**Major transformer manufacturers have responded to today's challenges by implementing digital technologies and connectivity provided by "smart" asset management services**


## ABSTRACT

In this article, we will consider the benefits of transformer digitalisation, which requires yielding actionable information within a reasonable turn-around time of the digital twin. The simulation turn-around time, that is, the time needed to set-up, run, and post-process the results, is important in both design exploration during development and in forecasting scenarios during operation. A pole-mounted, 100-kVA distribution transformer is used to show how simulations can be used to generate reduced-order FEA based models for predicting transformer loss (core, winding, and stray), dielectric, and temperature hotspots.



## KEYWORDS

digital twin, hotspots, real-time monitoring, simulation, transformer

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# Using computer-aided engineering to enable the digitalisation of transformers

## How to leverage digital-twin simulations in the making of transformer digital twins

### 1. Introduction

The disruption of supply chains by unforeseen events such as pandemics, severe weather events, labour, trade, and political disturbances, affect maintenance, upgrades, and delivery of new transformers. In addition, there is competitive pressure in emerging markets from low-cost suppliers who do not necessarily have to meet the same standards and testing cycles. In mature markets, utilities are operating equipment beyond their life, with reduced maintenance budgets. Additionally, the increase in grid instability attributable to the integration of intermittent renewables, electric vehicle (EV) charging, data centres, and a decline in traditional inertia generation is resulting in more dynamic loading of transformers [1]. Irrespective of the generation and demand changes, transformers are expected to last for decades—30 to 40 years for power transformers.

Major transformer manufacturers have responded to these challenges by implementing digital technologies and connectivity provided by "smart" asset management services. IoT systems, such as the Siemens Sensformer®, and the ABB Ability™ connectivity features, is enabling the digitalisation of transformers [1, 2]. According to ABB, transformer monitoring can reduce catastrophic failure by 50 %, repair costs by 75 %, and lost revenue by 60 %, while the annual saving of a transformer run with and without monitoring can amount to 2 % of the price of a new transformer [1].

#### 1.1 What is "Transformer digitalisation"?

Transformer digitalisation is digitally capturing the transformer development process, from ideation (design and analysis), realisation (manufacturing and supply chains management), to field utilisation to help predict hotspots that are important in forecasting the loading and remaining life. The main aim is to add revenue opportunities and improve market agility [2]. A holistic transformer

