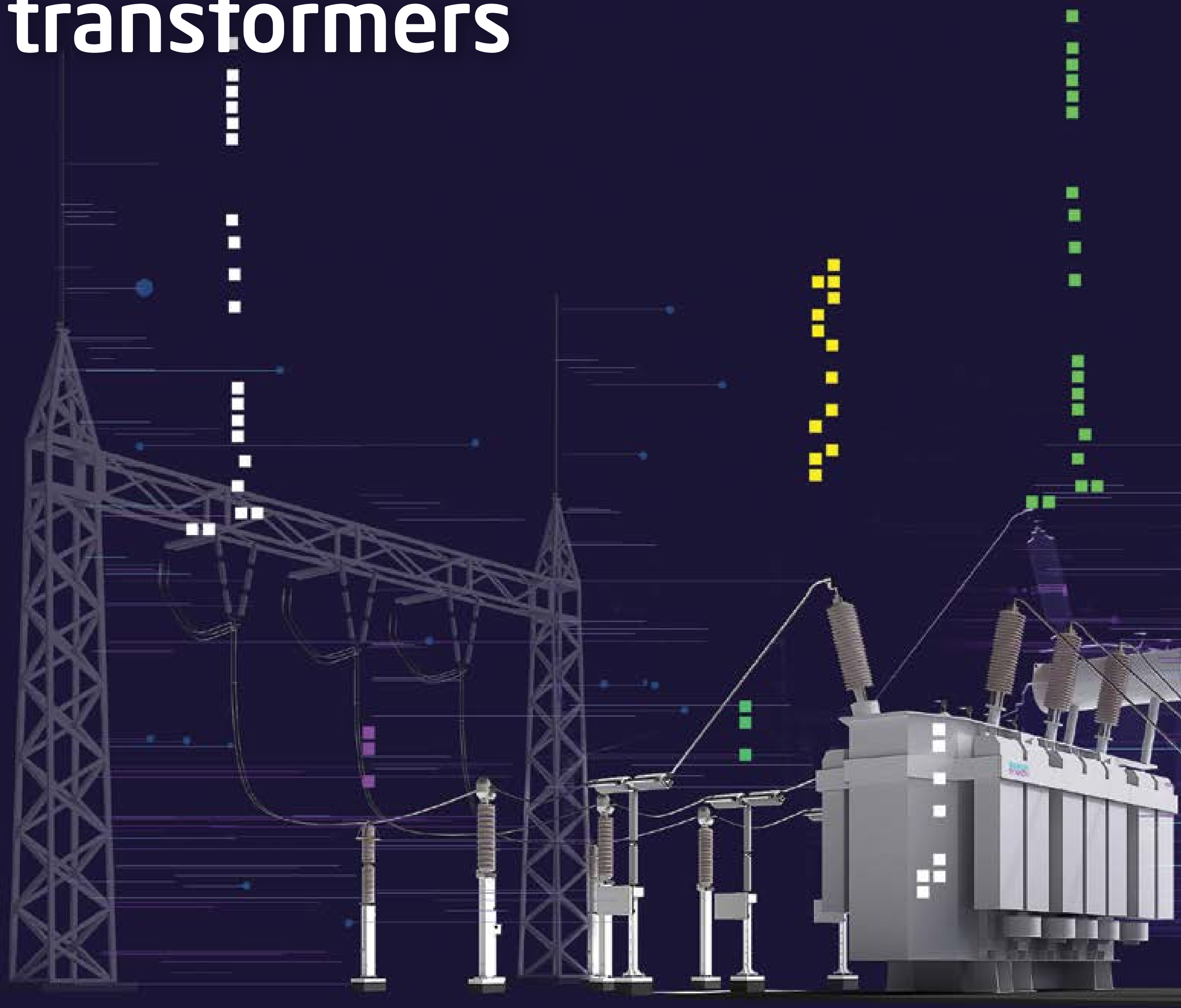
Sensformer: Powering the future with digitalized transformers



