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A Review of Digital Twin Technology and an Approach for a Robust Digital Twin for Power Systems Applications

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SUMMARY

Digital twins are a relatively new research topic in power systems. The main concept of a digital twin is a model of a real-world system that can run online with the physical system utilizing measurement data streams to synchronize. Digital twins are currently under-utilized in power system operation and control. The technology can be leveraged to predict problematic system conditions and develop mitigating strategies, diagnose anomalous system behavior, plan, and evaluate impact of potential control actions and perform post-mortem analysis. These benefits will be even greater as grid technologies continue to advance and add new challenges to power system operations. This study reviews existing digital twins, describes an approach for a robust digital twin for power systems, and outlines the required validation and maintenance of the components of this robust digital twin.

KEYWORDS

Digital Twin, Industry 4.0, Power Systems

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INTRODUCTION

The Fourth Industrial Revolution, or Industry 4.0, refers to the current technologies being implemented in industry that are intended to produce significant change rather than incremental change [1]. A primary focus of Industry 4.0 is the leveraging of existing sensors and data to develop new and innovative tools [1], [2]. From this perspective, a system needs to be considered as the composite of its physical components, its cyber components, and the applications and tools used to interact with the system [2]. This holistic perspective to envision and operate a system gave way to digital twins.

Definition

A power system can be defined in terms of its physical, cyber, and application layers. At its core, the digital twin is a model of the system that is comprised of these three layers [2], [3], [4], [5], [6], [7]. A digital twin is an accurate model of a physical system that utilizes data from the cyber system to not only accurately represent the physical system under a single condition, but also under the various conditions represented by the updates of data streamed to it from the physical system. The digital twin uses real-time simulators to either run online in parallel with the physical system it mirrors and/or run offline utilizing historical or simulated data. While offline simulation is quite useful, the primary factor that differentiates a digital twin from any other models is the ability to run online synchronized with the physical system, and then inform control actions in the physical system based on the digital twin simulation. This concept is shown in fig. 1.

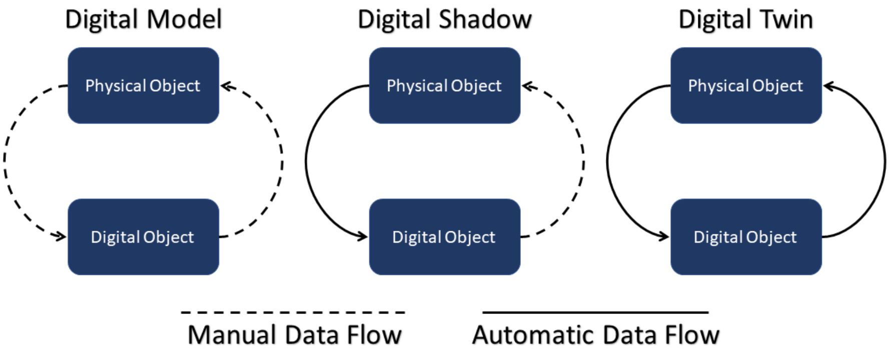

Fig. 1. Digital Model, Shadow, and Twin [3]

The digital twin should be able to respond to control inputs in a similar manner as the physical system. The digital twin should also generate output corresponding to the real-world measurements yielded by the physical system. Digital twins have been explored previously in other industries primarily focused on modeling physical phenomena [3], [4], [5], [6], [7]. Subsequently, digital twins are being explored in electrical representations to model power systems.

Need

Digital twins fill a critical gap in existing technology. Historically, root mean square (RMS) models were sufficient to model power systems. For years, load flow and short circuit models have been effective tools for grid simulation and contingency analysis [8], [9], [10], [11], [12]. As the grid is modernized, electromagnetic transient (EMT) models are required to precisely simulate grid behavior.

New devices are being implemented in power systems and connectivity is increasing. The entire cyber component of a power system must be considered as measurements and remote controls increase and add new susceptibility to failure or attack. While all these capabilities exist separately, they can be combined in a new type of digital twin. The true novelty of a digital twin is the ability to use such a powerful model in real-time, synchronizing with measurements from the physical system, and providing feedback back into the operation of the physical system. With such a powerful tool, the application possibilities to aid power utility operation are vast.

Purpose

The main purpose of a digital twin is to aid in the reliable operation of a power system. The twin runs in real time with the physical system, outputting expected measurements to compare with physical measured and estimated data. Operations personnel can use this comparison as another analysis tool.

