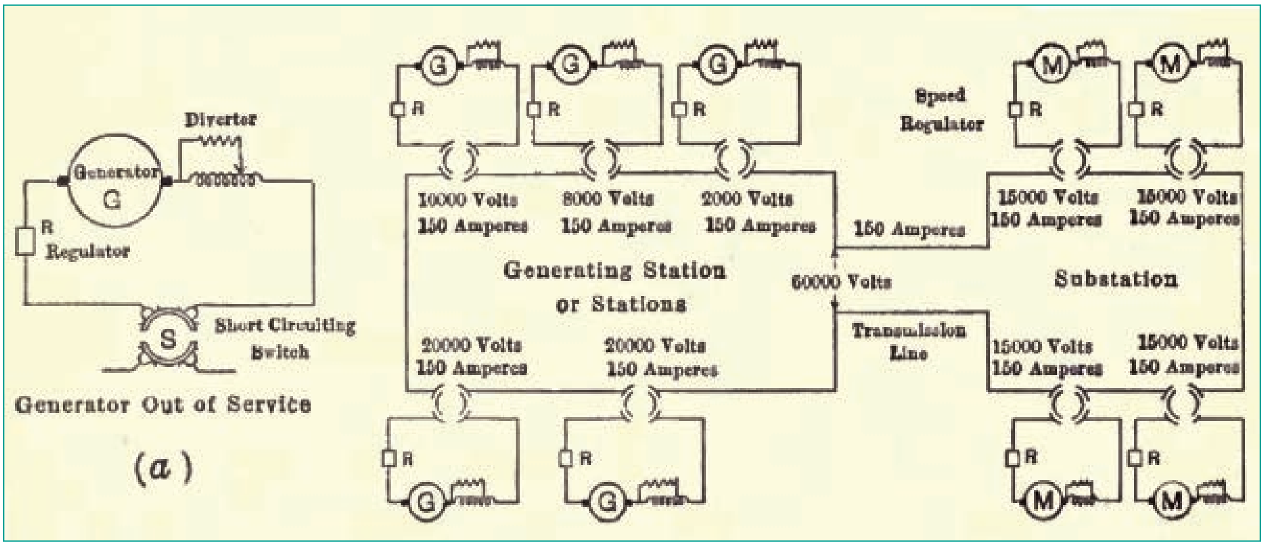

figure 7. The Thury System using constant current and variable voltage was proposed as a solution to long-distance transmission. (Source: Clarence V. Christie, *Electrical Engineering*, McGraw-Hill, New York, 1917; in the public domain.)

and, in some cases, several customers on one turbine.

- Turbine Nos. 4–6 each drove two 560-kW, 300-V dc Westinghouse generators, the current from which was supplied to the Pittsburg Reduction Company.
- Turbine No. 7 drove two 560-kW, 550-V dc General Electric generators. One of these generators carried a commercial load, which supplied current to the Niagara Falls Brewing Company and to 50 other users of power. The other generator carried a railway load for the operation of the Niagara Gorge Railroad. A booster with a range of 300 A was attached and was in circuit with the Youngstown and Lewiston railroad, 14 miles from the powerhouse. This turbine also had connected to it one 200-kW, 135-V generator, the current from which went to the National Electrolytic Company.
- Turbine No. 8 drove one 875-kW dc generator, feeding 5,000 A/175 V to the National Electrolytic Company. The generator was by General Electric and was a double commutator. This turbine also drove an ac generator of 1,000 kW, 11,000 V, and three phase.
- Turbine No. 9 drove a General Electric generator of 875 kW/5,000 A/175 V, the current from which went to the National Electrolytic Company, and also a 1,000-kW dc and a General Electric 325-V, 3,100-A generator, the current from which went to the Acker Process Company.
- Turbine No. 10 drove two General Electric 1,000-kW, 325-V, 3,100-A generators, the current from which was used by the Acker Process Company. The No. 8 Turbine drove an 875-kW, 5,000-A generator for the Niagara Falls Hydraulic Power and Manufacturing Company.
- Turbine Nos. 11 and 12 each drove two Westinghouse 750-kW dc, 300-V, 2,500-A generators for the Pittsburg Reduction Company.
- Turbine No. 13 drove a Bullock 1,000-kW, 11,000-V, three-phase generator on one end and, on the other end, a 700-kW, 2,200-V, single-phase alternator, made by the Walker Manufacturing Company. This latter machine supplied the current for more than 50% of the incandescent lighting throughout the city. It was operated for the Buffalo and Niagara Falls Electric Light and Power Company.
- Turbine No. 14 and Turbine No. 15 each drove two Westinghouse 1,000-kW, 300-V, 3,330-A generators for the Pittsburg Reduction Company.
- Turbine No. 16 and Turbine No. 17 each drove two Westinghouse 750-kW dc generators for the Pittsburg Reduction Company.
- Turbine No. 18 drove the exciters used in connection with the three-phase alternators referred to earlier.
- Turbine No. 19 drove a 400-kW, 500-V generator for commercial service.