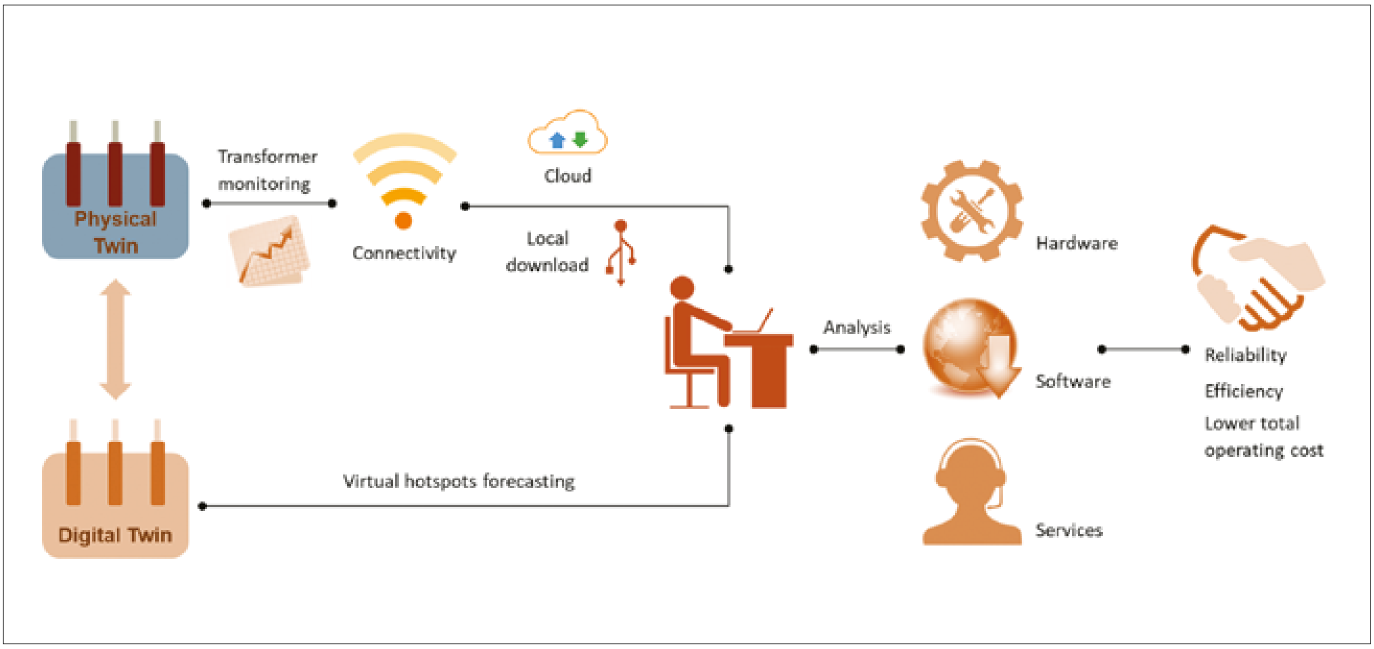



Figure 1. A digital twin is a key aspect of a digitalised transformer to improve performance reliability and life, as well as lower the operating costs [1]

**Transformer digitalisation is digitally capturing the transformer development process, from ideation, realisation, to field utilisation to help predict hotspots that are important in forecasting the loading and remaining life**

digital twin improves reliability and performance, even during extreme natural events by minimising outages through load and asset scheduling.

Simulation- and test-driven development mainly play a major role in the ideation and utilisation phases of the digitalisation process. In the ideation phase, computer-aided engineering (CAE) simulations are leveraged in performance analysis, while reducing over-design and the number of physical tests. This reduces the time to market and costs. In the utilisation phase, as illustrated in Fig. 1, real-time monitoring and feedback from the digital twin are necessary for efficient operation, predicting health and remaining life. Connectivity allows secure data transfer to the cloud, or it can be logged locally. Analysing this data generates actionable information, which is hardware, software, or services related to optimising transformer operation, and condition-based maintenance. Furthermore, unforeseen natural events are mitigated through asset and load scheduling.

This article looks at how Simcenter MAGNET™, low-frequency electromagnetics (EMAG) solution based on Maxwell's equations, aids in the creation of a transformer digital twin [3]. Defining low-frequency electromagnetics, by frequency range, restricts the fields of application. Hence, the wavelength is a better differentiator. That is, as long as the wavelength is much larger than the device extents in terms of the frequency of interest, such that the wave propagation effects can be neglected, then the problem can be termed as low-frequency [4].

## 2. Generating a transformer digital twin

To generate a holistic transformer digital twin, there is a need to consider the level it represents (component or system), the dominant physics (single, multiple or tightly coupled), the information it is based on (simulation, test, hybrid, and / or real-time), and finally how quickly it can yield actionable information vis-à-vis real-time.

A single-phase pole-mounted distribution transformer, with a rating of 100 kVA, 2.4 kV (primary), 120 V (secondary), 60 Hz, and a turns-ratio of 438 / 22, whose cooling is oil-immersed-air-cooled (ONAN), is used to show how EMAG simulations are applied in the making of a digital twin. The reduced quarter of the full model is seen in Fig. 2. In transformer EMAG design and analysis phase, some of the main objectives are:

- To ensure efficient electrical performance
- To assess the insulation and coolant dielectric performance at high voltages
- To ensure the highest hotspot temperature is within the design class.

In the field utilisation phase, the same EMAG simulations can be leveraged to:

- Generate EMAG fields (forces and losses) for fault analysis
- Create reduced-order models used in digital twins to forecast performance, health, and remaining life [6 - 8],

and data analytics tool on predicting transformer remaining life.

- In the positioning of sensors for hotspots monitoring in the physical twin.

Real-time monitoring gives the state of the transformer, whose associated faults are categorised into their EMAG domains, as shown in Table 1.

The next paragraphs look at the transformer design and analysis in terms of efficiency, insulation, and coolant dielectric break-down assessment, and the prediction of temperature hotpots.

