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A Digital Twin for an Inverter-Based Resource Power Plant

Real-Time Data Streaming Unlocks Situation Awareness

By Ratik Mittal, Zhixin Miao, and Lingling Fan

The global shift toward cleaner energy sources is transforming the modern power grid. Inverter-based resources (IBRs), such as solar panels and wind turbines, now play a crucial role in electricity generation. However, their integration into traditional power systems introduces new challenges, particularly in maintaining stability and reliability. Imagine a power grid humming steadily, delivering electricity to millions of homes. Now, picture a sudden disruption—an unexpected fluctuation that ripples through the system, threatening to throw the delicate balance into chaos. This is not a distant possibility; it has already happened. In Texas in 2021, a significant synchronization angle deviation in solar photovoltaic farms after a transmission line fault 200 miles away caused power plant tripping, forcing operators into a race against time to restore frequency. The event underscored a growing concern: as renewable energy sources continue to rise, so do the complexities of managing an evolving grid. Traditional power plants, powered by massive spinning turbines, inherently stabilize electricity flow through their mechanical inertia. In contrast, IBRs rely on power electronic inverters, which interact with the grid differently. To predict and prevent stability issues, engineers have turned to an innovative solution—digital twins. The concept, originally introduced by Michael Grieves and later refined by NASA's John Wickers in 2010, has gained traction across various industries, including power systems. But what exactly is a digital twin? According to PES-TR-122 ("Digital Twins for Electric Utilities: Definition, Considerations, and Applications"), a digital twin is defined as:

"A high-fidelity visual and virtual representation of a physical system and its underlying characteristics and operational state. It enables users to understand the current system and predict system behavior under different scenarios and conditions with context in mind."

A digital twin is a dynamic virtual replica of a real-world power grid that continuously updates using real-time data, advanced modeling, and simulation techniques. By mirroring actual grid conditions, it enables operators to test scenarios, analyze potential failures, and implement corrective measures before disruptions occur. Beyond simulation, digital twins can be essential for grid design, planning, real-time operations, contingency analysis, and asset management.

Current digital twin applications are mostly limited to small-scale systems, such as monitoring DC-DC converter components, diagnosing single-phase DC-AC converters, and predicting offshore wind turbine converter lifespan. Few implementations involve multi-unit systems, and those that do are often task-specific, such as networked microgrid unit commitment using steady-state or power flow analysis. Developing a digital twin for an entire power system, with its complex physical components and dynamic behaviors, presents significant challenges.

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One notable effort is by the Australian Energy Market Operator, which introduced a digital twin for the Australian bulk power grid, encompassing 55 GW of generation and 40,000 km of transmission lines. They successfully implemented a synthetic model in a real-time simulator, but a full-scale model requires immense computational resources, raising concerns about practical implementation.

In this article, we present a digital twin for an IBR power plant. This digital twin incorporates three key technologies to realize real-time situation awareness. The first technology is real-time digital simulation with the capability of real-time parameter updating. This technology enhances computer simulation from an offline to an online tool. Second, real-time data streaming is integrated via industrial-grade sensors to provide continuous measurements to the real-time simulator. The third technology integrates data streaming into real-time simulation, which is data-driven modeling or estimation. Using this data stream, critical modeling parameters are estimated to reflect actual system conditions. The virtual simulation model deployed has a goal to be computing efficient so that real-time simulation in an available hardware chip is feasible. Therefore, instead of modeling each inverter with all details, we employ a reduced-order model for the entire power plant.

Additionally, it is challenging to model an entire power grid in real-time. To develop an IBR power plant agnostic to its location, we adopt a generic representation for any power grid viewed from the point of interconnection. This generic representation is the Thévenin equivalent. Therefore, the digital twin represents a single IBR power plant interfaced with a grid represented by a Thévenin equivalent whose parameters are updated in real-time based on estimation over the real-time data stream. This digital twin, with a simplified grid representation, allows us to reflect the grid's dynamic behavior such as voltage fluctuations and fault contingencies, and further adequately capture the IBR's dynamic behavior, e.g., synchronization performance and stability performance.

To ensure efficiency without sacrificing accuracy, we have designed an adequate reduced-order model with the ability to capture system-level dynamics. This model enables real-time simulation with minimal computational demand. This streamlined approach enhances grid management by allowing operators to anticipate and mitigate potential disruptions proactively.

The digital twin presented in this article is specifically designed for grid-connected IBRs, with three primary objectives (Figure 1):

- ✓ **Estimation** of critical grid parameters
- ✓ **Replication** of physical system behavior
- ✓ **Prediction** of stability issues before they escalate

By integrating real-time data, estimating key parameters, and utilizing reduced-order modeling, our approach offers a practical and scalable solution for digital twin implementation in modern power grids.

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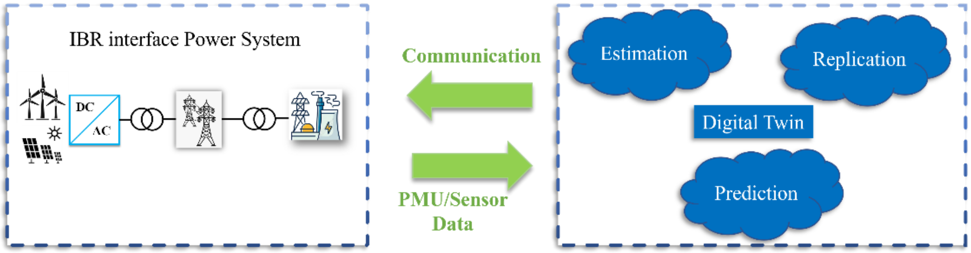

Figure 1 Objectives of the developed digital twin.

