NAME: Patrick PICHER
COUNTRY: Canada
REGISTRATION No.: 5441

GROUP REF.: D1
PREF. SUBJECT: 3
QUESTION No.: 3.1

The transformer is the most strategic asset in power-system substations and, for this reason, it has been the focus of many developments in the areas of digitalization, analytics, intelligent condition monitoring, condition assessment indices, physics-based modelling, and machine learning, among others.

To answer the present question, especially regarding which models for performance could be suited for development into digital twins, the meaning of digital twins must first be defined.

A new CIGRE working group (JWG A2/D2.65) was created in 2022 to study transformer digital twins, and one of its aims is to develop a definition thereof. The concept is illustrated in Figure 1.

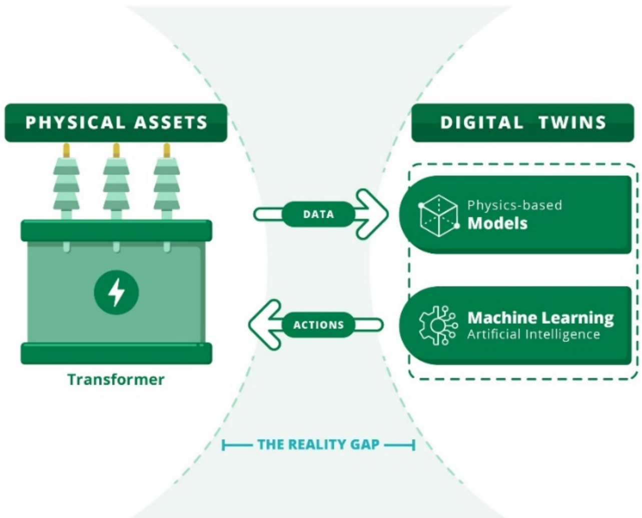

Figure 1: The concept of a transformer digital twin, from JWG A2/D2.65 ToR.

For this contribution, the following definition from the author's utility and adapted from [1] is proposed:

"A scalable **virtual replica of a physical asset** that, through **automatically updated data** and **simulation tools**, can continuously monitor and predict the **condition and behaviour** of its real-life counterpart, with the goal of optimizing the latter's performance."

- **Virtual replica of a physical asset:** Models that represent the functional behaviour of the asset or system in its operational context, synchronized at a specified frequency and fidelity.
- **Automatically updated data:** It could be data from dedicated monitoring sensors, SCADA data, or any other data from inspections and maintenance actions.
- **Simulation tools:** Includes any transformer analytics (physics-based, data-driven or hybrid) that can be used to convert raw data into actionable information.
- **Condition and behaviour:** The state of degradation and the way the transformer functions in the context of the power-system operation.

For power transformers, the following models (not an exhaustive list) could be applicable for digital twin developments:

- **Thermal model:** A model that can predict the internal temperature of the transformer to determine the dynamic loadability. The model can be based on loading guide equations (from IEC 60076-7 or IEEE C57.91), physics-based thermal-hydraulic network models, reduced-order models from CFD calculations, or even physics-informed machine learning models. Other models can represent **dielectric** and **mechanical** behaviour.

- **Paper-ageing model:** The ageing of the paper is estimated considering the temperature (thermal degradation), the water content of the paper (hydrolysis) and the type of oil-preservation system (oxidation). One of the objectives of CIGRE WG D1.76, created in 2021, is to review these paper-ageing algorithms and propose improvements.
- **Moisture-migration model:** The presence of water in solid and liquid transformer insulation plays a critical role in transformer life. Water presence is monitored because it causes accelerated ageing of solid insulation and increases the risks of electrical partial discharges and gas bubble formation (bubbling) during emergency overloading. The model tracks the water migration from the paper to the oil or vice versa depending on the temperature.
- **Bubbling model:** When the transformer winding conductor reaches a temperature at which gas bubbles start to evolve (the bubble inception temperature, or BIT), the probability of dielectric failure sharply increases. The BIT depends, among other things, on the water content of the paper and the total pressure the bubble must overcome to evolve. Ageing of oil and paper also has an impact on the BIT.
- **Anomaly-detection, diagnostic and prognostic models:** Anomaly-detection models include many transformer analytics used to interpret sensors and SCADA data: gas-in-oil monitoring, bushing insulation monitoring and tap-changer vibroacoustic monitoring, for example. Using a detailed fault tree representation including duration between degradation conditions, diagnostic models can recognize the problem (degradation state) and prognostic models can predict how things will evolve in the future.

As stated in [1], digital twins are motivated by outcomes, tailored to use cases, powered by integration, built on data, guided by domain knowledge, and implemented in IT/OT systems. The following is a story that touches on possible future use-case scenarios for the transformer digital twin, in relation to the given performance models, to help understand the business value of such technology.

"Following the failure of an electrical asset in a substation, the twin informs the operator of the possible load that can be applied for short-term and long-term emergency loading, conserving a safe bubbling margin, and quantifying the impact of paper ageing on the loss of life of the transformer's insulation. The twin considers the overall state of the transformer to make its assessment, that is, the state of the active part and of components such as the cooling system, bushings and tap changer. It also interacts with other assets in the substation to provide the operator a clear view of the power-transfer capabilities. To assess the cooling system's performance, the twin adapts its thermal-model parameters by comparing its temperature predictions with measured load and temperatures. To assess the active part's state, the twin uses DGA and other oil tests from periodic and continuous monitoring, and if there is a correlation between gas-in-oil, ageing tracers and the load, the twin adapts its dynamic-loadability recommendations. To assess the reliability of its predictions, the digital twin compares them with selected measured values on its physical counterpart and with measurements and predictions from other transformers and twins in the power system. For instance, a twin uses the vibro-acoustic measurement on the tap changer to assess its condition and compares against data from sister units in the same substation to detect any significant deviations. For bushing-condition assessment, the twin uses phasor measurements from the bushing tap and compares the values with bushings connected in parallel, with instrument transformers, with bushings on separate phases or with bushings on the other voltage levels. The twin links bushing-insulation monitoring with temperature to check if there is any significant correlation of concern. Following a short circuit, the twin assesses the mechanical stress and makes a mechanical-condition assessment by comparing the off-line frequency response measurement with its high-frequency model. Lastly, the twin condition-assessment module reports to the higher-level asset-management system to optimize capital and operational expenditures."

[1] "Definition of a Digital Twin," *Digital Twin Consortium*. https://www.digitaltwinconsortium.org/initiatives/the-definition-of-a-digital-twin/