# DIGITAL TWINS IN POWER TRANSMISSION: FROM CONVENTIONAL PLANNING TO INTELLIGENT GRIDS

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## Introduction

Digital twins have risen to prominence in recent years, evolving into a transformative technology across various sectors. This surge in adoption is driven by the convergence of advanced technologies, including the Internet of Things (IoT), artificial intelligence (AI), machine learning (ML), Supervisory Control and Data Acquisition (SCADA), and cloud computing. India is actively adopting the digital-twin technology, primarily to modernise power systems, industrial manufacturing, and infrastructure planning.

A digital twin (DT) refers to a virtual replica of a physical product, process, or service that enables real-time monitoring, analysis, and optimisation on the basis of continuous data updates from its physical counterparts.

When utilised in power systems, the DT technology can enhance visibility, predictability, and control. Unlike conventional static planning, DT-enabled transmission uses adaptive, data-driven approaches, allowing for 24/7 monitoring, predictive maintenance, and optimal use of assets. In the context of power transmission network operation and planning, DTs can improve system efficiency and be instrumental in smoothening renewable energy (RE) integration, thereby stabilising the grid while reducing operational cost.

India's smart grid initiative—driven by the National Smart Grid Mission—has moved from pilot stage to mass-scale deployment, especially through the Revamped District Sector Scheme (RDSS), under which India is rapidly deploying smart meters to meet the national target of 250 million by 2027. Though deployment across the country is currently uneven, India is moving towards a modern grid infrastructure to strengthen reliability and aid integration of renewables. Digital twins can help India's transmission planning to evolve from static to real-time, employing predictive models that simulate load flows, RE integration, and system faults. Integrating DTs into smart grids will convert them into intelligent, resilient systems through quicker decision-making and efficient capacity planning, reducing outages in an RE-rich.

> The real-world examples demonstrate that digital twins help in minimising design time and capital cost and achieve better life-cycle efficiency owing to virtual testing. Through cyber-physical simulations, they enable real-time monitoring, predictive maintenance, RE integration, load forecasting, and outage management, thus optimising power flow.

## DIGITAL TWINS AND POWER SYSTEMS

Though the unified standards for their adoption are not fully established at present, digital twins are contributing significantly to grid development, which is why they are considered vital for future-smart power systems.

### Application across the globe

Many developing economies are deploying digital twins in the power systems at an accelerating pace. For instance, Europe and American Electric Power (AEP), one of the largest transmission utilities in the United States, is utilising DTs to create real-time synchronised grid replica that merge IoT, SCADA, and AI, with predictive maintenance schemes. Similarly, in Germany and other European countries like Norway and Netherlands, DT-enabled predictive maintenance frameworks are being used to increase the integration of renewables and for fault detection in wind and solar systems, as well as to reduce operational costs and improve system availability. For instance, Siemens electrical digital twin creates a single, accurate, real-time model of the power system, minimising errors and helping utilities to run the grid more efficiently and closer to its full capacity safely. Another example is Venios GmbH, which utilises digital-twin analytics to enhance fault detection and asset monitoring, reducing the frequency of outages and lowering operational costs.

### Status in India

India is in an early-to-intermediate stage of adopting digital twins in transmission planning, with a couple of pilot projects currently underway. The BSES Rajdhani Power Limited (BRPL) project in Delhi is one of them, under which a large-scale real-time digital twin has been deployed in the Janakpuri area. The virtual copy of the power distribution system is already under testing in the real environment. Currently in the pilot/first rollout phase, the project aims to cover approximately 1.65 lakh consumers with AI-based monitoring, predicting faults and managing outages.

Thus, digital twins in India are now using real-time grid data for predictive, dynamic planning (load flow, renewable integration, fault analysis), enhancing reliability and efficiency, though large-scale standardisation is still evolving.

### The transformative potential of DT for India's power system

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The DT technology can substantially improve traditional grid planning by furnishing critical insights from simulations and incorporating data-driven decisions. It can also strengthen scenario simulation and contingency analysis: power system operators can simulate situations (such as faults or generation/load variations) without impacting the real grid, resulting in increased efficiency and cost savings. The benefits of DT-enabled transmission planning over traditional planning are given in Table 1.