## 2.1 Efficiency analysis

Efficiency is directly related to the operating cost of a transformer. Lowering the losses improves efficiency, which also reduces the cooling burden and the ageing of the insulation, hence durability is improved. In addition, stray losses on the transformer structures such as clamps, busbar housing, and the tank, can result in temperature hotspots that degrade the solid insulation and coolant. Hence, detailed FEA models are used to analyse stray losses as they are hard to predict analytically.

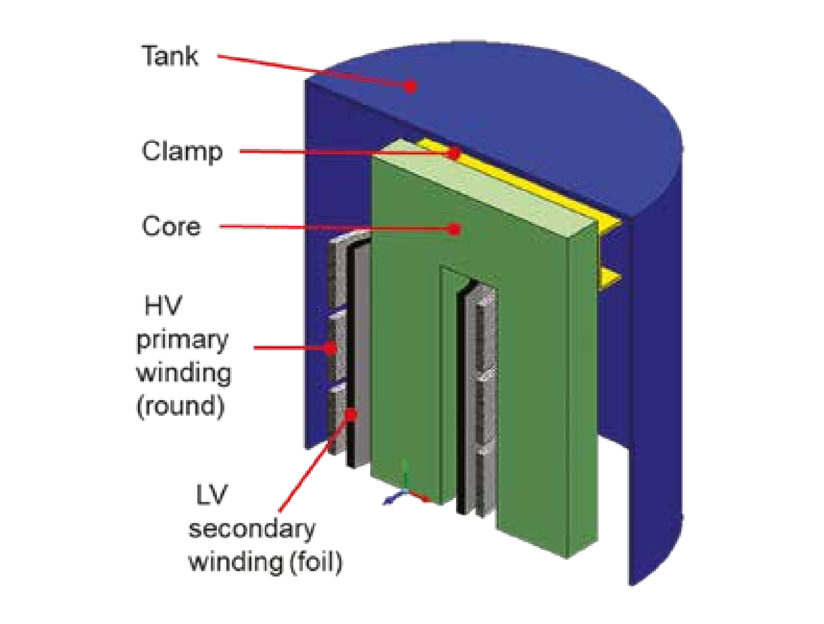



Figure 2. The reduced quarter model of 1-phase 100 kVA pole-mounted distribution transformer

**To generate a holistic transformer digital twin, there is a need to consider the level it represents, the dominant physics, the information it is based on, and finally how quickly it can yield actionable information**

Table 1. Categorisation of transformer faults into their EMAG domains [1]

| **Fault** | | **EMAG Domain** |
|---|---|---|
| **Mechanical** | Short circuit | EMAG forces |
| | Winding displacement | |
| | Winding looseness | |
| **Electrical** | Partial discharge | Oil and solid insulation dielectric assessment |
| | Faults overvoltage | |
| | Arching | |
| **Thermal** | Insulation aging | Thermal-dielectric assessment [5] |
| | Cooling issues | EMAG losses |
| | Overloading and uprating | |
| | Overheating (e.g., shorts, wrong connection) | |

**Detailed FEA models are used as digital twins to predict temperature hotspots, stray losses, or efficiency**

Transformer losses are categorised into no-load core loss, winding and stray load losses, and auxiliary losses. They are reduced by:

- Core and joint construction, and use of efficient core materials (no-load loss)
- Conductor design, winding design, and shielding (load loss)
- Operation at higher efficiencies to lower the cooling burden (auxiliary loss)
- Newer technologies, materials, and design methodologies deliver efficient designs, lower material use, and flexible profiles to ease logistics. For example, the ABB's patented cell design used in traction transformers has reduced oil consumption by 70 % [1]. For renewable remote applications, modular, compact, low-maintenance, and containerised solutions are preferred. In addition, in applications pre-disposed to switching transients and high-voltages, such as in renewable energy, traction, data-centres, and ultra-high voltage DC converter transformers (UHVDC), improved dielectric performance has to be ensured.