Study System

The testbed is illustrated in Figure 2, showcasing a system configured as a modified IEEE-9 bus system. This system operates at a transmission network voltage of 230 kV. Synchronous generators, modeled as constant voltage sources, are connected at buses B_1 and B_2. The various line impedances and system parameters are tabulated in Table 1. A grid-following IBR is connected at bus B_3, which serves as the Point of Common Coupling (PCC) bus. In the IBR power plant digital twin, the interconnected grid at the PCC bus is represented by a Thévenin equivalent circuit. When the interconnected grid experiences faults, the parameters of the Thévenin equivalent circuit, including the Thévenin equivalent impedance and the Thévenin equivalent voltage source, will vary.

Table 1 Parameters for modified IEEE-9 bus system.

Description	Value (SI, pu)
Power Base	100 MVA
V_1	$18\angle10^\circ$ kV
V_2	$13.8\angle0^\circ$ kV
Z_1, Z_2, Z_{32}, Z_{ine}	$0.201\angle84.28^\circ$ pu
Z_{14}, Z_{42}, Z_{13}	$0.1005\angle84.28^\circ$ pu

The inverter control consisting of fast inner current tracking (controlling inverter current $\boldsymbol{i}$) and slower outer power control is implemented in the ***dq*** reference frame based on the phase-locked loop (PLL). The PLL frame's *d*-axis is aligned with the PCC bus voltage space vector at steady state. A synchronous reference frame PLL (SRF-PLL) is used as the synchronizing unit. This SRF-PLL has the PCC bus three-phase voltage as the input and outputs an angle θ_{PLL} that tracks the PCC bus voltage's angle θ_{PCC}. This angle is further used in *dq/abc* and *abc/dq* frame conversion in the inverter control. The control topology of the IBR is presented in Figure 3. Proportional integral (PI) controllers are used for DC signal tracking in both inner and outer control. The outer control generates reference currents for the inner current control. The output of the control system is the IBR's terminal voltage (v_{tabc}), which transforms to modulating signal m_{abc}.

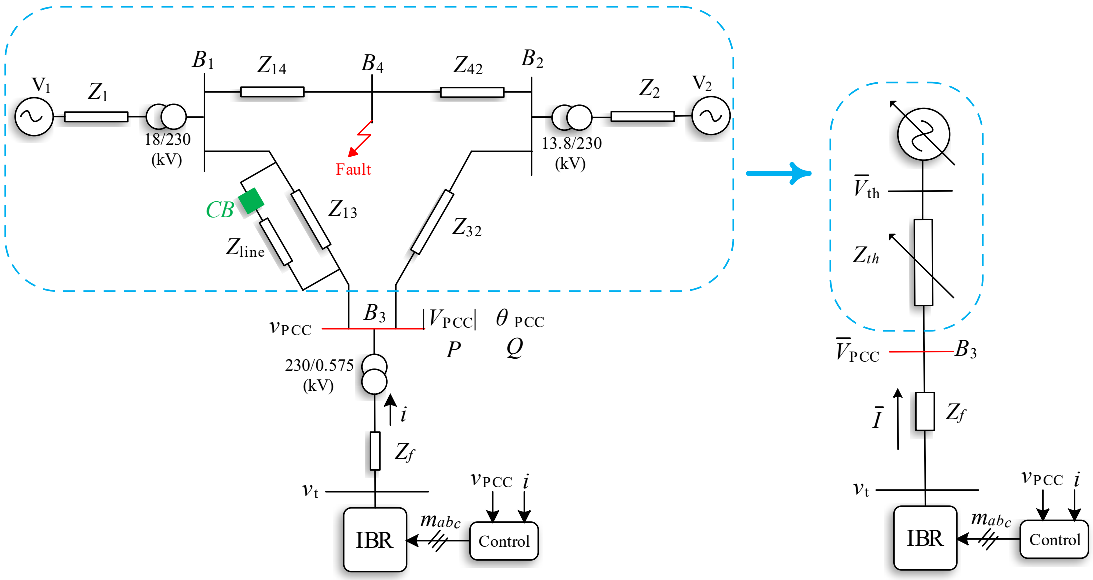

Figure 2 Test case system (IEEE-9 bus system) and simplified representation for the digital twin.

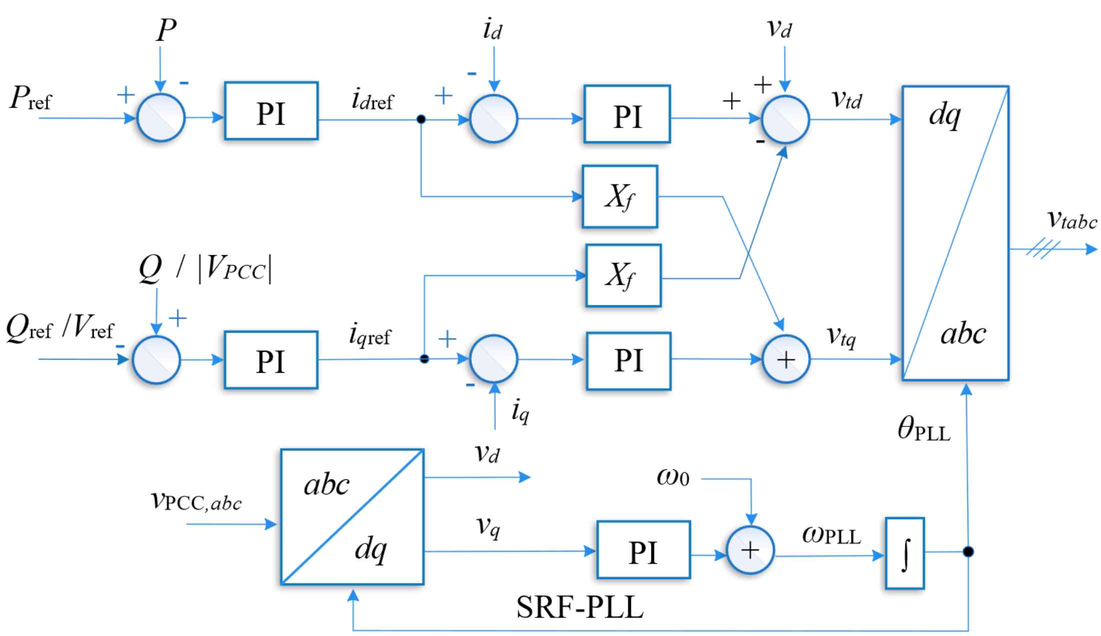

Figure 3 The control structure of IBR at bus B_3.