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**Table 1:** Traditional Transmission Planning vs DT-Enabled Transmission Planning.

| SI No | Aspect | Conventional Transmission Planning | Digital Twin–Based Transmission Planning |
|---|---|---|---|
| 1 | Data Source | Uses historical data and demand forecasts for planning studies. | Uses real-time data from sensors, SCADA, and Phasor Measurement Units (PMUs) for continuous system monitoring. |
| 2 | Model Nature | Static models updated periodically and mainly used for offline analysis. | Dynamic virtual replica continuously synchronised with the physical grid. |
| 3 | System Representation | Uses simplified network models and assumptions to approximate system behaviour. | Provides high-fidelity representation of the entire grid, including share of distributed energy resources (DERs) and operating status of equipment. |
| 4 | Planning Methodology | Evaluates grid-stressed scenarios and limited operating conditions. | Uses time-series data and dynamic simulations for realistic analysis. |
| 5 | Operational Feedback | Limited feedback from real system operation. | Continuous feedback from operational data, resulting in better planning accuracy. |
| 6 | Decision Support | Focuses on long-term expansion and contingency analysis. | Enables predictive analytics, scenario simulation, and proactive planning. |
| 7 | Accuracy and Reliability | May miss dynamic grid behaviour, owing to simplified models. | Provides higher accuracy through real-time measurements. |
| 8 | Technology Integration | Uses traditional planning tools [such as Power System Simulator for Engineering (PSS/E), Digital Simulation and Electrical Network calculation program (DIgSILENT), Electrical Transient Analyzer Program (ETAP), and PowerWorld). | Integrates IoT, sensors, AI/ML, SCADA, and high-performance computing. |

With the need to shift to RE sources intensifying, most countries are accelerating their efforts in this direction. India too has set ambitious RE targets for a rapid clean energy transition. Digital twins are seen as a powerful tool for optimising RE integration, as they can establish a real-time connection between the physical and digital grid, enabling forecasting and integration of variable RE sources (such as solar and wind) into the grid, while minimising energy curtailment and emissions. To illustrate, in a renewables-rich state like Tamil Nadu with wind generation variations and line faults, DTs can allow for various 'what-if' scenarios to be tested without impacting the real grid, helping to anticipate congestion, identify faults, and optimise the system, resulting in fewer outages and lower costs, along with efficient integration of intermittent RE sources.

## KEY ENABLERS FOR ACHIEVING FULL DT FUNCTIONALITY

While the utilisation of digital twins in India's transmission planning holds promise, certain measures are needed for enabling their full functionality, besides helping to overcome the challenges related to complexity of high-fidelity modelling, reliance on high-quality real-time data, and cybersecurity threats.

The following are considered the key enablers in this regard:

### 1. Real-time sensors

Introducing high-fidelity real-time sensors on transmission assets is critical to create a solid physical-to-digital interface for digital twins. The real-time information available in phasor measurement units (PMUs), IoT devices, and line monitors helps in determining the correct state and dynamic line rating and conducting transient analysis. To enhance grid observability in real time and improve the accuracy of decisions, utilities should focus on retrofitting old assets, implementing coordinated measurement technologies, and maintaining low-latency communication.

### 2. SCADA and Advanced Metering Infrastructure (AMI) Integration

Combining SCADA, AMI, and digital twins enables a two-way flow of data between working systems and digital models. The integration improves situational awareness owing to combined real-time operational and consumption data, which also allows dynamic simulations and contingency analysis. Utilities need to adopt standardised communication protocols, utilise real-time data sets, and incorporate consumer feedback, so that digital twins can respond to operational model decisions.

### 3. Interoperable Data Standards

Adherence to interoperable data standards like those provided by Common Information Model (CIM) and International Electrotechnical Commission (IEC) 61850 will be important in enabling the interconnection of heterogeneous grid elements within a single digital twin. Standardisation breaks down data silos and allows smooth inter-vendor and inter-system communication. To achieve scalability, consistency, and system-wide representation of digital twins, utilities should enforce compliance regarding new assets, create standardised asset registries, and adopt common data models.

