

Guest Editorial

Methodologies and applications of digital twin for renewable-dominant power systems

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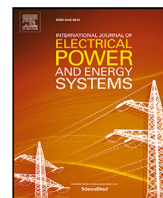
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Review



Guest Editorial: Methodologies and applications of digital twin for renewable-dominant power systems

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ABSTRACT

This editorial introduces the Special Issue “Methodologies and Applications of Digital Twin for Renewable-Dominant Power Systems”, which highlights key research addressing the challenges associated with integrating renewable energy sources into power systems. Digital twins provide an advanced framework for modeling, simulation, and optimization of these complex systems, driven by the need to address the impact of power electronics and multi-source energies. The contributions featured in this issue focus on the application of DT technologies in renewable-dominant systems, offering solutions for enhancing system stability, optimization, and operational efficiency.

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1. Introduction

The integration of renewable energy sources (RES) into the power grid at both transmission and distribution levels gives rise to new operational challenges for traditional power and energy systems. The RES is

widely manipulated by power electronic converters. Such renewable-dominant power systems involving converter-based RES have significant impacts on the system dynamics. Fast-switching dynamics from converters and the variability of renewable outputs complicate real-time monitoring, modeling, and prediction. These factors place higher

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demands on Digital Twins (DTs), which must achieve high-fidelity dynamic modeling, rapid data assimilation, and continuous updates to accurately mirror and forecast physical system behaviors.

DTs are characterized as a virtual representation that acts as the real-time digital equivalent of a physical object or activity, as shown in Fig. 1. The concept of DT can be applied at the grid level, the plant level and the device level. The DT system can be utilized to conduct simulations, investigate performance, and produce potential modifications, all with the purpose of creating insightful information that can later be applied to the physical system. The recent advances in DT technologies, driven by emerging technologies like edge computation, advanced measurement, and artificial intelligence/machine learning, may provide practical solutions to improve the performance of smart grids. To fully capture the characteristics of renewable-dominant power systems, it is essential for DT to consider the complexities due to multi-energy sources, multi-scale spatial and temporal characteristics, strong non-linearities, and uncertainties.

The DT system is a closed-loop system that integrates high-fidelity dynamic models, real-time data interaction mechanisms, and intelligent decision-making capabilities. One of its core features is the realization of dynamic bidirectional synchronization between the virtual entity and the physical system, ensuring that the virtual model is continuously updated to reflect changes in the physical system's state. Furthermore, through predictive analysis and optimization-based feedback, the DT can proactively guide the operation of the physical system.

The digital model of DT should be solved in real-time, or even faster, with sufficient accuracy. Learning-based algorithms can be integrated to effectively address the optimization challenges of complex systems. Reinforcement learning excels in dynamic decision-making, while artificial neural networks enhance predictive modeling and auxiliary optimization. The integration of multiple learning-based algorithms offers intelligent, efficient, and adaptive solutions to complex optimization problems in multi-energy systems, substantially improving operational performance, control robustness, and resilience against uncertainties.

In terms of the DT system application, DTs have been successfully implemented across various energy infrastructures, such as microgrids and smart substations. These implementations provide valuable experimental verification and optimized solutions for the development and operation of RES, enhancing their economic efficiency and reliability. When applied to RES, DTs enable improved strategic planning across diverse energy networks. In turn, this optimizes the efficiency, regulation, and flexibility of energy supply while contributing to the security and resilience of energy infrastructure.

This Special Issue "Methodologies and applications of digital twin for renewable-dominant power systems" seeks to investigate friendly and reliable integration of RES into power-electronics dominated power systems. Worldwide authors submitted valuable research to this timely Special Issue. All of these manuscripts are helpful and of certain significance. The Guest Editorial Board tried their best to conduct an extensive review process, resulting in an approval of eleven outstanding papers for publication.

