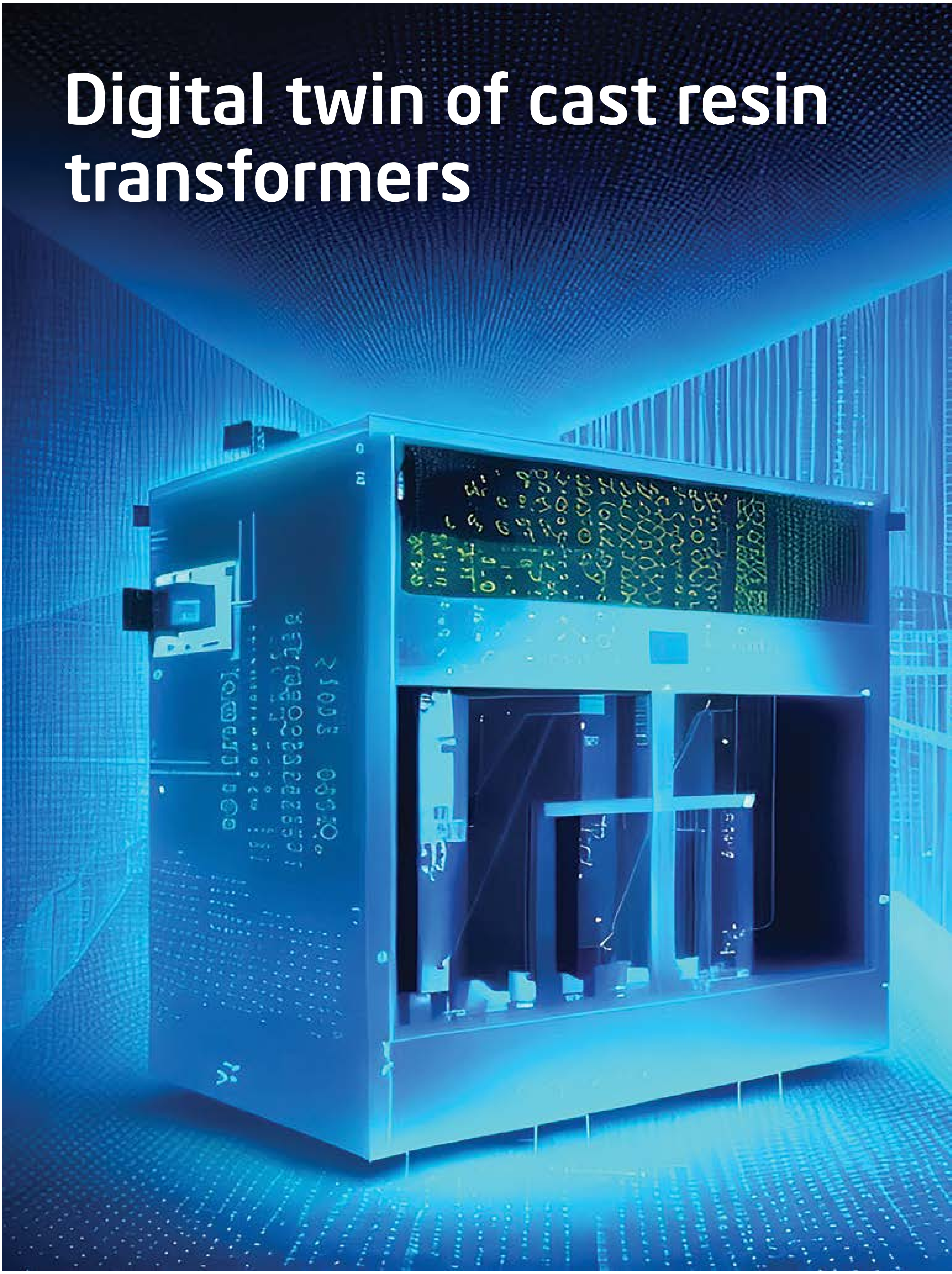
Digital twin of cast resin transformers



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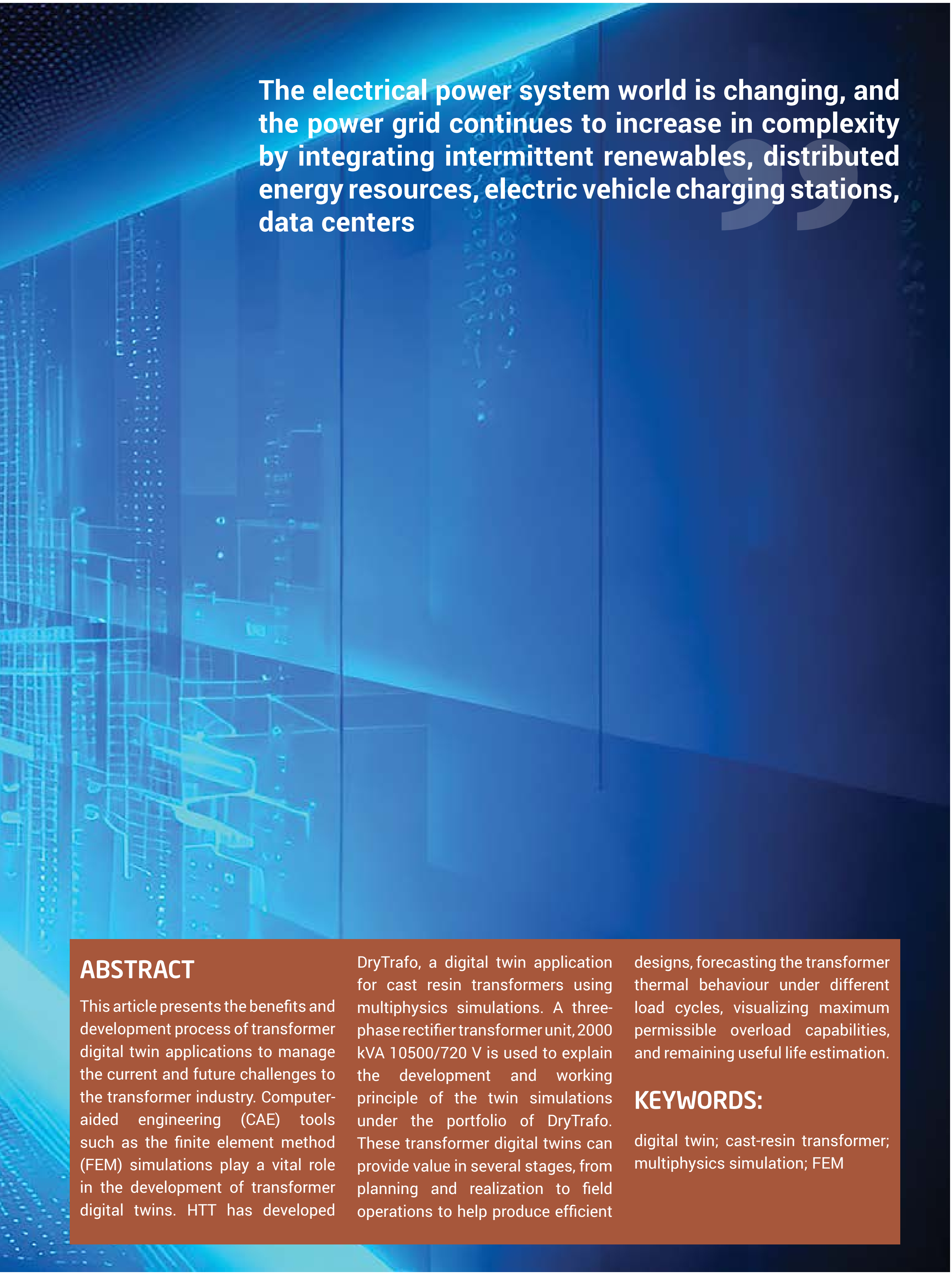

The electrical power system world is changing, and the power grid continues to increase in complexity by integrating intermittent renewables, distributed energy resources, electric vehicle charging stations, data centers

ABSTRACT

This article presents the benefits and development process of transformer digital twin applications to manage the current and future challenges to the transformer industry. Computer-aided engineering (CAE) tools such as the finite element method (FEM) simulations play a vital role in the development of transformer digital twins. HTT has developed DryTrafo, a digital twin application for cast resin transformers using multiphysics simulations. A three-phase rectifier transformer unit, 2000 kVA 10500/720 V is used to explain the development and working principle of the twin simulations under the portfolio of DryTrafo. These transformer digital twins can provide value in several stages, from planning and realization to field operations to help produce efficient designs, forecasting the transformer thermal behaviour under different load cycles, visualizing maximum permissible overload capabilities, and remaining useful life estimation.