In addition to the distribution of electric power as outlined, the Niagara Falls Hydraulic Power and Manufacturing Company had tenants to whom it supplied hydraulic power, as follows, making a total of 7,900 hp:

- *The Cliff Paper Company*: 2,500 hp
- *Cataract City Milling Company*: 700 hp
- *Pettebone–Cataract Paper Company*: 2,200 hp
- *Oneida Community Company, Ltd.*: 300 hp
- *City Water Works*: 400 hp
- *Niagara Falls Milling Company*: 1,800 hp.

It is interesting to compare the equipment in two powerhouses in Niagara Falls, NY, USA, at the turn of the 20th century. The Niagara Falls Hydraulic Power and Manufacturing Company had begun as a supplier of direct mechanical power and added electrical generators to supply load requirements as the need arose. What stands out here, in light of modern practice, is the large number of different ratings to match the specific customer needs. Compare this

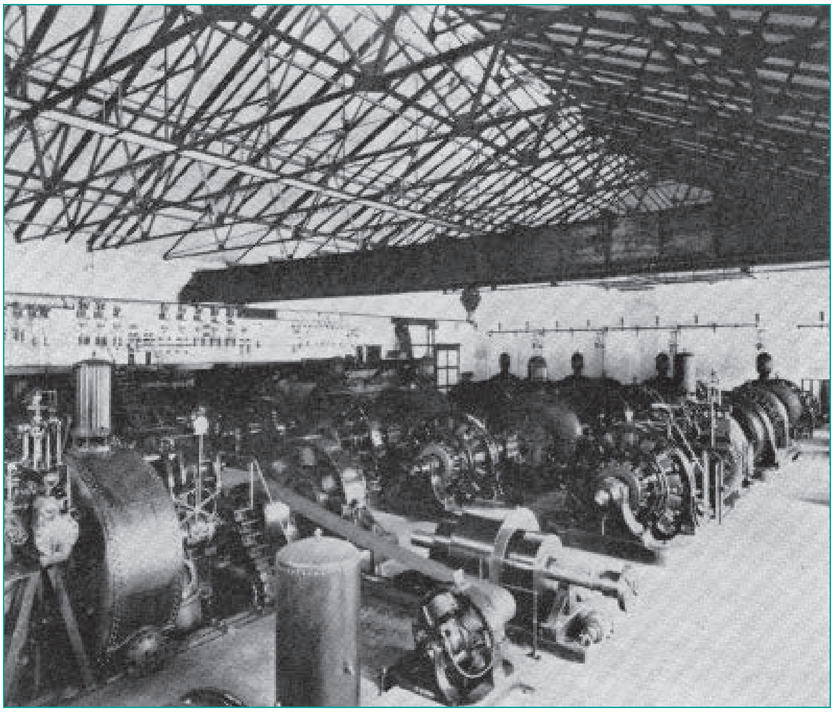

figure 8. As required by its customers, this station contained generators of various power ratings and voltages both ac and dc. (Source: George W. Davenport, *Niagara Falls Electrical Handbook*, AIEE, 1904; in the public domain.)