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The traditional transformer, which has been a cornerstone of the power grid for over a century, is being transformed into a digitalized version that can provide operators with real-time data on its operation and health

ABSTRACT

Transformer digitalization is a critical aspect of the development of a smart grid. Siemens Energy has developed a digital transformer solution called Sensformer, which integrates various sensors, communication interfaces, and data analytics capabilities into the transformer to enable advanced monitoring, diagnostics, and prediction capabilities. This article presents an overview of the Sensformer and its key features. It describes the installation and commissioning process of the Sensformer and the benefits of the technology in terms of improved reliability, efficiency, and safety of power systems. A case study is presented to demonstrate the features of the Sensformer in real-world applications, such as detecting hot spots in transformer windings, predicting transformer ageing, performing DGA and optimizing transformer loading based on real-time condition monitoring. The results show that the Sensformer can significantly enhance the performance and value of transformers and provide a reliable and cost-effective solution for grid digitalization..

KEYWORDS:

Sensformer; digital twin; IoT-cloud; relative aging; digitalization.

Sensformer is a digital product introduced by Siemens Energy in 2018 which provides real-time information about the performance and health status of transformers

Introduction

The rapid development of digitalization technologies has opened new possibilities for the power industry to optimize their operations and improve the efficiency of their power grids. The traditional transformer, which has been a cornerstone of the power grid for over a century, is being transformed into a digitalized version that can provide operators with real-time data on its operation and health. Transformers are a critical component of electrical power systems, and their performance directly impacts the reliability and efficiency of electricity transmission and distribution. Traditional conditioning monitoring systems have been used for years to evaluate the health and performance of transformers. However, with recent advances in digitalization, the development of digitally enabled transformers has become essential to address current and future challenges facing the power industry. These challenges include improving performance, health and safety, reducing costs and risks, and meeting environmental goals. Digitalization offers advantages such as reduced downtime, increased flexibility, cost savings, and improved environmental protection. This paper will focus on the digitalization of transformers, exploring the features and benefits of digital transformers, such as active overload management, temperature monitoring, and aging prediction. Overall, this paper aims to demonstrate how the digitalization of transformers can improve the efficiency, reliability, and sustainability of the power grid, providing a foundation for a fully digital grid.

Sensformer

Sensformer is a digital product introduced by Siemens Energy in 2018 which provides real-time information about the performance and health status of transformers. The product consists of an IoT gateway, cloud, and digital twin modelling of the transformer, which enables remote monitoring and management of the transformer's health status. The Sensformer solution is available for the complete power transformer portfolio, including Auto-, Net-Transformer, phase shifters, reactors, and HVDC transformers. One of the key features of Sensformer is its ability to provide real-time data on the transformer's performance and health status through a web-based user interface and mobile apps. This data can help utilities and other users optimize the performance of their transformer assets, identify potential problems before they become critical, and reduce downtime and maintenance costs. Another important feature of Sensformer is its digital twin modelling capability. A digital twin is a virtual replica of a physical asset. By creating a digital twin of the transformer, users can simulate and analyze its behaviour under various conditions in order to optimize its performance, identify potential problems, and develop predictive maintenance strategies. Some of the benefits of using Sensformer include improved reliability and availability of transformer assets, reduced maintenance costs, and increased efficiency in transformer operations. Additionally, Sensformer can help utilities make data-driven decisions about maintenance, repairs, and replacement. Siemens Energy extends the Sensformer solution to encompass non-Siemens transformers as well. This enables users to upgrade their existing transformer assets with the digital monitoring and modelling capabili-

Figure 1. IoT Box

ties of Sensformer, providing them with the same benefits as new installations.

Sensformer consists of the IoT gateway box shown in Figure 1. Real-time data communication is facilitated by its interaction with the transformer and the cloud. Figure 2 shows data flow from the transformer to the cloud via the IoT device and from the cloud to a mobile device/web UI. The IoT gateway that is installed into the control cabinet of the transformer measures the physical signals coming from the transformer. These signals include load, winding temperature, top oil temperature, cooler temperature, ambient temperature and the measurement of gases. The IoT device has the functionality of connecting the cloud through a GSM/LAN network. Therefore, all values obtained from the transformer are sent to the cloud platform for data analysis. Along with Sensformer, Siemens Energy has a broad range of Sensproducts family intended for grid digitalization.