KEYWORDS:

digital twin; cast-resin transformer; multiphysics simulation; FEM

A digital twin is a virtual replica of each physical transformer unit developed from the transformer design data

1. Introduction

In the past, grid conditions were quite stable, and transformers were therefore considered to operate under stable conditions in a centralized power grid. Due to stable load conditions, many transformers had a long lifetime. However, at present, the world is changing, and the power grid continues to increase in complexity by integrating intermittent renewables, distributed energy resources, electric vehicle charging stations, data centers, etc. All these factors result in more dynamic loading of transformers. Irrespective of the changing generation and demand trends, transformers are expected to last for 30-40 years. According to ABB, effective monitoring of a transformer can reduce repair costs by 75%, catastrophic failure by 50%, and lost revenue by 60%, while the annual saving of 2% of the price of a new transformer can be achieved with proper monitoring of the transformer [1]. However, manufacturers and asset owners feel the pressure to ensure competitiveness and effective allocation of capital and operational expenditures. Therefore, better insights are needed in order to ensure sound decisions on transformer design optimization, maintenance, repair, or new investment.

These challenges can be addressed by implementing smart and digital technologies, such as a transformer digital twin. In recent years, few transformer manufacturers have made efforts in power asset digitalization and asset digital twin developments, such as the Siemens Senseformer and the ABB Ability [1, 2]. These development activities in transformer digitalization support and remove uncertainty during design and configuration while supporting applications and ensuring availability and reliability through condition monitoring and advanced services.

2. What is a "transformer digital twin"?

A digital twin is a virtual replica of each physical transformer unit developed from the transformer design data. This replication is based on the design and operational data like winding current and voltages, type of insulation and cooling systems, ambient conditions, etc. Digital twins provide value in several stages, from planning and realization to field operations to help produce efficient designs, forecasting the transformer thermal behaviour under different load cycles, visualizing maximum permissible overload capabilities, as well as remaining useful life estimation, as depicted in Figure 1.

Computer-aided engineering (CAE) tools such as the finite element method (FEM) simulations play a vital role in the development of transformer digital twins as they shorten analysis and design cycles and assure optimized results by allowing a greater number of scenarios to be investigated. This reduces the time to market and overall cost. Moreover, these twin simulations help optimize transformer operations by simulating and forecasting transformer behaviour under various operating conditions. This provides improved operational reliability and productivity.

Hochspannungstechnik & Transformatorbau (HTT) makes extensive use of simulations in product development. Simulations cover a wide range of fields, including electromagnetics, thermodynamics, mechanics, fluid dynamics, and material science. Increasingly, simulations