This Special Issue compiles the research advancements in DT technologies for renewable-dominant power systems. In the area of multi-energy management, DTs enable real-time simulation and optimization of multi-energy networks by integrating holomorphic embedding methods with data-driven techniques, effectively addressing the challenges of complex dynamic behaviors and multi-timescale coordination. In the field of grid supporting, DTs leverage photovoltaic inverters, battery energy storage systems, and supercapacitors to mitigate issues related to reduced system inertia and voltage and frequency stability arising from large-scale renewable integration. For state estimation and prediction, DTs enhance equipment status monitoring, power forecasting, and distribution network parameter estimation by incorporating cloud-edge collaboration and intelligent algorithms, significantly improving accuracy and real-time responsiveness. In terms of system stability

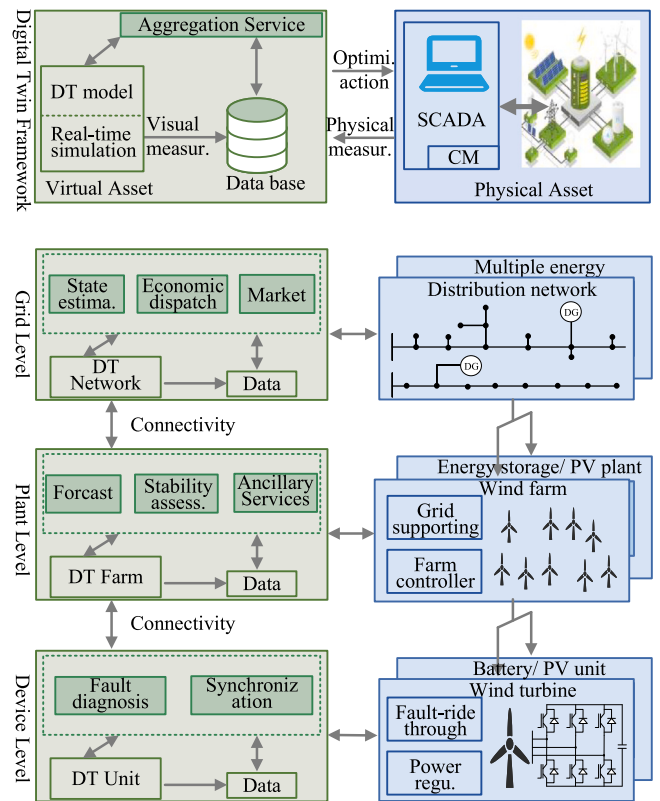


Fig. 1. Concept and applications of digital twin system for renewable-dominated power systems.

analysis and enhancement, DT platforms support online stability region modeling and operating point optimization, providing effective safeguards for the safe and stable operation of renewable-dominated power systems.

These papers provide innovative ideas concerning modeling, control, and system estimation based on DT technologies, offering applications of multiple energy management, grid-supporting regulation, power estimation and stability assessment. The Guest Editorial Board express sincere gratitude to authors contributing their innovative research to this special issue. Their contributions help to integrate renewable energy sources into grid more friendly and reliably.

The Guest Editorial Board expresses its sincere gratitude to the anonymous reviewers for their invaluable suggestions and constructive feedback, which were instrumental in upholding the high quality and rigorous standards of the published articles. Their dedication and expertise have significantly contributed to advancing the field and ensuring that the published works meet the highest academic standards.

The Guest Editorial Board wishes to express its sincere appreciation to the journal's Editorial Board for providing us with the opportunity to curate this Special Issue. Their support and encouragement have been crucial to the success of this project. We also extend our gratitude to the journal's production team for their expert technical assistance throughout the entire process, from the initial call for submissions to the final production of the accepted manuscripts. Collaborating with both the journal and the production team has been immensely rewarding. Working with all those involved in the organization and production of this Special Issue has been a highly enjoyable experience, and their contributions are deeply valued.

2. Review of topics addressed

This section summarizes the topics of the papers included in this Special Issue.

2.1. DT-based multiple energy management

Digital twins provide system operators with new approaches to operating and maintaining multiple energy networks. This is achieved by integrating interdisciplinary models using co-simulation techniques. Powerful modern computing facilities enable real-time simulations [1, 2]. Various learning-based algorithms can be embedded in the DT system to optimize operations [3].