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Estimation of Thévenin Grid Reactance and Voltage

From the perspective of the IBR, the grid connection at the PCC bus can be modeled as a Thévenin equivalent circuit. This includes a Thévenin equivalent impedance Z_{th} and an equivalent voltage source V_{th}. This setup can be viewed as a two-bus system (see Figure 2). Here, the Thévenin impedance primarily consists of a reactance X_{th} with the resistance R_{th} assumed to be nearly zero. The grid's voltage at this interface, V_{th}, is taken as a reference with a phase angle of zero degrees: $V_{th} = |V_{th}|\angle 0°$. But how do we estimate this Thévenin model's two key parameters: V_{th} and X_{th}? The key lies in the observable variables: the voltage magnitude at the point of common coupling ($|V_{PCC}|$), its phase angle (θ_{PCC}), and the power flowing through—both real (P) and reactive (Q). These four measurements are available through the phasor measurement unit (PMU) installed at the PCC bus. Note that the real and reactive power are associated with the PCC bus voltage and angle and the Thévenin equivalent's voltage and reactance. The two nonlinear equations have been shown in Figure 4.

Determining the Thévenin parameters requires solving the nonlinear power flow equations, which can be efficiently tackled using Newton's iteration method. Figure 4 Presents the block diagram of the estimation algorithm adopted to obtain the Thévenin grid reactance and voltage. In this research, Newton's iteration method has been implemented in the hardware prototype system to take in the analogy measurements (the phase voltage and current), convert them to voltage magnitude, voltage phase angle, real and reactive power, and output the estimated Thévenin parameters.

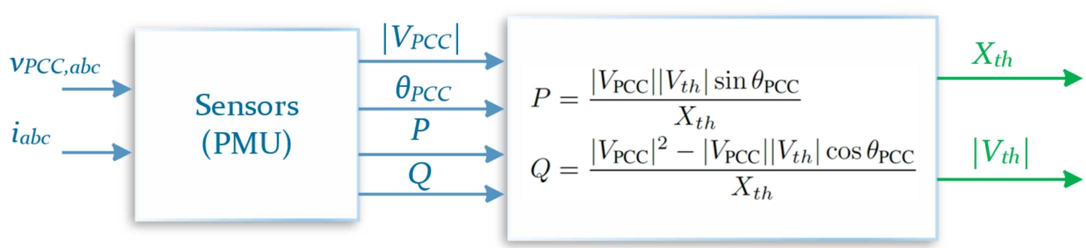

Figure 4 Block diagram representing the process of Thévenin grid reactance and voltage estimation from sensed PCC bus voltage and current.

Reduced-Order IBR Dynamic Model in Per Unit

For power grid dynamic studies, a grid-following IBR is often modeled as a controllable current source. It is a common practice in system-level dynamic studies to ignore the fast inner control loop, PLL, and line electromagnetic transient (EMT) dynamics, as shown in the WECC IBR generic model set REGC_A. Our earlier work (Fan, 2019) demonstrated that incorporating PLL dynamics into the current source representation significantly enhances the accuracy of stability analysis, particularly in weak grid scenarios. In this article, this type of reduced-order model is adopted to implement the digital twin. For the reduced-order model, the inner current control loop and the line EMT dynamics are ignored. The justification is as follows. The inner loop typically operates at a much faster time scale compared to the outer control. This time-scale separation allows us to approximate the inner loop dynamics as a fast, quasi-steady-state

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process. A distinct advantage of model reduction is the reduced computation burden. A key technology of the *dq*-frame representation is that instead of treating θ_{PLL} (the angle of the PLL viewed from the static frame) as a state variable, we use δ_{PLL} (the angle of the PLL viewed from the grid *dq* frame) as a state variable. The grid *dq* frame aligns with the constant grid voltage's space vector and its position against the static frame is $\omega_0 t$, where ω_0 is the nominal angular frequency 377 rad/s. Therefore, $\delta_{PLL} = \theta_{PLL} - \omega_0 t$. The model can be divided into four blocks: (a) outer loop block, (b) PLL block, (c) grid effect block, and (d) frame conversion block, as shown in Figure 5.

- ✓ **Outer Loop and PLL***:* As noted earlier, the outer loop regulates the real power (P) and the reactive power (Q) or the PCC bus voltage $|V_{PCC}|$, ensuring power reference tracking and generating the converter current commands i_d and i_q in the PLL frame. A second-order PLL is modeled. The PLL receives the PCC bus voltage angle δ_{PCC} as input and outputs its angle δ_{PLL} . At a steady state, these angles align, while during transients, they differ.
- ✓ **Grid Effect**: From Figure 2, the algebraic relationship between the PCC bus voltage, current, and grid voltage is established (refer to the grid effect block in Figure 5). It is important to note that these variables are expressed in the grid reference frame. For example, the PCC bus voltage is represented in the grid reference frame. is $v^g_d + jv^g_q$. The subscript "*g*" represents the grid reference frame.
- ✓ **Frame Conversion:** As discussed earlier, the IBR is synchronized with the power grid using a PLL, which provides us with the necessary synchronization angle δ_{PLL}. Since the converter control is working in the PLL frame, we need to convert the currents from the PLL frame to the grid reference frame.