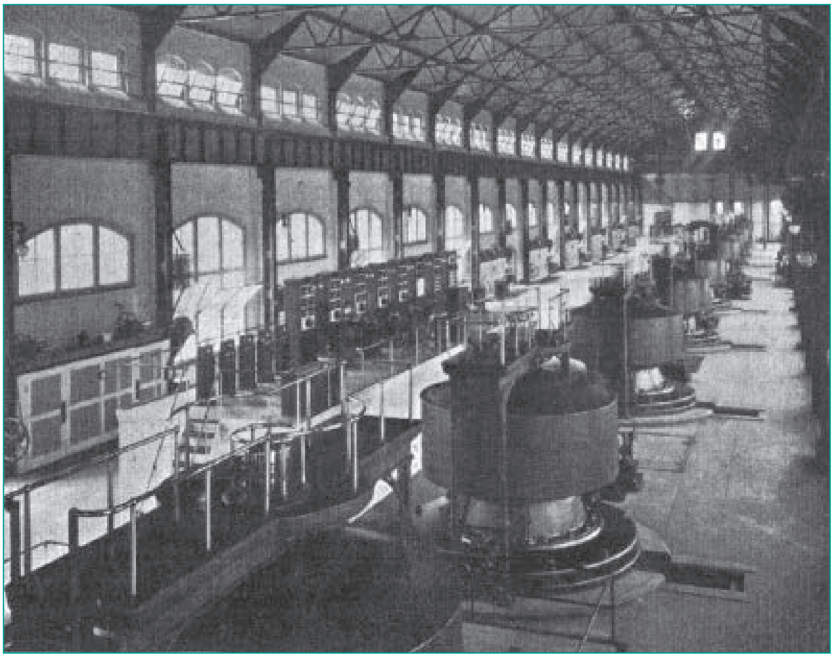

figure 9. Power House No. I contained 10 vertical shaft turbines, each driving an identical 5,000-hp alternator. The end user was required to convert the power to fit their needs. (Source: George W. Davenport, *Niagara Falls Electrical Handbook*, AIEE, 1904; in the public domain.)

to the machinery installed in the Niagara Falls Power Company's Adams Plant No. 1 (Figure 9).

In Adams Plant No. 1, all of the machines had the same 5,000-hp rating. The customer was expected to take this power at the voltage and frequency provided by the generating company and transform or otherwise convert the voltage and frequency to that required by the load. In other words, the customer knew the specification of the Adams Plant's bus and would have designed an interface to accommodate it.

This grid fed all classes of loads: single phase, two phase, three phase, six phase, etc., and loads of any frequency, including dc, can be supplied. The user simply connected to the grid at a point that can deliver the voltage needed or used a transformer to get that voltage. If a different frequency (including 0 Hz or dc) was required, it could be converted.

This was a truly universal system—one of the first examples of open architecture. It is no exaggeration to say that the system developed by the Niagara Falls Power Company in the two decades spanning the turn of the 20th century set the stage for the electrical age. For better or worse, the world as we know it began in Niagara Falls.

According to Lewis B. Stillwell, writing in the 1901 *Transactions of the American Institute of Electrical Engineers*, the engineering proposal presented to the owners stated that it was decided

> . . . to lay out a system that will enable you to take energy at the upper end of vertical shafts making 250 RPM, each shaft delivering 5000 hp, and to deliver in saleable and reliable form the largest practical and economical percentage of this energy; 1st, within the limits of Cataract City, the distance not exceeding two miles; 2nd, at the northern boundary of the City of Buffalo, 3rd at more distant points, e.g., New York and Chicago.

In each of these cases, energy is to be delivered in a form available for the following:

- ✔ power purposes
  - general mill and factory work, pumping stations, etc. (units of 10–1,000 hp)
  - operation of street railways (units of 100–1,000 hp)
  - miscellaneous work in factories, mills, the operation of elevators, and printing presses (units of 1–25 hp)
- ✔ lighting purposes
  - arc lights
  - incandescent lamps
- ✔ electrolytic purposes.

This open architecture, universal system was the 19th century version of the modern computer bus. They both accept a large variety of disparate devices provided that the user knows and acclimates to the architecture of the supply system. Would it be an exaggeration to say that the electrical age began in Niagara Falls with the commissioning of the first unit in Adams Plant No. 1?

For Further Reading

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IEEE PES 2024 Joint Technical Committee Meeting (JTCM 2024), 7–11 January, New Orleans, LA, USA, contact Russ Patterson, russell.patterson@qualusmail.com, https://pestechnical.org/

IEEE Electrical Energy Storage Application and Technologies Conference (EESAT 2024), 29–30 January, San Diego, CA, USA, contact David Rosewater, dmrose@sandia.gov, https://cmte.ieee.org/pes-eesat/

February 2024

IEEE PES Innovative Smart Grid Technologies (ISGT 2024), 19–22 February, Washington, DC, USA, contact Kathy Heilman, kathy.heilman@ieee.org, https://ieee-isgt.org/

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May 2024

IEEE PES Transmission and Distribution Conference and Exposition (T&D 2024), 6–9 May, Anaheim, CA, USA, contact tdgeneral@ieee.org, https://ieeet-d.org/

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IEEE Transportation Electrification Conference and Expo (ITEC 2024), 19–21 June, Chicago, IL, USA, contact Rebecca Krishnamurthy, rebecca.k@rna-associates.com, https://itec-conf.com

July 2024

IEEE PES General Meeting (GM 2024), 21–25 July, Seattle, WA, USA, contact Roseanne Jones, roseanne.jones@ieee.org