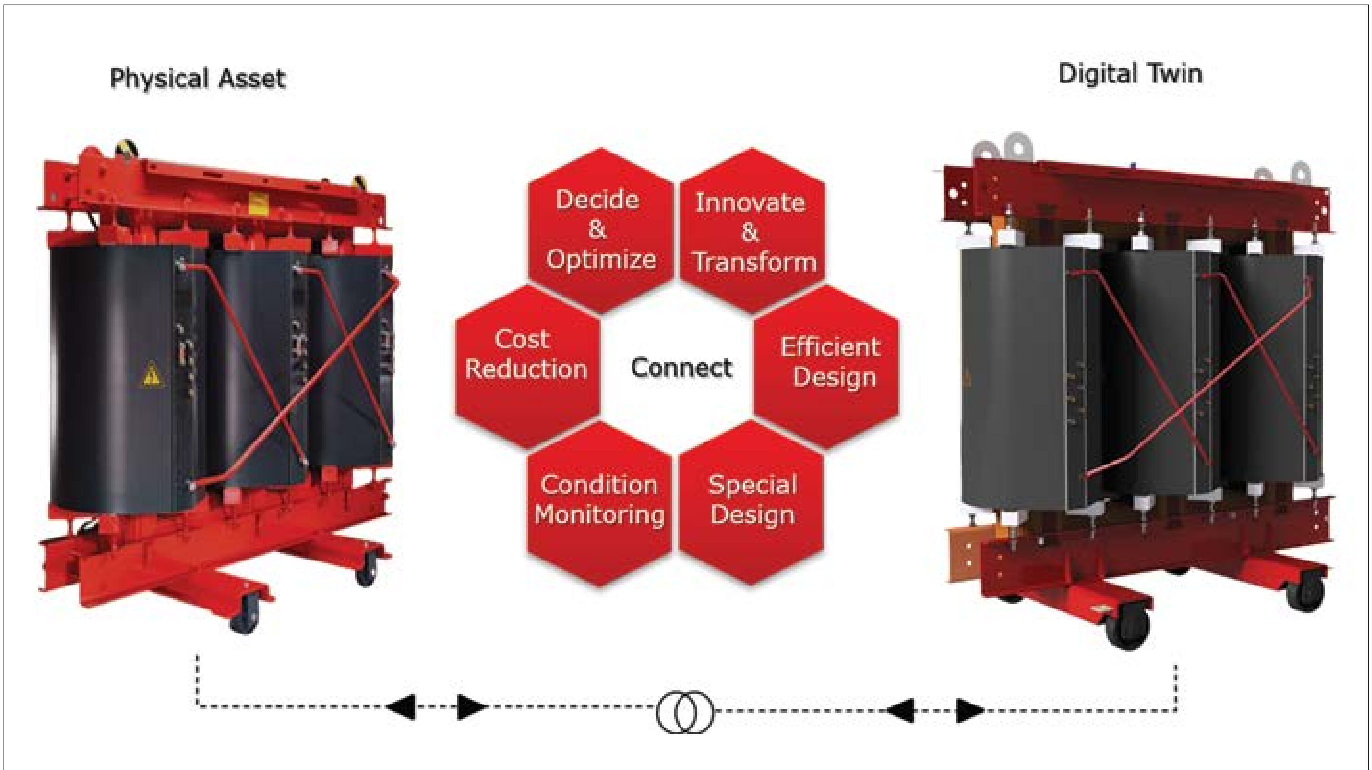

Figure 1. Transformer Digital Twin concept

also combine several of these domains and capture not only the sum of their effects but also the coupling and interactions between them in what is called multiphysics simulations. In 2022, HTT initiated a DryTrafo transformer digital twin project for cast resin transformers using multiphysics simulations [3]. Since then, various twin simulation applications have joined the portfolio, for example, electromagnetic simulations, power loss calculation, thermal analysis, hotspot temperature monitoring, etc. These tools provide more scope to be innovative, the possibility of testing a far greater number of variants and their combinations, experimenting with unorthodox approaches, enhancing the ability to make key decisions rapidly, and, of course, engaging customers with the specific designing and optimization of transformer operations during field utilization. This article looks at how a team of engineers at HTT develops multiphysics twin simulations and custom-built applications to develop transformer digital twins for their cast resin transformers.

3. Development of transformer digital twin

Several parameters must be considered before developing a transformer digital twin. Among them is the scale of the digital twin, e.g., component modeling or system level modeling, the type of predominant physics involved and their mutual coupling, input parameters such as design and operational data, computational accuracy, and finally, computation time, i.e., how quickly a twin model yields actionable information [4].

Another important aspect is the deployment of the digital twin, as the complexity of these tools limits their use to skilled users. With this in mind, HTT used the application builder tool to build specialized, easy-to-use shorthand apps from complex models. These applications are then shared with end users as standalone applications, which can run on a desktop or laptop computer without a COMSOL server license. In this way, the apps then make the simulation engineer's expertise available to everyone involved in the design and manufacturing processes across all engineering disciplines in the organization. Similarly, HTT has built various apps at different scales involving different dominant physics, and a graphical illustration of this is shown in Figure 2.

In this article, a three-phase rectifier cast resin transformer unit, 2000 kVA 10500/720 V is used to explain the development of twin simulations

In this article, a three-phase rectifier cast resin transformer unit, 2000 kVA 10500/720 V is used to explain the development of twin simulations. Figure 3 shows the schematic view of the transformer with basic components, where the low voltage winding is made of continuous aluminium strips (1) and high voltage winding is a foil winding separated by two layers of insulation material (2).