The Sensformer solution complies with the industry-leading cybersecurity requirements and uses state-of-the-art security and encryption technologies, including ISO/IEC 27001. End-to-end encryption is employed for data transmission to cloud storage, with each Sensformer having a unique ID used for encryption. HTTPS with 256-bit TSL encryption is used for transmission. To ensure strict separation and security of data from different customers in the cloud, Sensformer adheres to the best-in-class data handling and management guidelines. After the digital twin model of the transformer is built on the cloud platform, detailed information about the transformer can be accessed via a mobile device/web UI. Real-time temperature monitoring of oil and winding is displayed on the digital screen, with the digital twin providing real-time loss of life calculation and active overload prediction, as well as warning users when the temperature exceeds defined limits.

Sensformer features

1) Mixed reality view – The operator can interact with the web-based UI to verify physical signal values coming directly from the transformer. The digital twin of the transformer provides additional calculated signals called 'virtual sensors,' which can be treated as real sensors. These virtual sensors save money and time while enabling more insights into the transformer's inner life and condition. This includes extended temperature information with advanced 3D visualization, selectable signals of different values and components, as well as a virtual sensor notifier. This notifier can be parametrized to inform the operator about the status of the transformer anywhere and anytime.

2) Active overload prediction – Active overload prediction is based on real-time thermal modelling of the transformer, obtained using the historical operational data of the transformer. With the help of the digital twin, the real-time thermal image of the transformer can be simulated at any time during operation and stored in order to have a sound base for load prediction. Different load scenarios can be simulated before loading the transformer, so the level and duration of the overloading that the transformer can withstand is known to the operator at any time. The operating parameters are adjustable according to the operator's requirements,

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Some of the main features of Sensformer include Mixed reality view, Active overload prediction, Load Simulation, Lifetime prediction and DGA and Multigas Sensor Integration