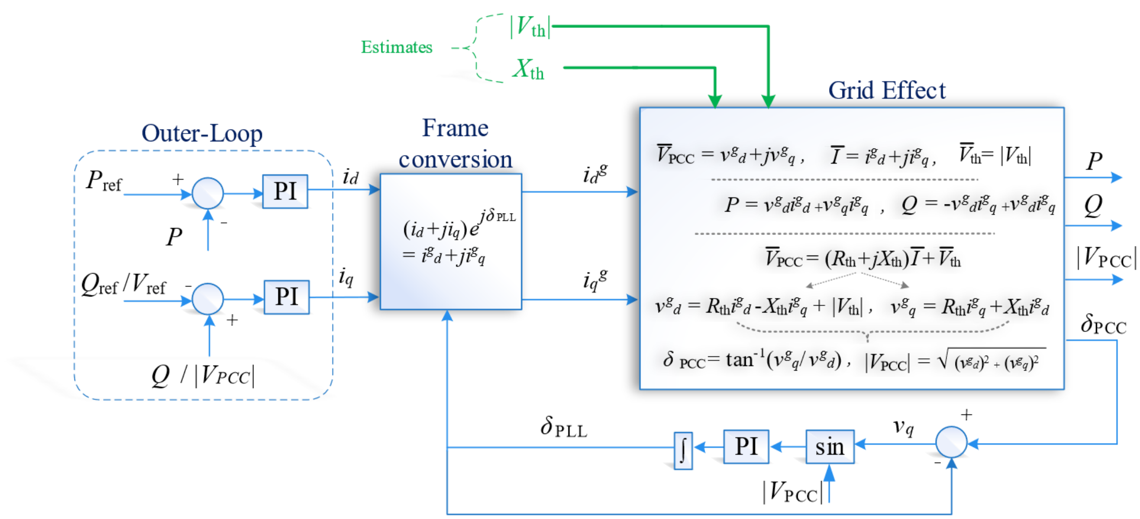

Figure 5 Reduced-order dq-frame model (in per unit) of the grid-connected IBR implemented in the digital twin. The block diagram represents the main modeling blocks.

Digital Twin Testbed Setup

A digital twin of the IBR power plant is developed for monitoring, estimation, control, and risk assessment. To set up the test bed, the study system (IEEE 9-bus system) is modeled in the Real-Time Digital Simulator

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(RT-Lab). Designed for real-time electromagnetic transient simulations, RT-Lab enables seamless interaction with external devices, such as PMUs, through its multiple input/output ports.

The digital twin of the study system is implemented in the National Instruments (NI) cRIO-9063, a sophisticated real-time controller built around the reconfigurable Xilinx Zynq-7000 System on Chip. This device is responsible for modeling a simplified representation of an IBR connected to a Thévenin equivalent grid. With the aid of NI LabVIEW FPGA, the cRIO-9063 processes data and executes operations with remarkable efficiency. Equipped with four 16-bit c-Series modules and high-speed Ethernet communication capabilities, it ensures seamless interfacing with external systems.

This System on Chip is driven by a host computer running LabVIEW. It applies Newton’s method to solve power flow equations and determine the Thévenin equivalent grid reactance and voltage magnitude. Through an Ethernet connection, this information is transmitted to the cRIO-9063, creating a real-time exchange of critical system parameters. Additionally, LabVIEW's graphical user interface allows for dynamic adjustments, enabling real-time modifications of controller gains, reference values, and other parameters. This feature enhances the digital twin’s adaptability, allowing researchers to predict and analyze system behavior under varying conditions.

The implementation of the digital twin unfolded in two distinct phases:

- ✓ **Setup 1** – In the initial phase, the RT-lab was directly connected to the NI cRIO-9063 via analog I/O modules. Here, key system parameters—such as point of common coupling bus voltage magnitude, phase angle, real power, and reactive power —were exchanged. The host computer processed this data calculated the Thévenin equivalent grid reactance and voltage magnitude and relayed the results to the cRIO-9063.

- ✓ **Setup 2** – The second phase introduced a more advanced industrial-grade configuration. Instead of a direct connection, the RT-Lab interfaced with an industrial PMU that transmitted phasor data in IEEE C37.118 format. This data, sent through designated TCP/IP ports, was aggregated and processed by a phasor data concentrator (PDC). The PDC then communicated with the host computer, which computed the Thévenin equivalent grid parameters and transmitted them to the cRIO-9063, further refining the system's real-time analytical capabilities.

The hardware setup for the digital twin is presented in Figure 6.