### 4. High-Performance Analytics

To unlock the predictive power of digital twins, advanced analytics such as AI/ ML and hybrid physics-data models are needed. These tools can be used to perform short-term forecasting, detect anomalies, and optimise grid functions. For enhancing reliability, lowering operational costs, and encouraging proactive decision-making, utilities should invest in data platforms that are scalable, integrate machine learning algorithms, and allow scenario-based simulations.

### 5. Regulatory Frameworks and Data Policies

Favourable regulatory and data governance guidelines are essential to enables safe and scalable deployment of digital twins. A clear definition of data ownership (including sharing, privacy, and quality protocols) builds integrity and ensures adherence from all stakeholders. For this, policymakers should set standards, encourage investments in digitalisation, and develop models to enable cooperation between utilities, regulators, and third-party service providers.

### 6. Cybersecurity Compliance

Digital twin architectures need to have dynamic cybersecurity protocols in place to guard against the ever-changing nature of cyber threats. As digital twins increase the connectivity level significantly, more advanced security measures are required to safeguard the grid infrastructure. Encryption, authentication mechanisms, intrusion detection systems, zero-trust architecture, and continuous monitoring and resilience testing should be implemented to facilitate secure and reliable operations by the utilities.

### 7. Operational Responsibility

Clearly defined operational roles and governance structures are essential for effective digital-twin deployment. The activities associated with data management, model validation, and decision-making should be clearly delegated to foster responsibility. Further, to render digital-twin insights accurate, reliable, and actionable, utilities should create cross-functional teams, establish standard operating procedures, and have efficient governance structures in place.

### 8. Skilled Personnel

The effective implementation of digital twins requires a multidisciplinary team of specialists working in the fields of power systems, data analytics, AI, and cybersecurity. Utilities should conduct training programmes and forge cross-domain collaborations, as well as partnerships with academic institutions, to develop the required talent pool. Competent, well-trained staff is essential for creating, sustaining, and analysing digital twin models and ensuring that they can be successfully integrated into the grid work.

### 9. Organisational Preparedness

Organisational preparedness and efficient change management is key to successful digital-twin implementation. The use of digital technologies requires utilities to adjust their workflows, decision-making processes, and operating structures. Pilot projects, stakeholder involvement, and incremental implementation plans can be useful in demonstrating value and easing the shift to digital-twin-enabled operations.

### 10. Long-Term Digital Infrastructure Investment

A long-term commitment to digital infrastructure, such as cloud/edge computing, communication networks, and data platforms, is essential for the scalable deployment of a digital twin. Such infrastructure should be able to handle large amounts of data while performing real-time operations and accommodate power system scale-ups. Utilities should focus on developing and implementing long-term investment plans that take into account redundancy and boost power system resilience, and upgrade the infrastructure continually to meet the changing grid needs and adapt to new technologies.

## Conclusion

The digital-twin technology can transform power transmission planning by replacing traditional planning with intelligent, real-time, and predictive grid operation. While digital twins have proved their utility in India through pilot projects, adopting them it at a large scale requires measures like building a strong data infrastructure, adhering to interoperability standards, developing cybersecurity frameworks, and investing in professional human resources. This, in turn, calls for a strategic approach that involves accelerating policy support and establishing regulatory structures through the smart grid initiative.

Further, it is important to note that the international digital-twin transmission planning is currently monitored by the guidelines developed by the Institute of Electrical and Electronics Engineers (IEEE 3835-2025), the International Organization for Standardization (ISO), and International Electrotechnical Commission (IEC 30186) on interoperability, data models, cybersecurity, and lifecycle-based grid integration. Hence, for widespread deployment of digital twins, India needs to prepare to comply with these guidelines. The key enablers identified and described in this paper can aid India in doing this as well.

India's journey towards complete digital-twin functionality is already underway. Strengthening it further by implementing the key enabling measures can help India move from reactive grid-outage management to predictive grid control, making way for reliable, renewables-ready, and efficient transmission grids.

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