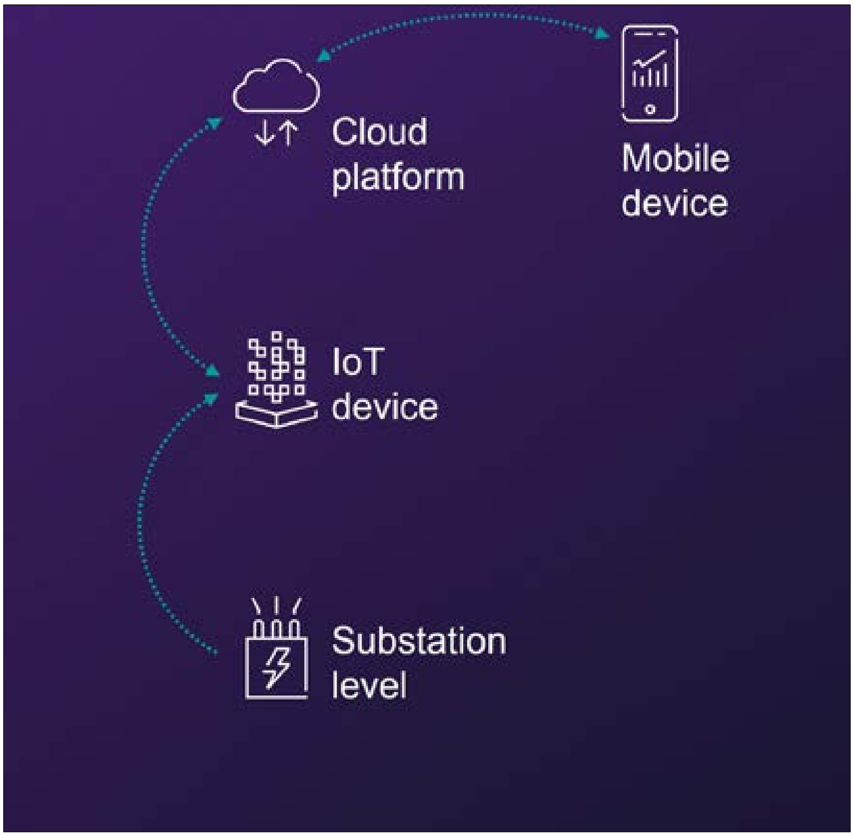

Figure 2. Sensformer data flow

> A digital twin is a computer-based model that replicates a connected transformer using design data and operational information

and overload prediction is possible up to 3/24 hours into the future. Thus, transmission capacity can be increased based on a very accurate forecast. At the same time, operating flexibility is maximized to match the operator's business needs.

3) Load Simulation – With a calibrated digital twin model, it is possible to evaluate the load cycle simulation for the following 24 hours based on the load profile and ambient temperature. This provides advanced information regarding the operating condition of the transformer, including the top oil temperature and winding hot spot. Different load scenarios, along with ambient temperature, can be simulated on the cloud platform in a short time.

4) Lifetime prediction – The Sensformer application allows operators to monitor the aging of insulation paper in transformers by analyzing load and other operational parameters of the transformer. By retrospectively evaluating the transformer's operating mode, it is possible to calculate the actual lifetime losses over a predefined period and generate both absolute and relative lifetime loss forecasts. In accordance with IEC loading guidelines, the system also supports continuous lifetime evaluation over a longer period. To accurately predict load, flexible parameterization for aging is necessary. By predicting the transformer's lifetime based on insulation aging estimation, operators can assess the age profile of their transformers at any given time, enabling them to plan for future capital expenditures with greater accuracy.

5) DGA and Multigas Sensor Integration – The integration of H2 guard and Multigas (Multisense5 and Multisense9) sensors with the Sensformer application is possible. This enables a detailed analysis of the concentration of gases present in transformer oil, along with trend analysis. If the specified limits for any particular gas are exceeded, the operator is alerted. Online DGA monitoring allows for continuous tracking of transformer health and provides in-depth information about the condition of transformer oil. The system can also detect faults using techniques such as Rogers Ratio and Duval Triangle based on standards. Furthermore, with the requisite sensor inputs from DGA, relative aging calculations are more precise due to the moisture modelling phenomena.

Sensformer benefits

1. Real-time information of operational parameters of the transformer is available anywhere and anytime.
2. Early warnings and push notifications on mobile devices to alert operators about critical situations (e.g., oil loss, excessive temperature, etc.)
3. Performance optimization is achievable by monitoring the different parameters of the transformer.
4. Sensformer data can be used to cut maintenance costs by reducing man-hours and preventing unscheduled outages.
5. Customers have 24/7 access to Sensformer applications and can use the information provided to cut operating expenses.
6. Historical data download is possible, and it can be used to understand transformer behaviour in detail.
7. Active overload prediction and insulation aging support the lifetime planning of transformers, which is beneficial for long-term grid modernization.

Digital twin

A digital twin is a computer-based model that replicates a connected transformer using design data and operational information. This virtual replica can be created