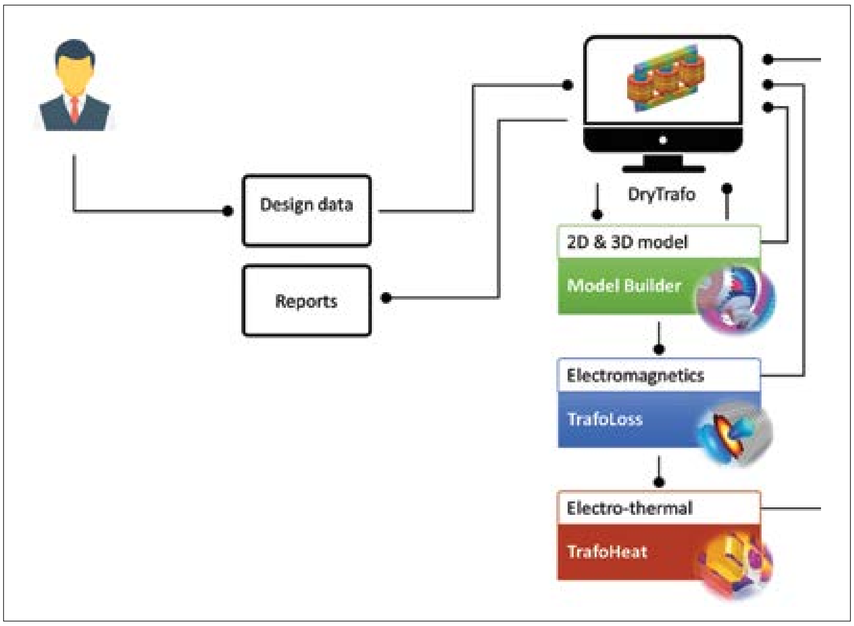

Figure 2. Graphical illustration of DryTrafo twin application

Figure 3. Schematic view of cast resin transformer with basic components

The simulation of actual transformer behaviour and computation of copper losses is carried out in COMSOL multiphysics software based on the finite element method

The major objectives in this process are as follows:

- Computation of power losses
- Dielectric performance assessment through electric field strength monitoring
- Thermal behaviour under various loading cycles and with different cooling systems
- Hotspot temperature analysis for temperature sensor installation
- Calculation of electromagnetic forces for fault analysis
- Ensuring optimized design and efficient electrical performance

3.1 Computation of power losses

Transformer losses can be classified into core losses, copper losses, and auxiliary losses. Core losses are mainly governed by hysteresis. Hysteresis losses are intrinsic to any magnetic iron core. These losses are maximum under the open circuit condition, as the maximum magnetic fields are induced in the core in this condition. However, the core may also experience losses because of eddy currents. These are generally smaller than hysteresis losses thanks to the use of laminated iron, which minimizes eddy currents. Copper losses are due to the electrical resistance of the conductor. These losses can drastically increase due to the skin and proximity effects. Auxiliary losses contribute to the losses that occur in metallic structures that support the transformer. In this article, the modeling of copper losses will be addressed in detail.

The simulation of actual transformer behaviour and computation of copper losses is carried out in COMSOL multiphysics software based on the finite element method [3]. FEM is a spatial discretization approach to numerically solve electromagnetic fields in the time and frequency domain and lead to a single solution. In this article, frequency domain study is used to solve Maxwell's equations. To emulate the actual measurement procedure, a short circuit test is simulated by shorting the LV winding and applying a voltage to the HV to ensure a nominal current flowing through the circuit in order to compute the copper losses in the transformer.

In the case of the three-phase cast resin transformer, the HV and LV windings are complex as well, as there is a large number of turns. While a reliable computation of copper losses demands explicit modeling of the detailed conductors to account for skin and proximity effects, such a detailed 3D model requires a large number of computation costs and time. However, the windings power loss and core loss distribution of each phase are almost the same, which is why only one of the three phases is supposed to be analyzed. Additionally, the structure of one phase is also axisymmetric. Thus, a 2D axisymmetric model which incorporates individual conductor domains to understand the current density of the conductors is developed. In this way, the solution time was significantly reduced. To gain confidence in the accuracy of the model, the adaptive mesh refinement feature is used, which allows the control of the mesh size and levels in different parts of the model. This strategy not only leads to a decrease in the use of computational resources but also increases the accuracy of the model.