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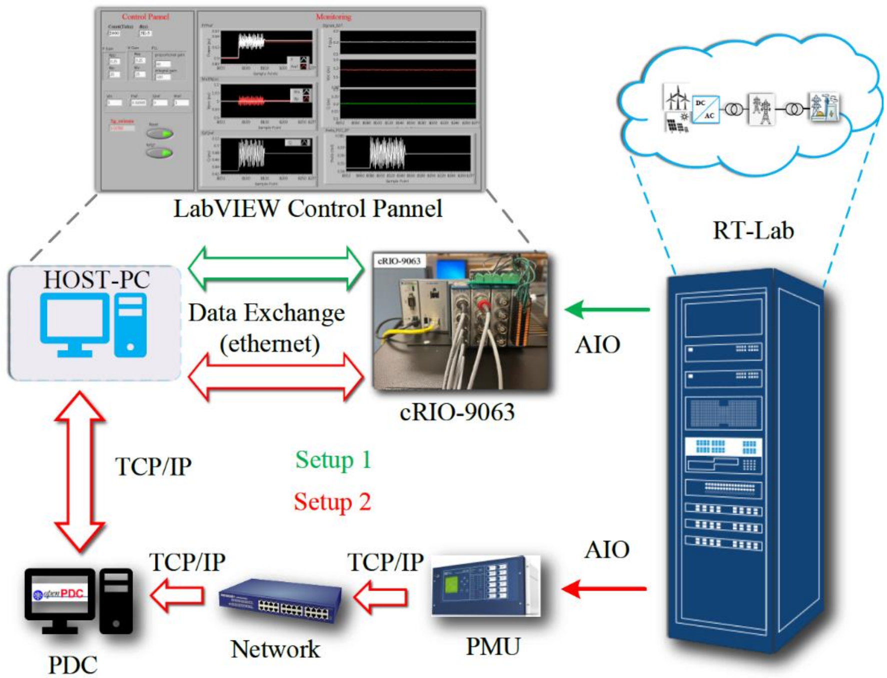

Figure 6 Hardware setup for digital twin at the University of South Florida.

Application 1: Estimation of Thévenin Grid Reactance and Voltage

One of the primary applications of the digital twin is real-time estimation, where the non-linear power flow equation is continuously solved. The test system, based on a modified IEEE 9-bus configuration, features the IBR operating in P-Q control mode. The results, illustrated in Figure 7, highlight the computed Thévenin grid reactance (X_{th}) and voltage magnitude ($|V_{th}|$) across three distinct case studies.

- ✓ **Case Study 1:** The reference values for real power (P_{ref}) and reactive power (Q_{ref}) of the IBR are varied. Despite these changes, the computed values for the grid reactance and voltage magnitude of the Thévenin equivalent circuit remain unchanged. These results, derived from measurements and calculations at the point of common coupling bus, validate the stability of the estimation process.

- ✓ **Case Study 2:** In this scenario, a transmission line tripping event occurs due to the opening of a circuit breaker (CB) at 1s, leading to the disconnection of a line (impedance Z_{line}) connecting buses B_1 and B_3. This event increases the grid reactance, which is reasonable since a line-tripping event results in a weaker grid or a larger grid impedance.

- ✓ **Case Study 3:** A three-phase fault occurred at bus B_4, introduced with a fault impedance of j 0.1 pu, lasting for six cycles from 2s. As the fault impacts the system, the Thévenin equivalent impedance and voltage are updated in real-time, demonstrating the ability of the digital twin to dynamically adapt to system disturbances.

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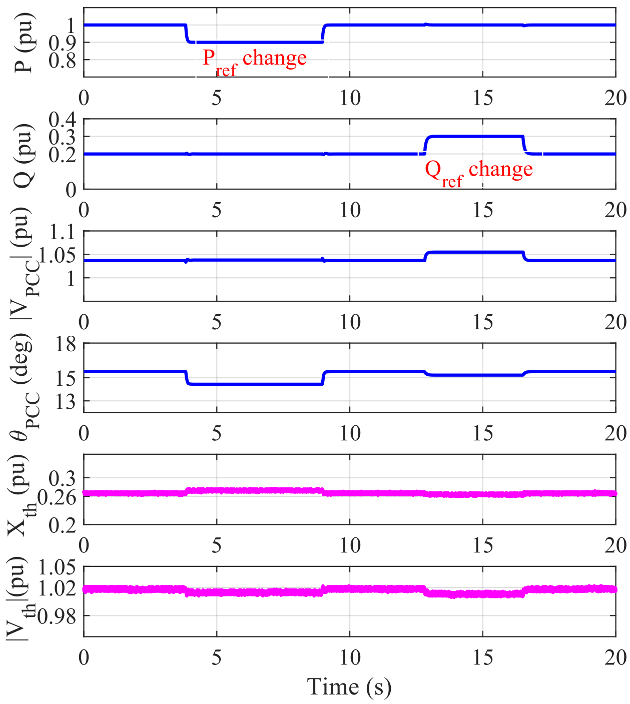

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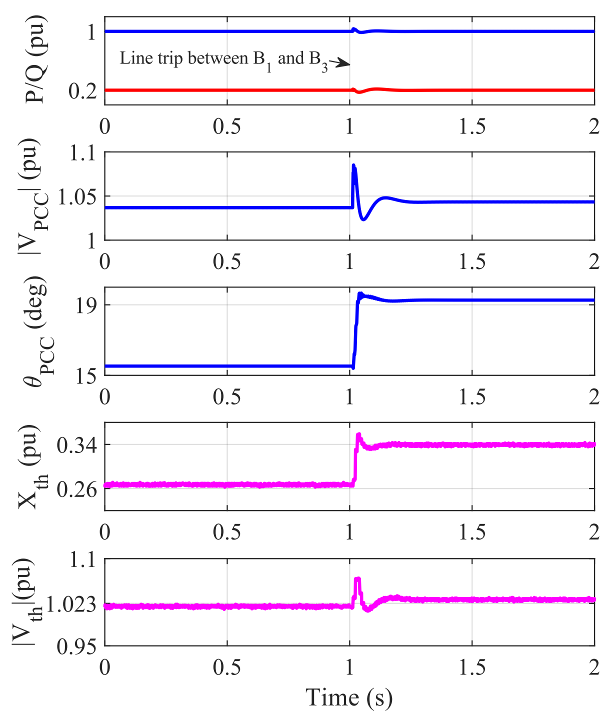