Additionally, the digital twin improves grid security by enabling transient contingency analysis faster than real-time. Unstable operating conditions can be identified and avoided. For example, users can assess voltage and frequency stability and determine how each phenomenon is impacted by distributed generation in the system in real-time.

The cyber-physical model enables contingency analysis to also include malicious data injections or other cyber-attacks. The N-1 criterion is the standard minimum for transmission system operations. With the use of a digital twin, a similar approach can be extended to include contingencies involving cyber components, since they are explicitly represented in the model.

The digital twin can also be used to generate simulated data to study the physical system. This data may be used to train machine learning or other AI models to later operate on the physical system.

Benefits and Value

The benefits of digital twins largely depend on how the users leverage the technology. The following are some examples and use cases that provide benefits to security, reliability, and analysis for the grid.

Digital twins can improve system efficiency in several ways. Primarily, digital twins facilitate insights into the grid where other options are time consuming, expensive, impractical, imprudent, or inaccurate. The digital twin provides an opportunity to easily evaluate concepts intended to be used in the physical system.

Dynamic stability analysis on frequency stability enables reserve generation to be maintained to ensure a stable operating point given current conditions. Excessive reserve generation can be safely reduced, while avoiding insecure operation. FACTS devices may also be simulated with different operating settings to minimize some loss from power transmission.

Cyber-physical modeling and analysis also improves security from failures in communications or controls and malicious cyber-attacks, enabling more robust security.

Digital twins allow users to evaluate immediate impacts of control actions by performing those actions on the twin first. After a simulated response is output in real-time, judgement can be made to perform the action on the physical system or not.

Events can be diagnosed using the digital twin, and protection devices can be simulated or run as HIL. Loading historical data allows for precise investigation into recorded scenarios, as well as the ability to simulate different mitigating strategies for future responses. The protection of the grid should become more robust.

The Ever-Changing Grid

The grid is rapidly changing with increases in new technology [13], [14], [15], [16]. Inverter-based resources (IBRs) require EMT simulation due to their fast-switching frequency. The loss of inertia from replacing conventional generation decreases frequency stability. Certain generation types like photovoltaics (PV) can adversely impact voltage stability. Strategies to manage the unpredictable variations in generation from renewable energy can be assessed in operating tools.

Efforts to measure, estimate, and automate power systems place utmost importance on communication and controls. This connectivity must be viewed as being as important to system operations as transmission lines and power generation.

POWER SYSTEM DIGITAL TWIN VIABILITY

Real-time simulation refers to simulation that occurs at the timescale of the phenomenon being simulated. At this speed, the real-time simulation can run in synchronism with the physical world. Real-time simulation of the power grid was first accomplished in 1930 at M.I.T. with the construction of the Network Analyzer [17], [18], [19], [20]. The simulators required each component to be modeled with a separate circuit and interconnected in the same manner as the physical system. Relatively recently, real-time simulation of power systems has been achieved digitally [20], [21]. The shift to digital representations drastically reduces the size of the simulator and enables much easier development of models and real-time applications.

One such application is Hardware-in-the-Loop (HIL) simulation. With HIL, physical devices such as controllers or protective relays are connected to the simulator so that the devices behave as if they were in the physical system. This process has been used to ensure operation of protective devices before deployment [23], [24]. It has also been used to study the behavior of new IBRs and their corresponding controllers [25], [26], [27]. The dynamic simulation capabilities of digital real-time simulators enable more accurate study of new fast-switching devices [28].

More elements of the power system continue to be measured and estimated as technology progresses. Grid measurements such as SCADA data or synchrophasor streams are used to accurately determine the state of unmeasured points in the system [29], [30], [31], [32], [33], [34], [35], [36], [37], [38]. Digital real-time simulators are capable of running using data from these applications [39]. All these tools can be leveraged to advance digital twin technology in power systems.

EXISTING DIGITAL TWIN IMPLEMENTATIONS IN POWER SYSTEMS

At a basic level, contingency analysis tools and system estimators can be considered digital twins, given that they operate on real-time data, simulate some model of the power system, and the output is used in operation of the physical system. More recent work has been done to expand digital twins in power to dynamic models.