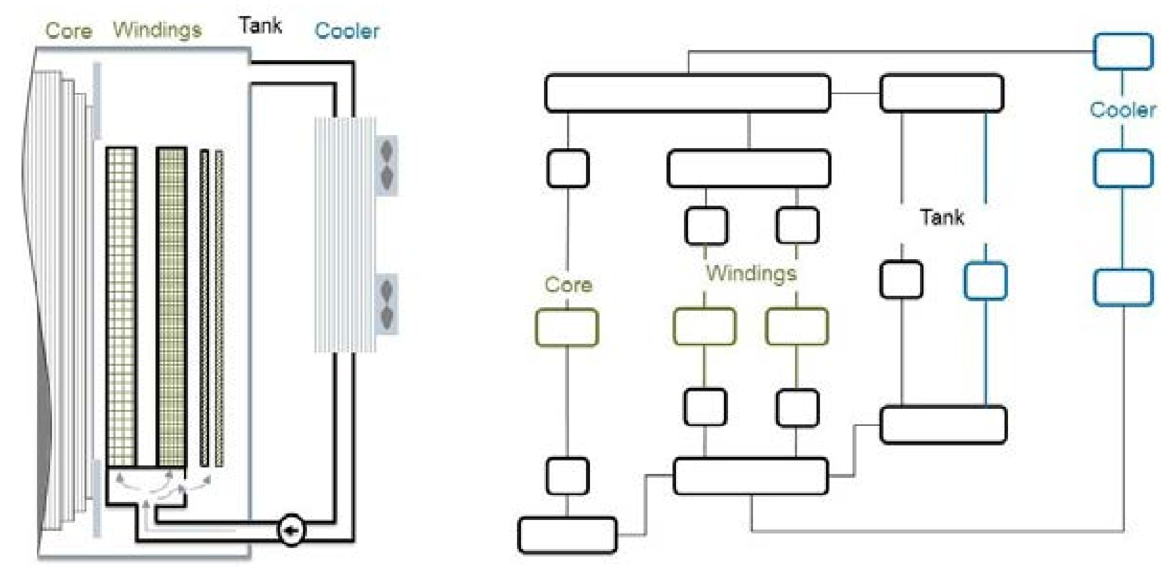

Figure 3. Heat sources of a transformer to build a thermo-hydraulic model, including the oil flow

in real-time, using current data input, or in advance, based on simulated operating scenarios. The digital twin provides a detailed and accurate representation of the transformer, allowing engineers and operators to monitor and optimize its performance, predict potential issues, and simulate future operating conditions. In cases where detailed design data is not available, modelling is done based on IEC/IEEE standards. By using a digital twin, utilities or operators can improve asset reliability, reduce downtime, and enhance overall operational efficiency.

By inputting various operational data for the following 24 hours, customers can simulate a load cycle and gain a deeper understanding of their transformer's future behaviour

The thermo-hydraulic model presented in Figure 3 is a powerful tool for computing the temperature behaviour of the transformer. It takes a variety of factors into account, including the transformer ratio and tap position, and distinguishes between different types of losses, such as ohmic and eddy losses, which have distinct temperature dependencies. One unique feature of this model is its ability to incorporate real material characteristics, such as the masses and heat capacities of conductive and insulating materials, to accurately predict the dynamic temperature behaviour that occurs during operation. In addition, the model accounts for the hydraulic resistances of various transformer components such as the core, windings, and radiators. It calculates oil flow based on buoyancy forces and, optionally, additional pump pressures if pumps are present. With this level of detail and accuracy, the thermo-hydraulic model enables engineers to model the exact digital twin of the connected transformer.

Consequently, and contrary to more simplified models, the Siemens Energy digital twin does not rely on fixed thermal time constants. Instead, it can account for the relevant dynamic heat transfer mechanisms in the transformer. Using this thermo-hydraulic approach, the heat transfer equations take into account the relevant physical quantities such as oil temperature, oil flow, losses, etc. Considering the oil flow distribution and heat transfer mechanisms results in a thermal transformer model covering different cooling modes and the transient behaviour between these modes, like ODAF to ONAF or ONAN. The result is a precise temperature calculation. Moreover, due to the multi-mass approach linked to the oil flow, it is possible to integrate the model with other important physical transformer models, such as those for moisture calculation.

Currently, the digital twin model in Sensformer can be used for three scenarios. Firstly, it can simulate load and ambient temperature cycles for a period of 24 hours in the future. Secondly, the model can determine permissible overload with specified boundary conditions. This feature enables the transformer to be operated more efficiently and optimally without the risk of damage or failure. Finally, the digital twin model can automatically calculate the relative aging of the transformer, which is crucial in predicting its remaining lifespan and scheduling maintenance activities.