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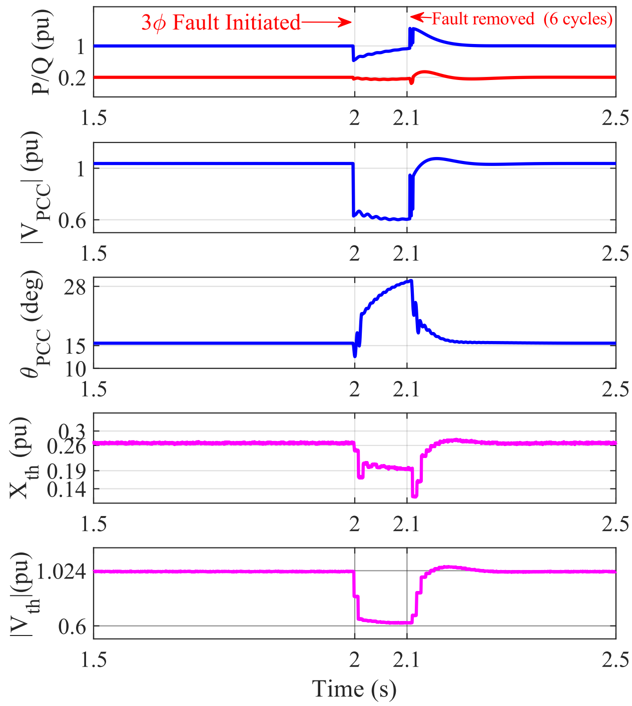

(c)

Figure 7 Time-domain responses of real power P, reactive power Q, $|V_{PCC}|$, θ_{PCC} and the obtained X_{th} and $|V_{th}|$ from the digital twin. The results showcase the performance of the estimation algorithm implemented in the digital twin for three case studies. (a) Case Study 1, (b) Case Study 2, and (c) Case Study 3.

Validation

The results obtained for the estimated X_{th} and V_{th} can be validated through the admittance matrix approach. The results were confirmed through theoretical calculations using the conventional admittance matrix to impedance matrix approach. For the meshed network under investigation (see Figure 2), the admittance matrix is formed. To evaluate the Thévenin equivalent impedance, the impedance (the inverse of the Y_{bus} matrix) is determined as Z_{bus}. The Thévenin equivalent circuit, as seen from the PCC bus, is derived by expanding the third row of the Z_{bus} matrix. In this expression, Z_{33} represents the Thévenin equivalent impedance. The calculated values are $Z_{th} = Z_{33} = 0.2\angle 84.2894^{\circ}$ pu and $V_{th} = 0.9962\angle 5.1^{\circ}$ pu. The theoretical values are $X_{th} = 0.2$ pu and $|V_{th}| = 0.9962$ pu, whereas the values obtained in real-time are $X_{th} = 0.26$ pu and $|V_{th}| = 1.024$ pu. The values obtained in real-time are now utilized within the digital twin to closely replicate the modified IEEE 9-bus system. Figure 8 presents a pictorial representation of the Y_{bus} matrix approach for validation (for Case Study 1). Although the process showcased in Figure 8 represents Case Study 1, this can also be implemented for Case Study 2 and 3 as well by incorporating Z_{line} and Z_{fault}, respectively. Table 2 compares the values of X_{th} and $|V_{th}|$ obtained from the estimation algorithm with those from the theoretical Y_{bus} matrix.

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Step-1

$$\begin{bmatrix} \frac{1\angle 10^\circ}{Z_1} \\ \frac{1\angle 0^\circ}{Z_2} \\ I_3 \\ 0 \end{bmatrix} = \underbrace{\begin{bmatrix} \frac{1}{Z_1}+\frac{1}{Z_{13}}+\frac{1}{Z_{14}} & 0 & -\frac{1}{Z_{13}} & -\frac{1}{Z_{14}} \\ 0 & \frac{1}{Z_2}+\frac{1}{Z_{42}}+\frac{1}{Z_{32}} & -\frac{1}{Z_{32}} & -\frac{1}{Z_{42}} \\ -\frac{1}{Z_{13}} & -\frac{1}{Z_{32}} & \frac{1}{Z_{13}}+\frac{1}{Z_{32}} & 0 \\ -\frac{1}{Z_{14}} & -\frac{1}{Z_{42}} & 0 & \frac{1}{Z_{14}}+\frac{1}{Z_{42}} \end{bmatrix}}_{Y_{\text{bus}}} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix}$$

Step-2

$$Z_{\text{bus}} = Y_{\text{bus}}^{-1}$$

Step-3

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = \underbrace{\begin{bmatrix} 0.1251\angle 84.3^\circ & 0.0759\angle 84.3^\circ & 0.1027\angle 84.3^\circ & 0.1005\angle 84.3^\circ \\ 0.0759\angle 84.3^\circ & 0.1251\angle 84.3^\circ & 0.0983\angle 84.3^\circ & 0.1005\angle 84.3^\circ \\ 0.1027\angle 84.3^\circ & 0.0983\angle 84.3^\circ & \mathbf{0.2}\angle 84.3^\circ & 0.1005\angle 84.3^\circ \\ 0.1005\angle 84.3^\circ & 0.1005\angle 84.3^\circ & 0.1005\angle 84.3^\circ & 0.1507\angle 84.3^\circ \end{bmatrix}}_{Z_{\text{bus}}} \begin{bmatrix} \frac{1\angle 10^\circ}{Z_1} \\ \frac{1\angle 0^\circ}{Z_2} \\ I_3 \\ 0 \end{bmatrix}$$

Step-4

$$V_3 = \underbrace{Z_{13}\frac{1\angle 10^\circ}{Z_1} + Z_{23}\frac{1\angle 0^\circ}{Z_2}}_{V_{th}} + Z_{33} I_3$$

Figure 8 Calculation of X_{th} and $|V_{th}|$ values from theoretical Y_{bus} matrix approach.

