

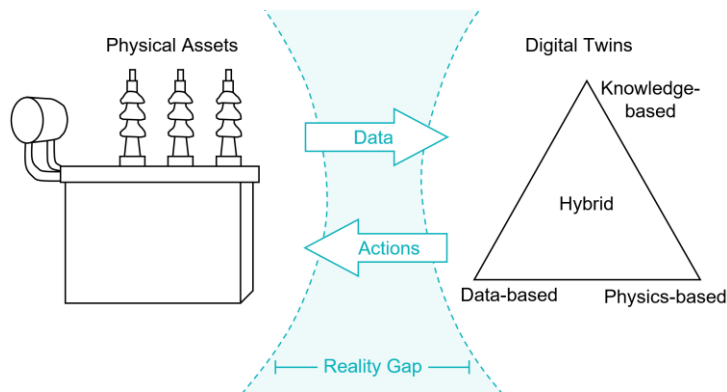
Digital twin technology to assist with asset management

Digital twin technology has emerged as one of the most significant developments in asset management and industrial digitalisation. By combining operational data, engineering knowledge, and analytical models, a digital twin enables organisations to assess asset condition, predict future behaviour, and support informed decision-making throughout an asset's lifecycle. CIGRE Joint Working Group (JWG) A2/D2.65 has developed a dedicated framework for transformer digital twins and guidance for their implementation across the industry. The JWG members were Adam Suleiman and Paul Grey.

A digital twin can be defined as a virtual representation of a physical asset that is continuously updated using data from its real-world counterpart. While digital twins have gained widespread attention in industries such as aerospace and advanced manufacturing, their adoption within the power sector has been comparatively slower. Given the critical role that power transformers play in the reliability and security of electrical networks, they present an ideal application for digital twin technologies.

The proposed framework describes a progressive maturity path for digital twin development. At its most basic level, a digital twin provides a real-time digital representation of the transformer and its operating environment. As capabilities mature, diagnostic functions can be introduced to detect abnormal conditions and support fault identification. More advanced implementations incorporate predictive capabilities that forecast future asset condition, failure risks, and remaining life. Beyond prediction, prescriptive digital twins evaluate alternative operating scenarios and recommend optimal actions, while the most advanced systems are capable of autonomous interaction with power system operations through closed-loop decision-making processes.

To understand current industry practice, a global survey involving 70 experts from utilities, manufacturers, research institutions, and service providers was conducted. The findings indicate that digital twin adoption has progressed beyond the early awareness stage but remains largely in the pilot and demonstration phase. While many organisations are exploring digital twin applications, large-scale operational deployment remains limited. Nevertheless, industry participants overwhelmingly recognise the strategic value of digital twins, particularly for condition monitoring, diagnostics, predictive maintenance, asset risk management, and lifecycle optimisation. The survey also identified several challenges that must be addressed to accelerate adoption, including data quality, interoperability between systems, cybersecurity concerns, and workforce capability development.



A fundamental requirement for any transformer digital twin is access to reliable and comprehensive data. Transformer information is typically distributed across numerous sources, including design and manufacturing records, factory and site test results, inspection reports, maintenance histories, online monitoring systems, operational performance data, and end-of-life assessments. Effective digital twins require these diverse datasets to be integrated within a unified digital architecture that enables seamless interaction between data, analytical models, and asset representations. Such integration forms the foundation for accurate monitoring, analysis, and decision support.

The analytical capability of a transformer digital twin depends heavily on its underlying models. Physics-based models remain essential because they describe the electromagnetic, thermal, dielectric, and mechanical processes governing transformer behaviour. Accurate representation of transformer condition cannot be achieved through isolated analysis of a single domain; instead, a comprehensive digital twin must integrate multiple physical phenomena to capture the complex interactions that occur during operation.

Recent advances in artificial intelligence and machine learning have further expanded digital twin capabilities. Data-driven methods can identify complex patterns within large datasets and support prediction tasks that are difficult to achieve using conventional approaches alone. However, their effectiveness is often constrained by limited data availability, inconsistencies in data quality, and a lack of physical interpretability. As a result, hybrid approaches that combine engineering knowledge with machine learning techniques are increasingly considered the most promising solution. Methods such as grey-box modelling and physics-informed neural networks offer the potential to improve both prediction accuracy and explainability.

Reliability is another critical consideration. A transformer digital twin must consistently deliver timely and accurate outputs while minimising the gap between predicted and actual asset behaviour. Achieving this requires rigorous verification and validation processes, clear definition of operating boundaries, continuous model updating, uncertainty quantification, and transparent communication of confidence levels. These practices enable asset managers to make risk-informed decisions with greater confidence.

Looking ahead, successful implementation of transformer digital twins will depend on more than advanced analytics alone. Organisations must invest in high-quality data, adopt open standards to enhance interoperability, and establish robust governance and cybersecurity frameworks. Flexible architectures that accommodate future technology developments are equally important. Most importantly, digital twin initiatives should focus on high-value use cases that deliver measurable operational and business benefits. By combining strong data foundations, multi-physics modelling,



artificial intelligence, and effective governance, transformer digital twins have the potential to transform asset management and support a more reliable, efficient, and resilient power system.