In terms of EMAG design and analysis (the ideation phase of the digital twin), a balance has to be struck between accuracy and the solution time. By leveraging the advanced features of Simcenter MAGNET™, and analysing each loss component independently, the solution time was significantly reduced. For more information on this in terms of the model settings, mesh elements, and hardware used in the analysis of the core, winding, and stray losses, see [6]. These features are the nonlinear AC time-harmonic solver, that approximates the core nonlinearity, in addition to the standard linear capability. Simcenter MAGNET™ uses the p- and h-refinement to increase the model accuracy and reduce the solving time. It can be set at the component or global model level. P-refinement increases the accuracy at the regions of interest by using higher-order elements (p-order), while the h-refinement, i.e., mesh refinement, increases the accuracy by discretising these regions further. Support for structured meshing and surface impedance approximation further reduces the number of mesh elements [7]. In addition, Simcenter MAGNET™ supports multi-terminal coils, and insertion of active (switches) and passive (resistors, inductors, and capacitors) electrical circuit components in the analysis of complex busbars and taps.

Fig. 3 shows the models that were used to analyse the power loss hotspots. For the no-load core loss, a p-order of 2 was only set on the core. The nonlinear AC time-harmonic solver reduced the solving time by 81 %, from about 8.5 min to 1.5 min. The impact on the average loss was minimal, that is, less than 1 %. This is with respect to a transient solution. The time-harmonic frequency-domain solver is faster than the transient time-domain solver, as it generates a single steady-state solution. In contrast, the latter requires several solutions in the form of time steps over a period. To improve its accuracy, the time-harmonic frequency solver in Simcenter MAGNET™ approximates the nonlinearity of the core. For the winding load-loss analysis, the turns have to be explicitly modelled to account for both conductive, frequency, and proximity effects. A 2D axisymmetric model reduced the solving time by 93 %, from about 2.5 h to 11.5 min. The average winding losses were underestimated by 2.4 %, in comparison to a 3D model. The number of problem nodes, which is the sum of p- and h-nodes, was reduced from 4.74 to 0.67 million. For stray load loss analysis, the solving time was reduced from 3 days to about half an hour, by applying the surface impedance boundary condition (SIBC) to the structural components, vis-à-vis a solid-body mesh. The same mesh size of 3 mm and a p-order of 2 was applied

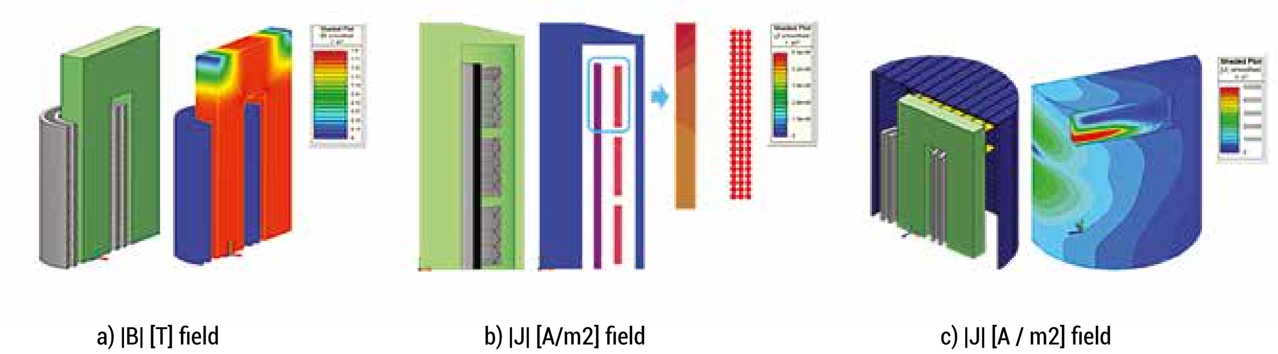



Figure 3. The models used to analyse the a) no-load core loss, b) the winding load loss, and c) the stray load loss hotspots [6]

to the structural components. The nodes similarly were reduced from 4.70 to 0.61 million.

Hence, in the analysis of loading, overloading, faults, uprating, and upgrading, these loss models will save time in predicting loss hotspots.

**Careful modelling and simplification of the FEA models can drastically reduce the simulation time without losing the accuracy of the solution**

### 2.2 Solid insulation and oil dielectric analysis

Solid insulation and transformer oil degradation result in catastrophic failure, with very high replacement and outage costs. These liabilities are met by the equipment manufacturer at the design stage and before the warranty lapses. The dielectric assessment ensures that the insulation and the oil do not reach their dielectric break-down under fault conditions, such as a lightning strike and overvoltages because of system transients.