The Sensformer Advanced offers customers valuable insights into the condition of their transformers. By inputting various operational data for the following 24 hours, customers can simulate a load cycle and gain a deeper understanding of their transformer's future behaviour. The thermo-hydraulic model then predicts temperature behaviour for the transformer, such as top oil temperature and winding hotspots over 24 hours, starting with the current thermal condition of the transformer. Customers can also determine the maximum permissible overload capacity for the transformer over the following 3 hours, considering different boundary conditions such as temperature limits and aging values. Additionally, the Sensformer Advanced can automatically calculate the relative insulation aging of a transformer based on the IEC loading guide formulas. It also considers the moisture present in the oil for loss-of-life calculation. This loss of insulation life is calculated based on data from the previous 24 hours, the previous 30 days, and since the Sensformer application was commissioned. This provides customers with a real-time assessment of the transformer's lifetime and the ability to compare the thermal load of multiple transformers.

Customized design modelling

Each transformer has its unique design, which includes factors such as oil-natural or oil-directed cooling, the number of windings, coolers, fans, and other specifications. To accurately predict the transformer's behaviour, a digital twin model is created, which is tailored to the transformer's specific design. The digital twin model is parameterized with design information such as oil volume, heat capacities, insulation thicknesses, ohmic resistances, hydraulic resistances, dimensions, materials, thermal data, fan and pump characteristics, and many other factors. By utilizing real-world data, the thermohydraulic calculation of the digital twin model can predict the transformer's overload capacity, aging, and service requirements with a high degree of accuracy. This level of accuracy is crucial for ensuring the safe and reliable operation of transformers in the power system.

The main difference between simplified standard thermal models and the Siemens Energy digital twin is the multi-mass approach. Simple models often consider only the thermal behaviour of a single winding for a specific tap position and specific cooling mode. It is only possible to simulate the hotspot temperature for load and ambient changes for this

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winding. However, this is clearly less accurate and not sufficient in terms of real thermal stress within a transformer, as the position of the highest temperature can vary from one winding to another when a transformer is operated at a different tap position.

In contrast, the Siemens Energy digital twin covers all windings and the possible cooling modes of the transformer. Depending on the tap position, the loss distribution occurring in the windings is calculated, and consequently, the hotspot in the transformer can be continuously calculated. The Siemens Energy digital twin is based on a multi-mass model, which also includes the oil flow. Only these models will really constitute a complete digital twin of a transformer, which will allow a very deep insight into the transformer.

Temperature behaviour is a crucial aspect of digital twin technology, as it provides valuable insights into the accuracy of the calculation model used. Figure 4 illustrates a comparison of measured and calculated values of top oil temperature over a certain period of time for an oil-natural-cooled medium power transformer. The results show that the digital twin provides the most accurate correlation between the measured and calculated temperature values. In contrast, the conventional IEC standard model produces higher deviations, leading to less accurate estimated conditions. This highlights the importance of using a comprehensive multi-mass approach such as the one used in the Siemens Energy digital twin, which considers all windings and possible cooling modes. By accurately predicting temperature behaviour, the digital twin can provide valuable information for monitoring and optimizing the transformer's performance, leading to improved reliability and efficiency.

Successful installation of Sensformer Advanced in India

As part of our initiative to drive digitalization activities for transformers in India, we have successfully commissioned the Sensformer Advanced solution on a transformer within our premises. This retrofit solution is installed on an existing transformer with a capacity of 25 MVA, 220/22 kV. This pilot project has demonstrated the capabilities of this technology and its potential benefits, providing us with first-hand experience in refining our processes and developing best practices for our customers.