A two-part series of papers presents digital twins of multiple energy networks capable of real-time simulation, facilitated by the holomorphic embedding method [1,2]. It optimizes multi-energy flow management, significantly improving energy utilization efficiency and operational flexibility. In Part I of this series, the focus is on mechanism-driven modeling to ensure that high-resolution solutions are computationally feasible [1]. The authors propose a holomorphic embedding-based model (HEM) for multiple energy networks, utilizing time-dependent holomorphic functions to represent the dynamic behaviors of gas and heat flows. Additionally, a convergence radius model is introduced to extract essential convergence information for the HEM. The HEM is particularly suitable for DT applications because it provides stable, non-iterative, and fast semi-analytical solutions to complex system equations. By avoiding numerical convergence problems and supporting faster-than-real-time simulation, HEM ensures the real-time fidelity and continuous synchronization necessary for Digital Twin systems operating under dynamic and uncertain conditions.

While Part I focused on mechanism-driven modeling of the holomorphic embedding-based model, Part II shifted to data-driven simulation to ensure synchronization between the digital twin and the actual physical system [2]. A parametric synchronization method is introduced to enable the HEM to closely align with the dynamic behavior of the physical system, accounting for time-varying characteristics. Additionally, a machine learning-based surrogate model is proposed to accelerate the search for the HEM's convergence radius, which is essential for maintaining the DT's real-time computational performance. Finally, the digital twins are validated using the OPAL-RT simulation platform, which is equipped with a real-time simulator. In a medium-sized MEN test case with a small time step of 0.01 s, the digital twins achieve faster-than-real-time performance, even without parallel computing.

The authors of [3] developed a digital twin-based parallel energy management strategy for large-scale energy networks, specifically targeting We-energy systems. By implementing a triple-parallel structure, the states of energy networks are monitored in real-time, enabling flexible responses to fluctuations in distributed renewable generations and facilitating energy plug-and-play integration. The optimization model accounts for abandoned renewable energy, promoting its increased utilization. A multi-timescale optimization strategy is proposed to address the varying timescales within multi-energy networks. To enhance information acquisition and processing while mitigating the curse of dimensionality, a DT-based deep Q-learning algorithm is introduced.

2.2. DT-based grid supporting

Renewable energy sources, such as photovoltaic and wind power, exhibit a low kinetic inertia. The grid-tied converters of RES offer minimal inertial response when using traditional control strategies. As a result, there is a growing need for enhanced grid voltage and frequency support. A DT-based framework proves valuable for monitoring and grid supporting.

The authors of [4] propose a hierarchical coordinated control strategy for photovoltaic inverters to maintain voltage stability in low-voltage distribution grids. The top layer of the proposed architecture features an automatic voltage regulation (AVR) application, which utilizes real-time and historical voltage measurements and grid parameters. The AVR application solves a constrained optimization problem to determine local control set-points that ensure the voltage remains within specified limits across the grid. The middle layer contains a

local Volt/VAR controller that the AVR adjusts. The bottom layer consists of the inner-loop controller of the photovoltaic inverter. This approach not only enhances voltage quality in the grid but also efficiently manages the reactive power output of photovoltaic inverters. Additionally, a DT of the cyber-physical system is employed to interact with the control system, ensuring its proper operation. The effectiveness of the proposed methodology is validated through simulations on a representative low-voltage feeder in Denmark.

Moving to the scenario of wind power generations with a battery energy storage system (BESS), a DT-based multi-purpose regulation strategy was developed in [5]. The BESS is designed to mitigate fluctuations in both the active and reactive power of the wind farm, participating in frequency regulation and damping low-frequency oscillations. A conceptual framework and structure for the multi-purpose functionality of the BESS are presented. The DT technology is applied to configure the optimal capacity of the BESS. The performance of the multi-purpose BESS is validated through simulations in a two-area system model constructed using DiGSILENT PowerFactory.