Small Digital Twin

Many of the works relating to digital twins in power focus on small components of larger systems. In 2018, a digital twin was proposed for offshore wind turbines [40]. The primary use case of this digital twin was for the evaluation of remaining useful life (RUL) in each turbine. While the algorithm to calculate RUL was implemented, all digital twin components of this study were merely theorized.

Digital twins for power converters have also been proposed. In 2020, [41] defined how a digital twin for a power converter may be implemented. By reducing complexity, the intention is to deploy the digital twin on Field Programmable Gate Arrays (FPGAs) alongside the converter for embedded operation. In 2021, [42] proposed the usage of digital twins in DCDC converters to evaluate device health. The study was implemented on a buck converter, utilizing the digital twin to estimate real-time values for measurements not captured in the physical system. The twin was able to match the physical system very closely, as shown in fig. 2. This data was fed into algorithms to calculate the degradation of the capacitor and MOSFET components. Degradation was successfully estimated based on the change of resistance in the device.

On the AC side, a digital twin is implemented in [43] to model the low and high voltage sides of a transformer. Measurements from the low voltage side are fed to the digital twin, which is used to predict waveforms on the medium voltage side. This twin is proposed to allow monitoring of the medium voltage side with measurement devices only on the low voltage side. The digital twin was tested using historical data and the medium voltage output of the digital twin is validated.

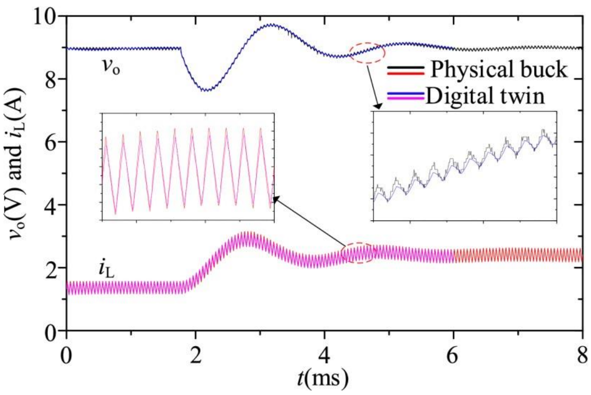

Fig. 2. Comparisons of inductor current and output voltage between digital twin buck converter and its physical counterpart (sampling rate = 1 MHz). [42]

Several studies have utilized digital twin technology for PV resources. In [44], a digital twin is created for a residential PV source and power converter. The digital twin can accurately model the system under normal operating conditions. The error between the physical and digital systems is constantly calculated and used in an algorithm to determine when faults occur. Fault detection and identification in the PV panel were able to be achieved in 80 ms and 1.2 s, respectively. The topology for the digital twin implementation is shown in fig. 3.

Focusing more on distributed PV from the perspective of the grid operator, a digital twin has also been proposed to predict distributed PV power generation more accurately [45]. The model is a neural network with weights set by a genetic algorithm. The network receives weather and climate data and produces expected power output. The model is made into a digital twin by implementing real-time data for an instantaneous power prediction.

Power estimation algorithms for PV tend to be unable to accurately represent impacts of climate. One study utilizes a digital twin to estimate the error in simulated operating parameters and use that error to correct the maximum power point tracking estimated setpoint [46]. As shown in fig. 4, the digital twin is used to accurately estimate power output even in rainy weather.

Microgrid

Several studies have leveraged digital twins for microgrid operation. One study introduces algorithms to be implemented on microgrid digital twins to

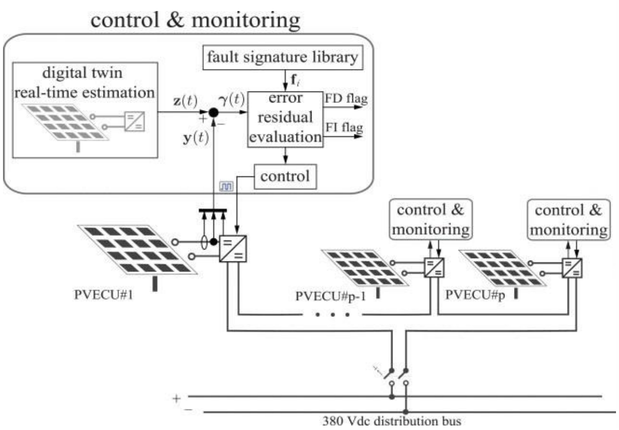

Fig. 3. Proposed digital twin topology for fault estimation in PV systems. [44]