It should be noted that due to the omission of the grid impedance's resistive part and with the assumption that the grid voltage as seen from bus B_3 is zero in the non-linear power flow equation, the obtained values X_{th} and V_{th} are slightly larger than the theoretical values. Overall, the estimation algorithm can lead to reasonably accurate estimates of grid parameters.

Table 2 Comparison of X_{th} and $|V_{th}|$ values from the estimation algorithm and theoretical Y_{bus} matrix.

	X_{th} (pu)		**$\|V_{\text{th}}\|$ (pu)**	
	Estimation	Theoretical	Estimation	Theoretical
Case Study 1 (power change)	0.26	0.2	1.024	0.9962
Case Study 2 (line tripping)	0.34	0.34	1.026	0.9930
Case Study 3 (fault contingency)	0.19	0.1512	0.6	0.5970

Application 2: Replication of Physical Power System Events

One of the key functions of the digital twin is to accurately replicate real-world power system behavior. By incorporating estimated values of the Thévenin equivalent grid reactance and voltage magnitude, the digital twin effectively simulates actual system conditions. To assess its accuracy, two distinct test cases were considered: 1) a three-phase fault scenario with a fault impedance of $j0.1$ pu, lasting for six cycles from t = 2s, and 2) a transmission line tripping event due to the opening of breaker CB at t = 1s, leading to

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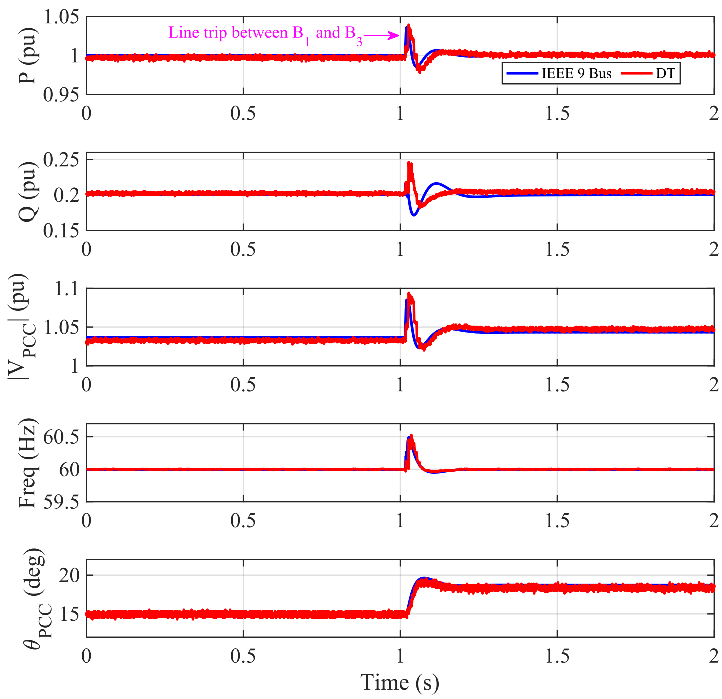
the disconnection of a line with impedance Z_{line}. As shown in Figure 9, the digital twin's simulation results closely align with the expected system response, demonstrating that the digital twin effectively replicates actual power system behavior. These findings reinforce its reliability as a powerful tool for system monitoring, analysis, and decision-making.



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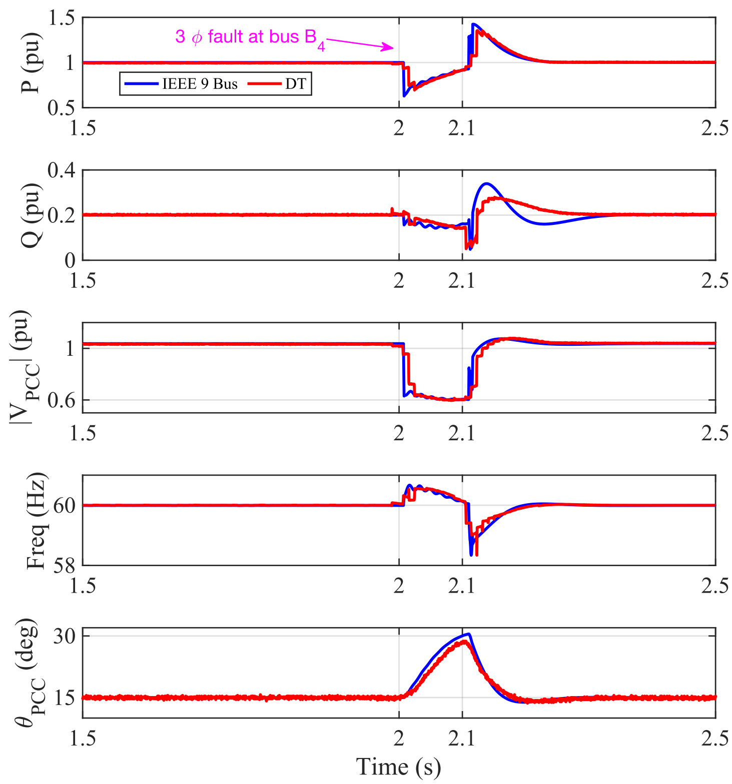

(b)

Figure 9 Time-domain responses of real power P, reactive power Q, $|V_{PCC}|$, θ_{PCC}, and the frequency (Hz), comparing the digital twin (red curve) with the original IEEE-9 bus power system (blue curve). The results demonstrate the digital twin's effectiveness in replicating the actual power system under different conditions. (a) Case Study 1 and (b) Case Study 2.