The large-scale integration of RES into the grid through a voltage-source inverter (VSI)-based DC system leads to a continuous reduction in system kinetic inertia, negatively impacting grid frequency stability. A generic security-constrained inertia emulation (SIE) scheme is proposed to address this issue. This scheme integrates a suitably sized supercapacitor into a VSI-based DC system via a bidirectional DC-DC converter [6]. The SIE control enables inertial response by adjusting the supercapacitor voltage in response to grid frequency variations. An inertia adjustment algorithm is introduced to mitigate potential security risks, such as VSI overcurrent and DC system overvoltage. The SIE scheme offers a plug-and-play advantage, as it can be implemented without modifying the existing system. Furthermore, the SIE parameters are optimized through small-signal stability analysis. The effectiveness of the proposed scheme is validated using a modified IEEE 39-bus test system, considering generator outage and grid fault scenarios. It is noted that the capability of the SIE is constrained by the physical characteristics of the storage devices. The magnitude of the emulated inertia is limited by the charge and discharge rate of the supercapacitor, while the duration over which inertia can be sustained depends on the available energy capacity.

2.3. DT-based estimation and prediction

The output power of RES is inherently variable and fluctuates in practical systems. A key challenge is to estimate the current and near-term output power accurately. As distributed RES continues to increase, the topology and line parameters of the distribution network undergo frequent changes. To address these challenges, the DT techniques offer a robust framework for estimating and predicting both RES performance and network conditions.

The long-term efficient operation of PV systems is critical to their profitability. Unlike large-scale PV plants, distributed PV systems are more dispersed and typically owned by different entities. A significant challenge to maximizing profitability for these systems is the lack of professional maintenance. The authors of [7] propose a cloud-edge collaborative dust deposition monitoring scheme for distributed PV systems that does not require additional equipment, sensors, or meteorological data. The DT-based strategy improves the maintenance scheduling and operational efficiency of PV assets. By utilizing operational and historical data from distributed PV systems within the same area, the system can provide guidance on whether a PV system requires cleaning. The implementation involves the creation of temporal and interactive models based on the operational characteristics of these systems, achieving an overall classification accuracy of over 98%. Additionally, a data-driven random grouping method is introduced to enhance the monitoring scheme's adaptability. This approach prevents model mismatches that could occur due to the addition or removal of PV arrays.

As the penetration of PV generation increases, regional power forecasting becomes increasingly critical for the stable and economical operation of the power system. Based on data from selected reference PV plants, an upscaling minute-level regional PV power forecasting scheme is proposed in [8]. The reference PV plants are chosen through a comprehensive evaluation of prediction accuracy, utilizing artificial neural networks and the Pearson correlation coefficient. A correction method for PV output power is introduced to ensure the accuracy of regional power forecasting. A flexible approach is proposed to reduce the accumulated error in rolling forecasts, integrating forecasting results at different temporal resolutions. The power forecasting results are derived at 1 min, 5 min, and 15 min intervals, and the performance of the proposed method is compared with that of traditional rolling forecasting.

The time-varying characteristics of distribution networks make measurement data from intelligent instruments insufficient. This data does not meet the requirements of the existing topology and parameter estimation methods. The authors of [9] propose a hybrid data-driven method for jointly estimating distribution network topology and line parameters using small data sets. Given the sparse nature of distribution networks, a neighbor node selection mechanism based on partial correlation analysis is designed. The initial topology is robustly identified using the OR criterion, even with limited data. By combining the approximate linear power flow equation with linear regression, the initial values for line parameters and phase angles are estimated. Additionally, the initial topology, line parameters, and phase angles are optimized iteratively using a Newtonian method. A decoupled linear power flow model is introduced to simplify the Jacobian matrix, thereby accelerating the iteration process. Compared with existing methods, the proposed method only needs small data sets and has a faster calculation speed with the same estimation accuracy. The sensitivity test results show that the proposed method is robust to noise and sampling resolution.

2.4. DT-based stability analysis and enhancement

Grid synchronization and small-signal stability are critical for integrating RES with the utility grid. While offline analysis has been extensively used, online applications are valuable for practical implementation. The DT system provides an ideal platform for data acquisition, state estimation, and stability enhancement.