Figure 5 shows the actual site picture of the transformer and the commissioning of Sensformer. All the sensors on the transformer are connected to the IoT box and transmit the data of various operational parameters in real-time to the cloud platform for analysis. Figure 6 shows real-time data of the transformer on the platform and data analytics for decision-making. Figure 6 (a) shows the fleet management and status of all the transformers in the fleet and their running condition. Figure 6 (b) shows the loading of the transformer and critical operating parameters. Figure 6 (c) shows the real-time data for each of the sensors which are connected to the IoT box. Figure 6 (d) shows the transformer's behaviour in real-time and the virtual sensor calculation for detailed insights into the transformer behaviour. Multisense 9 is integrated with the Sensformer application to check the condition

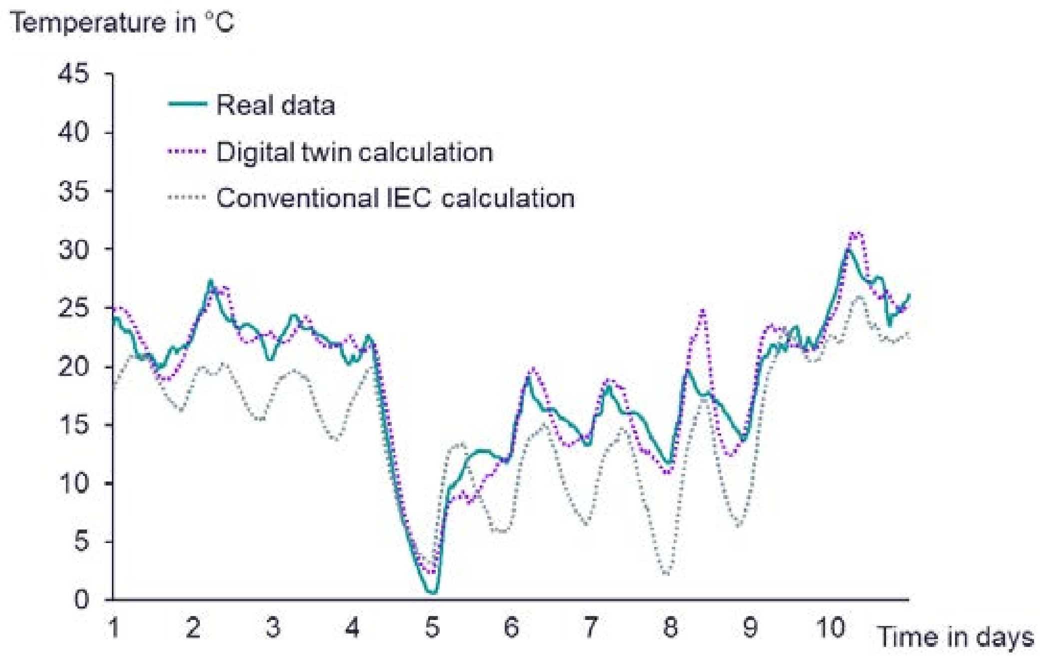

Figure 4. Comparison of different calculation methods for transformer top oil temperature

of the transformer oil, the concentration of different gases and their trend analysis. The platform employs advanced analytics and machine learning algorithms to process the data, providing insights into the transformer's health and condition. This enables predictive maintenance, reducing downtime and repair costs and ultimately extending the transformer's lifespan. Online monitoring eliminates the need for physical inspections and minimizes the risk of human error.

The successful implementation of this pilot project highlights Siemens' commitment to digital transformation and paves the way for the adoption of digitalization in the power sector in India. This installation is used as a demo platform for our potential global customers to showcase the capabilities and features of the Sensformer application. This solution is an IoT-based digital tool that allows for transformer health monitoring and transformer fleet management, optimizing transformer utilization in real-time. With this solution, Siemens aims to drive innovation in the power sector, delivering sustainable and reliable energy solutions to its customers.

Conclusion

The Sensformer system offered by Siemens Energy is a digital solution for transformer online monitoring to access critical information about the status and performance of transformers. It provides customers with real-time access to critical data on their transformers, including loadings, aging forecasts, temperatures, and dissolved gas concentrations. This system enables early fault detection with automated alarms and provides maximum transparency regarding the actual condition of the transformer. The digital twin intelligence also allows for virtual simulation of the transformers' operating parameters under different load conditions.