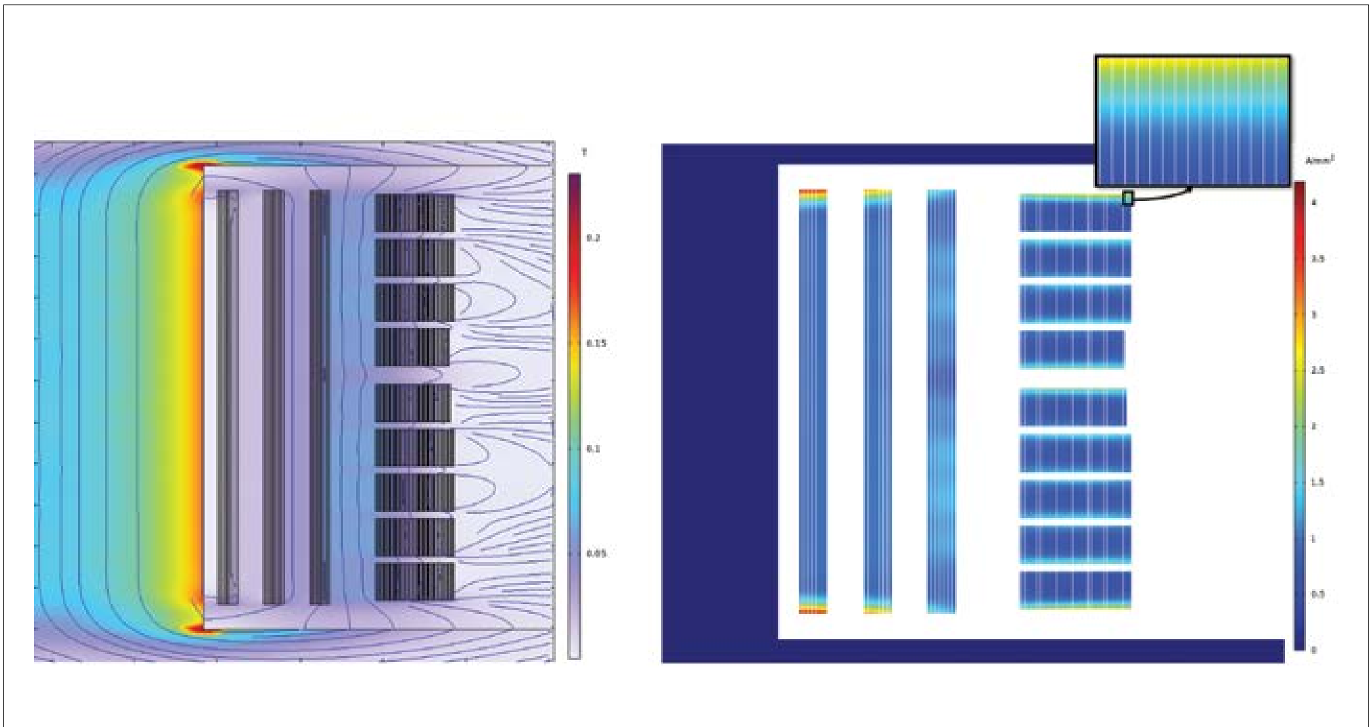

Figure 4. DryLoss twin application results of magnetic field density (left) and current density (right)

Figure 4 illustrates the simulation results of the TrafoLoss twin application. The results are validated with measurements at different stages. A comparison of simulation and measurement results is shown in Table 1. The TrafoLoss app can effectively replicate the transformer short circuit routine test with a maximum deviation of 5%. The key features of the TrafoLoss twin app are given below:

- Computation of DC and AC losses, which facilitates the design optimization as well as provides the opportunity to study the performance of different types of windings and their arrangements.
- Magnetic and current density fields provide a visual assessment to identify high and low-loss pockets in the transformer geometry.
- Generation of automatic reports, which facilitates the communication of results in the most readable format for designers.

Dry-type transformers' thermal performance is generally worse than that of oil-filled transformers due to their cooling medium (air) and the fact that they use natural convection for heat transfer

3.2 Thermal Analysis

Dry-type transformers are highly sensitive to temperature changes. Their thermal performance is generally worse than that of oil-filled transformers due to their cooling medium (air) and the fact that they use natural convection for heat transfer. The hotspot temperature determines the loading of the transformer, the aging of the transformer, and, thus, its remaining useful life. Therefore, it is imperative to have reliable thermal calculation tools at the designer's disposal to achieve an optimized design for dry-type transformers. With this in mind, HTT has developed a TrafoHeat twin application based on the maxwell-CFD multiphysics approach. HTT's TrafoHeat twin app can satisfactorily compute winding temperature rise, including hotspot temperature, by considering all details of winding, core, and cooling system within seconds.

Heat transfer in a cast resin transformer mainly involves conduction, convection, and radiation. The effect of heat radiation is much smaller as it is mainly reflected in