Fast and accurate tracking of grid voltage attributes is essential for the stable and reliable control of grid-side converters. The synchronous reference-frame phase-locked loop (SRF-PLL) is commonly used for this purpose, but it has stability and slow transient response limitations. As a result, PLL-less grid synchronization methods are becoming increasingly popular. The authors of [10] propose a discrete Fourier transform-based bandpass filter (DFT-BPF) to extract the fundamental frequency positive sequence component from unbalanced and distorted grid conditions. A simple frequency estimator is developed that accurately estimates the fundamental frequency. Additionally, a curve-fitting-based error correction technique is used to adaptively estimate the amplitude and phase angle of the fundamental component without relying on a frequency feedback loop. Experimental results demonstrate the effectiveness of the proposed scheme.

The RES operates across a wide range of operating points, leading to diverse small-signal stability performances within a high-dimensional parameter space. The relationship between stability performance and operating points is implicit, presenting challenges for assessing stability regions and margins. To address this, a data-driven method for stability assessment and enhancement is proposed in [11]. The DT-based strategy allows continuous tracking of the small-signal stability margins of wind power plants under varying operating conditions, and guides real-time operating point optimization to prevent instability. For stability assessment, a regression-based analytical model is introduced to evaluate the stability region and margin as functions of multiple

parameters, such as active power, reactive power, and wind speed. The model utilizes impedance data from the wind farm. A minimum characteristic locus is defined as a single-parameter index to represent relative stability. For stability enhancement, the explicit mapping achieved in the DT system allows for real-time optimization of the operating point, thereby improving the system's stability margin.

3. Further work on digital twin

With the rapid development of edge computing and artificial intelligence, the concept of DT has gained increasing significant traction. DTs are expected to provide increasing value for energy integration. Future research can be explored in the following directions.

Enhanced Estimation Based on DT: While installing more sensors can improve system observability, practical deployments must balance cost and benefit. DT technologies will combine renewable generation characteristics, physical modeling, and limited sensor data to build a virtual perception system. This system will enable accurate inference and dynamic tracking of key parameters such as renewable outputs, power fluctuations, nodal voltages, and frequency dynamics.

Enhanced Analysis Based on DT: Modern power systems are highly complex, especially with the increasing penetration of power electronics and renewable energy sources. Many dynamic mechanisms remain insufficiently understood. Through continuous simulation and evolution enabled by DTs, it will be possible to explore complex coupling mechanisms, such as grid-forming dynamics and weak-grid oscillation phenomena. This will enhance the system's observability, controllability, and predictability.

Enhanced Intelligence Based on DT: DT platforms will generate large-scale simulation datasets, which can be leveraged with artificial intelligence, machine learning, and reinforcement learning algorithms. This will enable autonomous decision-making and optimization. Besides, DTs will be widely applied for lifecycle management of assets and health monitoring, providing real-time fault prediction and early warning of abnormal operating conditions.

4. Closing remarks

This Special Issue focuses on methodologies and applications of digital twins for renewable-dominant power systems. The published research presents advanced modeling techniques, data interactions, and various applications of digital twin systems. These applications include multi-energy management, grid-supporting control, and state estimation. Several papers address the estimation and prediction of output power and stability performance in renewable-dominant power systems.

The Guest Editorial Board hopes that readers will find this Special Issue a valuable resource for future research and development in the field.

CRedit authorship contribution statement

Haoran Zhao: Supervision, Conceptualization. **Peng Wang:** Methodology, Conceptualization. **Peter Palensky:** Formal analysis, Conceptualization. **Shaahin Filizadeh:** Investigation, Conceptualization. **Yongqian Liu:** Visualization, Conceptualization. **Ying Chen:** Visualization, Conceptualization. **Jiebei Zhu:** Visualization, Conceptualization. **Peng Li:** Visualization, Conceptualization. **Aleksandra Lekić:** Visualization, Conceptualization. **Vladimir Terzija:** Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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