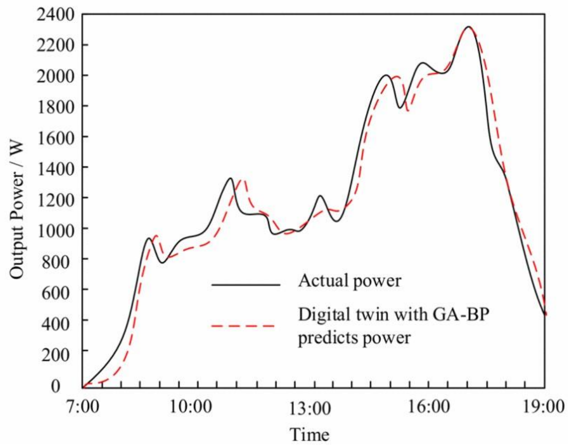

Fig. 4. Estimated PV output versus real output in rainy weather. [46]

improve cybersecurity using output from the digital twin physics-based simulation [47]. The algorithms use the digital twin to validate measurements and detect false data injection, denial of service, and man-in-the-middle attacks.

Another study focuses on similar cyber aspects in microgrids; however, the model is designed for the sole purpose of accurate simulation of power transfer between multiple microgrids at a point of common connection [48]. This study primarily focuses on detected false data injection and denial of service attacks.

Full microgrid digital twins are proposed in another work, but not yet created. [49] recommends the incorporation of advanced physics-based models, with data streams from sensors, models of communication systems, and artificial intelligence operating on the simulation output.

Transmission & Distribution

Existing studies on larger digital twins in power systems are limited. One study introduces an extremely basic twin of a system consisting of only a voltage source, a transmission line, and a resistive load [50]. The model has no physical counterpart, so the digital twin definition is not fulfilled completely.

While another study claims to create a novel digital twin, again the digital model has no physical counterpart, and all data streams are simulated. In [51], the IEEE-13 test system was implemented in a multi-timescale simulation utilizing load flow and electromagnetic transient simulation simultaneously. The simulation can incorporate simulated data measurements, although no physical system exists to gather realistic data.

One implementation is based on a physical system. A digital twin of a 40 thousand bus system was created in [52]. However, the model used is only capable of load flow for contingency analysis. The novel component was the creation of a model capable of updating in real-time with SCADA measurements while also incorporating state estimation output at a different timestep.

Another implementation is described as a virtual digital twin [53]. The testbed was configured to run the Western Electricity Coordinating Council (WECC) 181-bus model. The testbed consisted of digital models, a virtual energy management system, and simulated measurement systems. The testbed can also run models at varying timesteps. The measurement system can be configured with historic data to recreate real-world scenarios. However, there is no capability for synchronous operation with the physical system, therefore the system does not fully fulfil the definition for digital twins.

One study does include synchronous operation of its digital twin – resilient Cyber Secure Centralized Substation Protection (rCSP) [54]. Measurements are taken from a substation and fed into a protection model to compare estimated measurements and sampled measurements. When a significant deviation is detected, the twin calculates the probability that the error is caused by a fault, equipment/instrumentation failure or an altered data cyber-attack. The twin has been modeled for four physical substations and is being evaluated at each. This is a clear example of an advanced power system digital twin.

Other works put forth recommendations to further expand the use of digital twin technology, citing use in other industries and providing arguments for their use in power systems [55], [56]. The industry recognizes that digital twin technology can be beneficial in power system control centers. Comparison has been created between general simulation technology and control-center technology, as shown in table I from [56].

TABLE I
EVOLUTION OF SIMULATION AND CONTROL CENTER TECHNOLOGY. [56]

	Simulation Technology [41]	**Control Center Technology**
1st Generation	Individual Application: Simulation Limited to very Specific Topics	Hard Wired, Fully Analog Communication
2nd Generation	Simulation Tools: Simulation is a Standard Tool for Engineering	IP/TCP based Communication
3rd Generation	Simulation-based System Design	Dynamic Assessment Tools
4th Generation	Digital Twin: Simulation is a Core Functionality of Systems	Digital Twin Centric Control Center Architecture

A ROBUST POWER SYSTEM DIGITAL TWIN

Due to the wide definition of digital twin, specificity is required to differentiate new technology from existing digital twin technology like state estimation and contingency analysis. Given the complexities of today's power systems, we outline a more robust digital twin below. The basic architecture diagram is shown in fig. 5.