August 2024

IEEE Sustain Tech Expo (Sustain Tech), 25–28 August, San Diego, CA, USA, contact Silvia Ceballos, sceballos@computer.org

October 2024

IEEE PES Asia-Pacific Power & Energy Engineering Conference (APPEEC 2024), 25–27 October, Nanjing, China, contact Yingjun Wu, yingjunwu@hotmail.com

November 2024

IEEE International Conference on Power System Technology (Powercon 2024), 4–6 November, Kathmandu, Nepal, India, contact Shailendra Kumar Jha, shailendra@ku.edu.np

IEEE PES Innovative Smart Grid Technologies Conference Asia (ISGT Asia 2024), 10–13 November, contact Chandrasekhar Atla, sekhar.atla@ieee.org

IEEE Sustainable Power and Energy Conference (iSPEC 2024), 24–27 November, Kuching Sarawak, Malaysia, contact Nur Fadilah Ab Aziz, mfadilah@uiten.edu.my

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analysis results. This is our task. We were curious whether one digital twin of the power system might be the answer, and, in my opinion, the only solution for this challenge is the digital twin! The requirements go beyond the existence of simulations, where, primarily, the results are exchanged. The digital twin is a concept that makes it possible to link any objects by means of a uniform description and definition of the objects as well as an additional temporal dimension.

If I had asked a consultant or a software company, it might have recommended a new additional platform solution that it would probably call a digital twin. This platform would put all the information together; we would then call it a digital twin, and all the challenges would be met. It sounds easy, doesn't it?

But wait, wasn't there the pitfall of different definitions of a digital twin? For example, a German expert group of researchers, industries, and system operators was formed to define the digital twin in power systems. This was quite challenging because of the need to define it for the whole power system community. An energy management system simulation of a high-voltage dc link, for example, would not meet the demands of grid planning experts, while a good model for grid extension planning would not meet the needs of system dynamic engineers. As a consequence, the digital twin is not only a digital representation for a single purpose (like the existing digital multiples mentioned above) but it gives additional value to at least a second relevant domain. This should be perfectly fine; however, do we really put 3D models of components together with dynamic grid data in just one new system and, additionally, to existing solutions, as promoted by some? While striving to present new processes, a new tool, and a new way of collaborating with my colleagues who try to realize grid extension projects or answer the latest governmental request for system stability, the potential for success of this idea shrinks. This could be difficult.

As a system operator, we have to guarantee the perfect interaction of all elements in the system, both today and in the future. Within the TSO, we have many disciplines, with many views on the system. Each discipline needs special business views. Having a brownfield situation with existing IT systems fitting those processes, putting all views and requirements in just one system for all perspectives, is not helpful. In contrast, we want to guarantee that the ecological overhead line management discusses the same overhead line sections as the project business unit. We need a single source of truth in terms of the logical level—absolutely. This is fundamental for the digital twin.

A single source of truth reduces redundant data within digital multiples and leads to a digital twin. Instead of raising one single "digital twin platform" as the single point of truth, we have decided on another approach, which we believe is the logical one. By connecting different systems via standardized data models and universal unique identifiers for every little entity, we aim to provide a logical single point of truth for our company. With this approach, we create a digital twin as a logic element among existing systems that works like a hinge. While electric grid modeling is based on the Common Information Model standard, the project business units move toward the Building Information Method of working and modeling; both perspectives have their values and singularities. Forcing one discipline's data into the standards of another would lead to struggle and too much adaption of the standard. Linking both standards logically still guarantees talking about the same grid entities without making those adaptions necessary. It is obvious that interdisciplinary thinking is mandatory for the responsible team.

Linking different data domains in a company with the concept of the digital twin promises more efficiency in handling data and information in interdisciplinary work between teams and business units. At the same time, the need for the use of more detailed and confidential data increases, which makes data exchange more challenging. Therefore, besides all technical aspects and logic design, functioning data governance in the company is obligatory. While business units had sovereignty over their data (silos) for a long time, sharing data, defining locations of golden records, and establishing roles for data handling are unique to each company's culture. Implementing data management, as well as digital twins for power systems, requires an effective change in management.

The current situation for the Central European TSOs leads to demanding system operation; political decisions induce even higher pressure on the grid extension. Within the power system, many stakeholders must be considered. Consequently, the implementation of a digital twin requires a lot of tact and sensitivity to keep the motivation and good will of all parties involved. We have been working on a standardized data model for grid analysis, planning, and operation purposes for several years; this is one part of our digital twin approach. Additionally, we started some pilot projects to gain the interest of our colleagues in the digital twin. Once they are able to walk virtually into a substation, wearing virtual reality glasses and gaining information on the asset information system, they will begin to discuss the potential of the digital twin at the TSO.