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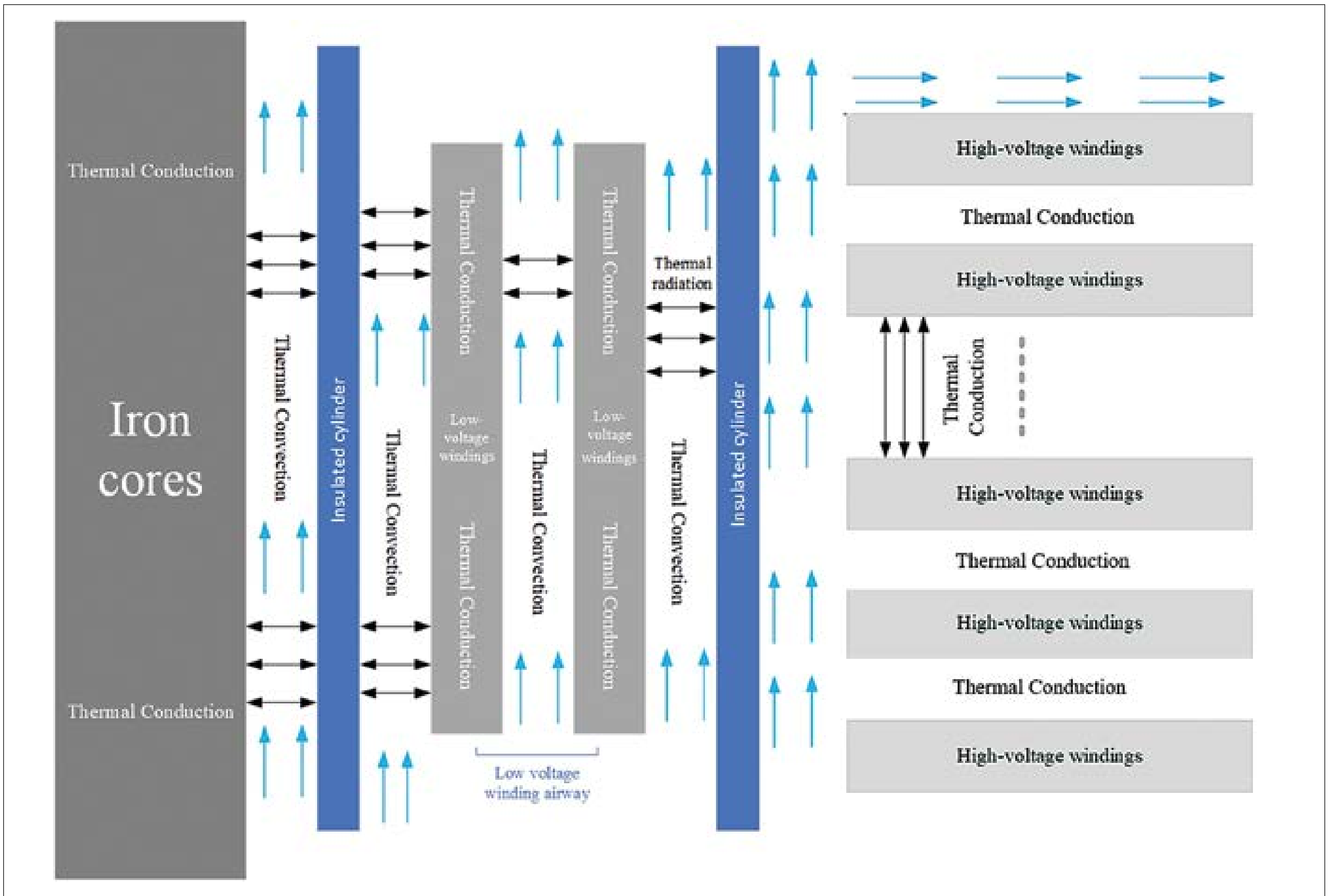

Figure 5. Transformer heat dissipation structure

Table 1. Comparison of simulation and measurement results

	Short circuit Impedance and short circuit losses (IEC 60076-1:2011, clause 11.4)		Winding temperature rise according to IEC 60076-2	
	Short circuit losses P_k [W] at 120°C	Short circuit impedance Uk [%]	System 1 ΔT_1 [K]	System 2 ΔT_2 [K]
Measurement	14202	6.19	85.1 K	80.6 K
Simulation	14441	6.05	88.3 K	76.5 K
Deviation	1.68 %	2.26 %	3.2 K	4.1 K

non-contact solid materials. During the operation of the transformer, the electromagnetic losses in the core, windings, and structural parts are the main heat sources of the cast resin transformers. The solid parts mainly transfer the heat to their surface by conduction and dissipate heat to the surrounding environment. Between solid and air-fluid, heat is mainly transferred by convection due to the temperature difference in both mediums. The internal heat dissipation phenomenon of a cast resin transformer is shown in Figure 5.

The TrafoHeat app considers all the physical phenomena that occur during the standard heat run test. For thermal calculations, it solves three physical field modules in the time domain to capture thermal images of the transformer, i.e., solid and fluid heat transfer, laminar flow, and surface radiation. Thanks to the multiphysics feature, these heat transfer studies are tightly coupled with electromagnetic physics, which takes into account the electrical losses, and skin and proximity effects, temperature effects on material resistivity are also considered. The temperature distribution of each component of the cast resin transformer is shown in Figure 6. In this figure, hotspot temperatures and their locations can also be identified in different components. The multi-component thermal analysis and multiphysics approach make TrafoHeat a different digital twin app from conventional thermal models. The simulation results are validated with the measurement results at different stages, as appreciated in Table 1. HTT's TrafoHeat app can satisfactorily capture the real-time thermal image of the cast resin transformer with a maximum deviation of 5 K from the measurement results.