Components

A robust digital twin must have a few key components. The twin model may run on a digital real-time simulator. It should be capable of dynamic simulation. The communication and control models must accurately reflect connectivity in the physical system. Interfaces must be created with the grid, including control inputs into the grid and measurements from the grid. Additionally, it should be able to leverage HIL functionality. The main benefits of the robust digital twin will be drawn out from the model by stacking applications on top of the base model.

Cyber-Physical Modeling

Modeling the cyber aspects of the grid is important to accurately understand its operation [57], [58], [59], [60], [61]. Cyber-physical models should include communications and controls as they exist in

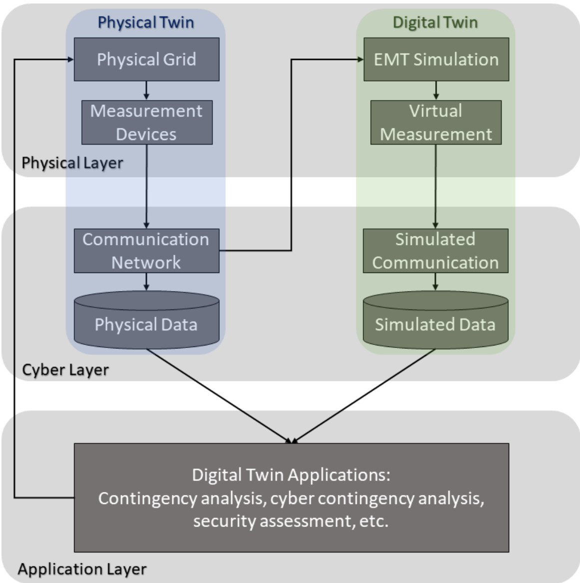

Fig. 5. Architecture Diagram for Robust Digital Twin

the physical system. For example, the communication protocols, latency, and data packet loss should all be considered. Once the model has been validated, it can be used to consider new contingencies and improve system security [62]. These contingencies could include malicious data injection, outside access to remote controls, loss of communications, and loss of remote controls.

Data Sources

The robust digital twin should be capable of using data from a wide variety of sources. For online operation, it should be able to use streaming data like SCADA, PMU measurements, or GOOSE messages. In offline mode, it should be able to operate on real-world data from historians or simulated data. It should be able to combine three-phase and phasor, high and low speed, and real or state estimated data.

Users and Use Cases

The primary users of the robust digital twin will be in power system operations. Through online simulation, tools will be developed to help them continue to operate the grid in the face of any changes that come. Many of the potential use cases have been previously mentioned, like advanced grid security analysis or anomaly detection in measurement or state estimation data.

However, the vast capabilities of the digital implies that other groups within the power industry will also benefit. Protection engineers can take advantage of HIL to include protection devices in the simulated environment before deployment. Cybersecurity specialists can create assessments considering both cyber and physical aspects of the grid. Planning engineers can use the HIL capabilities to test power electronics and other controllers with real data.

Validating and Maintaining the Digital Twin

Once the robust digital twin is constructed, it must be validated across each layer of the model. The electrical simulation must accurately produce values that mirror the physical system. The communication layer must have a similar latency and loss as the real world. The device controllers must have accurate response and latency characteristics.

However, the accuracy requirements are dependent on the phenomena being considered. Power flow and ambient conditions are the simplest to achieve. Transient states like faults, load shedding, breaker switching, etc. introduce much more complexity across all three layers of the digital twin.

Once validated, the model must be continuously updated to ensure accuracy is maintained. To the extent that the physical system can change, the model must be updated as well. If any change would cause a difference in performance between the physical and digital systems, it must be detected and accounted for.

CONCLUSION

In this paper, digital twin technology was reviewed and its application to power systems described. It was shown that digital twins are already being used for power system operations in tools like energy management systems. The benefits of digital twin technology were presented. The technology can be leveraged for significant gain. A few key uses were prediction and mitigation of problematic system conditions, diagnosis of anomalous system behavior, and evaluation of potential control actions before execution in the physical system. Digital twin advancements are possible and have many use cases in power systems. Technological advancements in power systems have and continue to introduce new technologies like distributed energy resources and FACTS devices that create new challenges. A new robust digital twin was outlined to take advantage of high-fidelity simulations and capture many phenomena to aid in operation of the ever-changing grid.

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