However, the reality of implementing a digital twin at a TSO is quite far in the future. Connecting and synchronizing different systems during operation presents many challenges, both small and large, while the initial investment is quite high, and the benefits are not easily understood. I am convinced, though, that my company will benefit from the digital twin in upcoming years. In the long run, enabling faster exchanges of unambiguous data and information between business units and core processes will support and advance colleagues working there.

In my view, the digital twin in power systems is an important component in the efficient digitalization of system operators. It is not a new species, as digital representations are quite common for power system engineers. And because of being used to simulate the power system, the digital twin is not a revolution, either, in comparison to other disciplines. The digital twin of the power system is a consequent and powerful evolution of the existing digital "multiples" in their commonly isolated process and data domains. Bringing new views, modeling approaches, and interpretations of the power system together through logical connections lowers barriers in the exchange of data and information; this leads to more efficiency and effectiveness. Nevertheless, connecting data and systems is still a bit more than just an evolutionary process. Bursting business unit data silos and changing minds on the handling of data within companies seems to be closer to a revolution that aims for both satisfying and efficient working together. Therefore, go ahead and implement digital twins of the power system while guaranteeing effective data management. p&e

Digital Object Identifier 10.1109/MPE.2024.3349908

in my view

Jan Kays

the digital twin

new species, evolution, or revolution?

IN STUDYING THE AGENDAS OF conferences and listening to research institutes or consultants, a new phrase has arisen in recent years: the digital twin. Assuming an answer to some everyday challenges, this topic made me curious. There are many interpretations and definitions of a digital twin in the research as well as the professional community. Depending on the individual focus, people assume that a digital twin is a dynamic model of a power grid, an energy management system simulation of a high-voltage dc converter station, or a 3D model of substations, and so on. In general, it is seen as a digital representation of the reality. My own picture of a digital twin got sharper after spending time on research and listening to interesting talks and presentations.

Being responsible for data management within a German transmission system operator (TSO), my team and I are working on the exploitation of the company's data assets. At a TSO, many data flow together and begin with information about the grid assets and project data for grid extension; the system operation center produces and requires much information for a safe and reliable system operation. Redispatch processes, billing and clearing in the power system, as well as all the financial and regulatory data are other areas also included on an inexhaustive list of interesting data domains. From my perspective, this is an exciting area to work with, but the long history of the TSO (currently in use nearly 100 years), as well as high data security requirements, can make working with data challenging. So, we wondered whether a digital twin could help us bring data management together with process efficiency to reach the next level in our TSO. A short answer is yes. Let me explain why.

Digital Object Identifier 10.1109/MPE.2023.3328292
Date of current version: 12 January 2024

One remarkable exchange with research partners opened my eyes about our privileged situation in power system engineering. While other research disciplines are currently proud of being able to simulate reality and planning with computers, we, the power system engineers, have simulated our power systems for decades, with sufficient accuracy. Of course, performance has improved, and the simulated sizes of power systems have increased, so simulation became a standardized way of analyzing static and dynamic power system behavior. Social demand for a highly reliable power system, in combination with the complexity of system operation as well as no alternative methods like large-scale intrusive tests, have forced power system engineers to simulate the system. Either for dynamic system response to disturbances, the static load flow for different time horizons like five to 10 years, or in combination with the available power plants the following day, the engineers developed models of the real grid to find reliable and accurate answers.

In the beginning, the simulations were executed on large computer systems. Then, personal computers allowed for performing simulations at the individual desks of the power system engineers, one with a focus on planning, one on dynamics, and so on. So far, so good. Over the years, different views on the system evolved based on different aspects of the real grid. Depending on the definition, you could assume those models and simulations to be digital twins. We did not, however, have one digital twin; instead, there were digital multiples of our power system. Every multiple was able to give answers to specific questions.

Having digital multiples might be acceptable as long as the power system engineers do not have connected computers or shared calculation clusters and as long as the power system is in a steady state, but both aspects have changed dramatically in recent years. Changing structures in the power systems demand grid extension and adaption as well as more challenging system operation. Higher loading of the power system and, thus, operation closer to critical limits of the system require a higher quantity and quality of power system simulation and analysis. There are complex and long permitting procedures for grid extension as well as the regulatory frame demand for comprehensive grid planning. All this provides motivation for efficient information and data management, especially within the TSO, in order to achieve consistent, fast, and holistic

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Digital Object Identifier 10.1109/MPE.2023.3340528