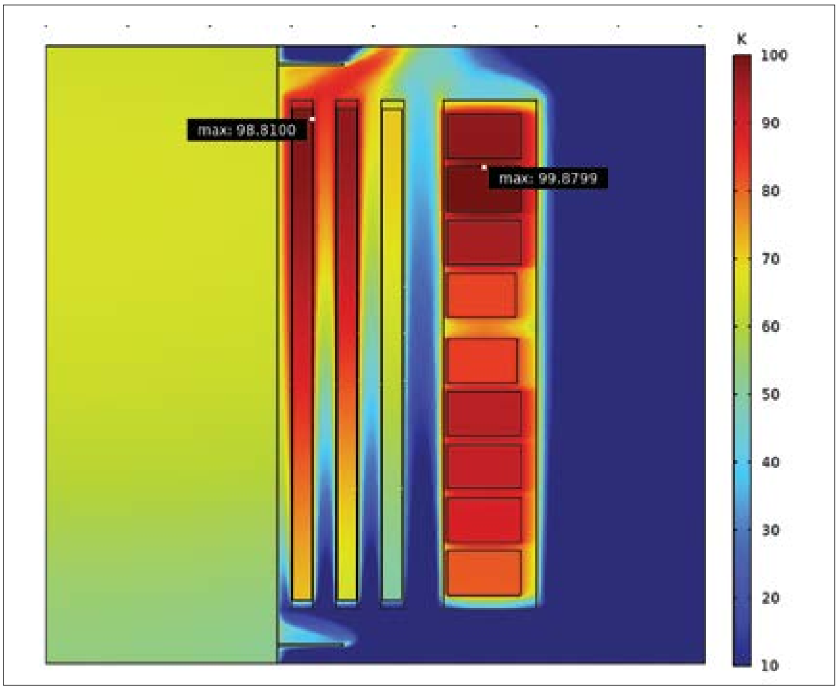

Figure 6. DryHeat twin application result of temperature distribution and hotspot indication

The multi-component thermal analysis and multiphysics approach make TrafoHeat a different digital twin app from conventional thermal models

Currently, the TrafoHeat app can be useful in the following scenarios:

- Analyzing the thermal behaviour of cast resin transformer
- Possibility of design optimization to reduce thermal stress
- Determining permissible overload capability with user-defined boundary conditions
- Monitoring hotspot temperature and their locations to install temperature sensors
- Forecasting thermal performance for different load cycles and ambient temperature cycles for 24 hours in the future.

4. Conclusion

The growing complexity of grids brings new challenges to the transformer industry, which can be mitigated by implementing smart and digital technologies such as a transformer digital twin. In this article, a three-phase rectifier transformer unit,

2000 kVA 10500/720 V is used to explain the development of digital twin applications, for example, DryLoss and DryHeat, under the portfolio of DryTrafo. DryLoss twin application computes AC and DC losses, and it also provides a visual assessment of magnetic and current density fields to identify high and low-loss pockets in the transformer geometry, which facilitates design optimization. DryHeat twin application analyses the thermal behaviour of cast resin transformers, including the identification of hotspot temperature. It is also valuable for determining permissible overload capability with user-defined boundary conditions and forecasting thermal performance for different load cycles. Another key feature is automated report generation. This facilitates the communication of results in the most readable format for designers.

In conclusion, DryTrafo offers insight into transformer designs and allows engineers to provide a complete optimization of transformer design within minutes. Further digital twin applications will follow in the near future, complementing the dynamic and new challenges to the transformer industry.

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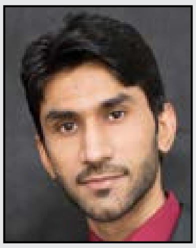

Mehran Tahir received his M.Sc. in power engineering from the Technical University of Munich, Germany, in 2016. In 2017, he was appointed as a scientific assistant at the Institute of Power Transmission and High Voltage Technology (IEH), University of Stuttgart, Germany. He completed his PhD work in High voltage engineering in 2021. In 2022, he joined Hochspannungstechnik & Transformatorbau GmbH (HTT) and worked as Head of Technology. At HTT, he is responsible for designing and calculating Dry and oil-immersed transformers and leading the R&D team. He is an active member of the IEEE, CIGRE SC A2 (Power Transformers).