By providing real-time data on transformer performance, the Sensformer system enables customers to take proactive measures to minimize risks, optimize transformer operation, reduce OPEX costs, and enhance transformer lifetime planning, thus improving the reliability and efficiency of power grids.

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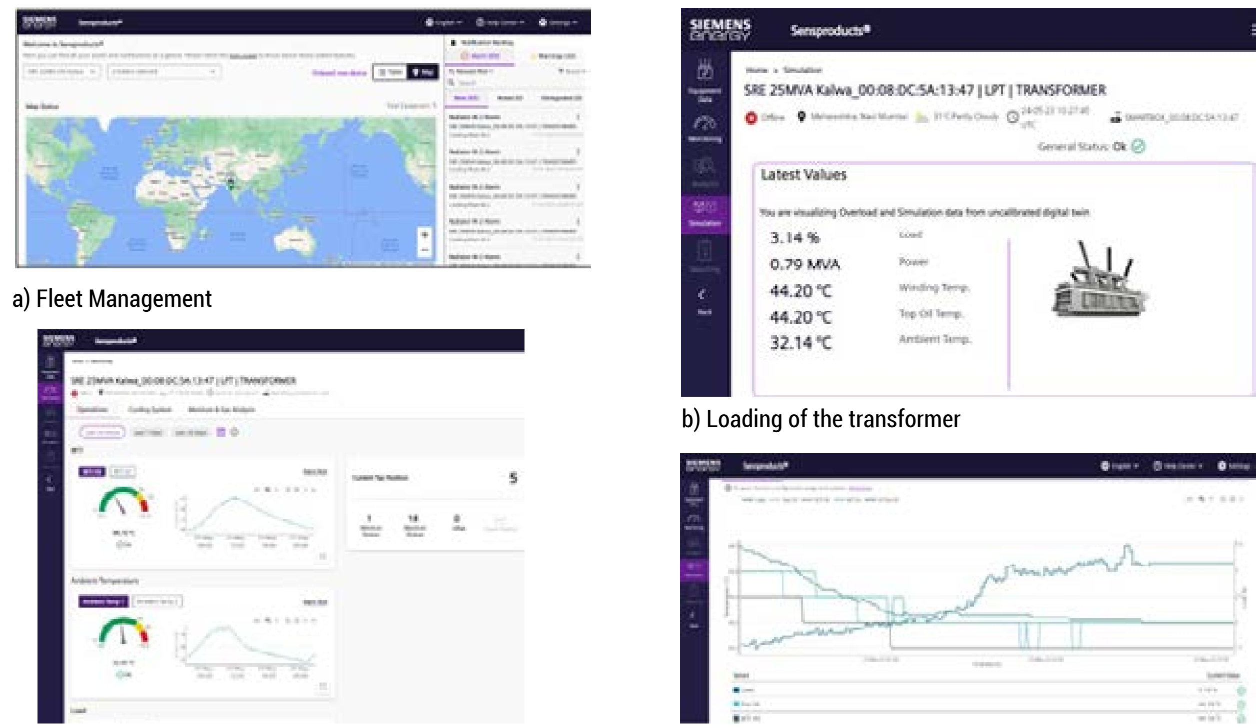
Figure 5. Site picture during Sensformer commissioning



a) Fleet Management

b) Loading of the transformer

c) Operational parameters of the transformers

d) Real-time data analysis

Figure 6. Sensformer Advance Platform showing Live Parameters

The Sensformer system offered by Siemens Energy is a digital solution for transformer online monitoring to access critical information about the status and performance of transformers

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Manan Pandya has 20 years of diverse experience in large power transformer manufacturing, design, R&D and Innovation at ABB and Siemens. He has expertise in transformer mechanical design, electrostatics, and electromagnetics field simulation. He was awarded the "Innovator of the Year 2017" award at Siemens India and holds 3 international patent applications. He established the Transformer Competence Centre at Siemens India for supporting engineering and R&D of Global Siemens transformer sites. Currently, he is working at Siemens Energy Transformers, Nuremberg, Germany, as an operational excellence manager.

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