Application 3: Small-signal Stability Assessment

Beyond estimation and replication, the digital twin also serves as a predictive tool, offering insights into power system stability and potential mitigation strategies. To assess its robustness, a small-signal disturbance test is conducted in which the power order is incrementally increased. Here the IBR is assumed to be in real power and PCC voltage control. During weak grid interconnections, the system exhibits low-frequency oscillations, highlighting potential stability concerns. The power reference P_{ref} is increased in steps keeping V_{ref} as 1 pu, and the system response is monitored. It is observed that under weak grid conditions, the IBR power plant goes under low-frequency oscillations of about 3.5 Hz, with P_{ref} = 0.95 pu being the marginal stability case. In the case of the digital twin, when P_{ref} = 0.9 pu, the IBR power system experiences undamped oscillations, indicating marginal stability. This stability limit is close to the limit of the physical system. In the digital twin, by decreasing the bandwidth of the PLL (by adjusting the PI gains), the oscillations are mitigated. Comparisons of the time domain results obtained from the physical power system and the digital twin are presented in Figure 10. This demonstrates the digital twin's ability to anticipate instability and provide corrective actions within a significantly shorter time frame.

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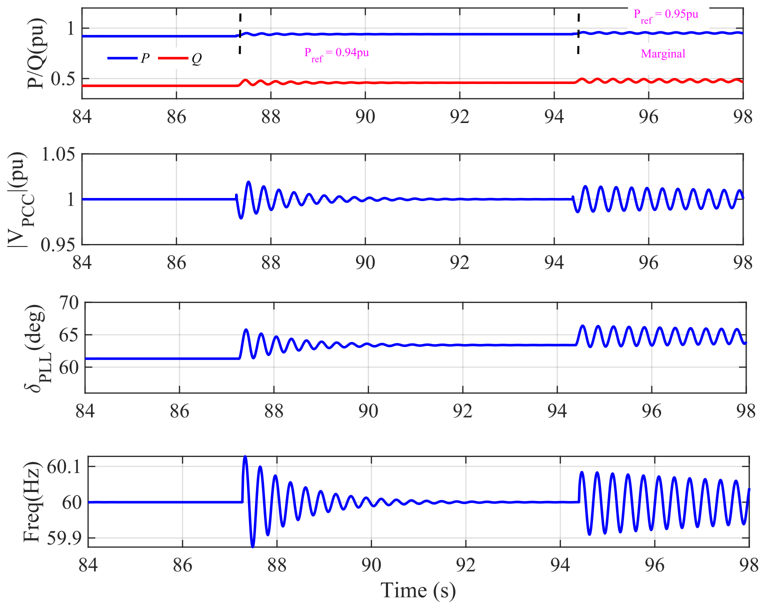

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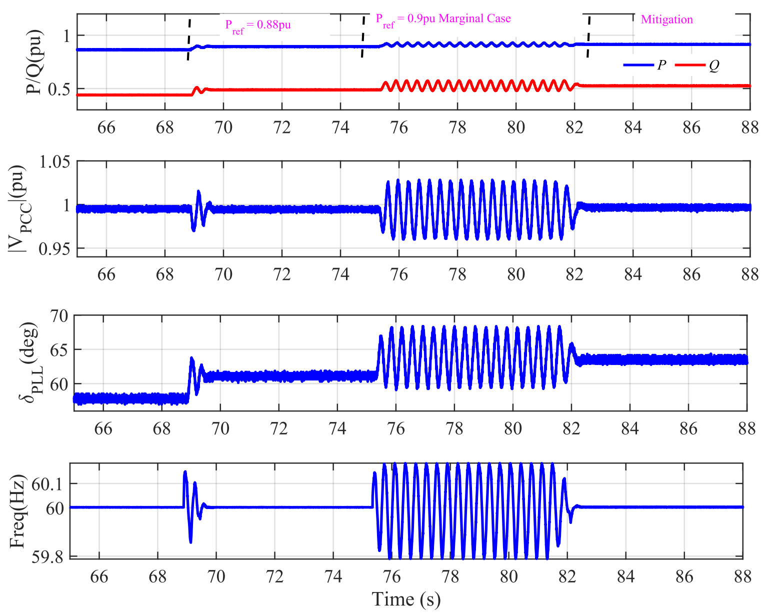

(b)

Figure 10 Time-domain responses of real power P, reactive power Q, $|V_{PCC}|$, δ_{PLL} (PLL angle), and the frequency (Hz), comparing the digital twin with the original power system. The results demonstrate the digital twin's effectiveness in replicating the actual power system under a small signal stability test. (a) Results from the actual system and (b) Results from the digital twin.

Summary

In summary, this study presents the development and successful implementation of a digital twin specifically designed for a grid-connected IBR power plant. By integrating a reduced-order model of the IBR system and dynamically updating the grid impedance with real-time data, the digital twin effectively captures and replicates the behavior of the physical system. Its accuracy and reliability are validated through critical test scenarios, including a three-phase fault and a line-tripping event. The results confirm that the digital twin closely emulates its physical counterpart, demonstrating its strong potential for real-time analysis, system monitoring, and predictive decision-making in modern power systems.

For Further Reading

- L. Fan, "Modeling Type-4 Wind in Weak Grids," in *IEEE Transactions on Sustainable Energy*, vol. 10, no. 2, pp. 853-864, April 2019, doi: 10.1109/TSTE.2018.2849849.
- S. Pandey, A. K. Srivastava, and B. G. Amidan, "A Real Time Event Detection, Classification and Localization Using Synchrophasor Data," in *IEEE Transactions on Power Systems*, vol. 35, no. 6, pp. 4421-4431, Nov. 2020, doi: 10.1109/TPWRS.2020.2986019.
- R. Kar, T. Banerjee, Z. Miao and L. Fan, "Thévenin Equivalent Representation of Meshed Grids for IBR Dynamic Phenomena Replication," 2024 IEEE Power & Energy Society General Meeting (PESGM), Seattle, WA, USA, 2024, pp. 1-5

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