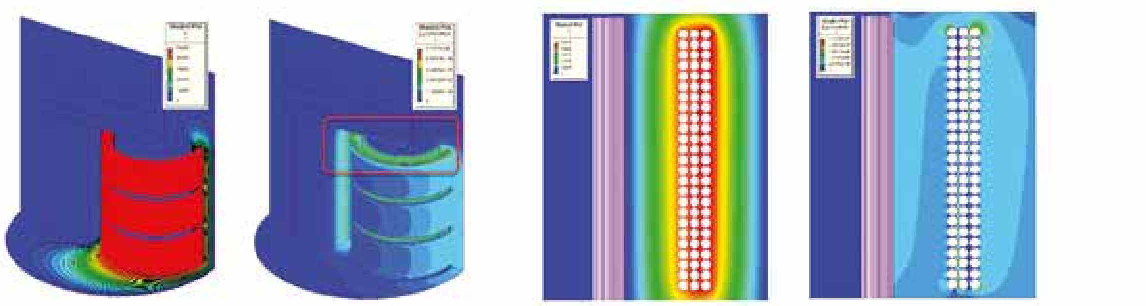
The dielectric strength is checked at the end-winding and the high-voltage inter-turn regions. An electrostatic solver is driven by the peak test voltage if known. This test voltage is derived from a transient model that considers both the inductive and capacitive coupling of the transformer, energised by the lightning impulse (LI) test voltage [8]. In this case, for demonstration purposes, the peak value of the lightning impulse voltage was assumed and distributed linearly along the winding. A 3D model was used to check the end-winding regions' electric field strength, to ensure it is less than the transformer oil break down strength, as shown in Fig. 4 a). A 2D axisymmetric model was then used to assess the high-voltage inter-turn electric field strength, as shown in Fig. 4 b), which is less than the winding insulation break-down strength. As a result, the effect of overvoltage stress on the insulation and transformer oil is rapidly assessed using the fast electrostatic solvers and reduced-order models.

### 2.3 Temperature hotspots analysis

The hotspot temperature rise determines a transformer's loading and the ageing of the solid insulation and transformer oil, hence the remaining life [1]. For instance, an 8 °C oil temperature rise above the rated, can cut the insulation life by half [1]. Consequently, it is an important consideration in the dynamic operation, overloading, uprating, and upgrading studies. Thermal hotspots analysis also helps in the mounting of temperature sensors. Therefore, digitalised transformers allow the real-time regulation of the hotspot temperature, optimising their life. For example, Siemens' Sensformer® advanced comes with a digital twin that provides the complete real-time thermal image of the transformer, which enhances performance and lifetime prediction [9].

Simcenter MAGNET™ supports coupled magnetic / electric field-thermal FEA analysis. The model is reused negating remeshing. Furthermore, the EMAG solvers can be invoked externally to extend the analysis to CFD thermal, structural, and vibro-acoustics analysis.

The EMAG power losses from the solid bodies are transferred to the coolant as heat via the cooling surfaces. In FEA and lumped parameter thermal network solvers, this is represented by boundary conditions, whose convective heat transfer coefficients are estimated analytically. Lumped parameter thermal networks (LPTN) predict the heat flow and nodal temperatures, by interconnecting thermal resistance, capacitance, and heat sources within the transformer. Both FEA and LPTN require empirically and / or computational fluid dynamics (CFD) thermal calibration, as it is challenging to consider the thermal-fluid flow coupling between the transformer and the tank that is ideally modelled using CFD [10].



a) End-winding region V [V] and |E| [V / m] fields     b) Zoomed view of V [V] and |E| [V / m] fields in the HV inter-turn regions

Figure 4. The models used to analyse the a) end-winding, and b) the inter-turn dielectric field strength

**A 3D model with electrostatic solver was used to check the end-winding regions' electric field strength during the lightning impulse voltage test, to ensure it is less than the transformer oil break down strength**

In this work, Simcenter FLOEFD™ a front-loading computer-aided design-centric CFD solution [11], was used in the CFD-thermal analysis of the transformer. This was in addition to coupled magnetic-thermal FEA analysis in Simcenter MAGNET™. The same thermal model, in terms of geometry, was used in the two analyses.

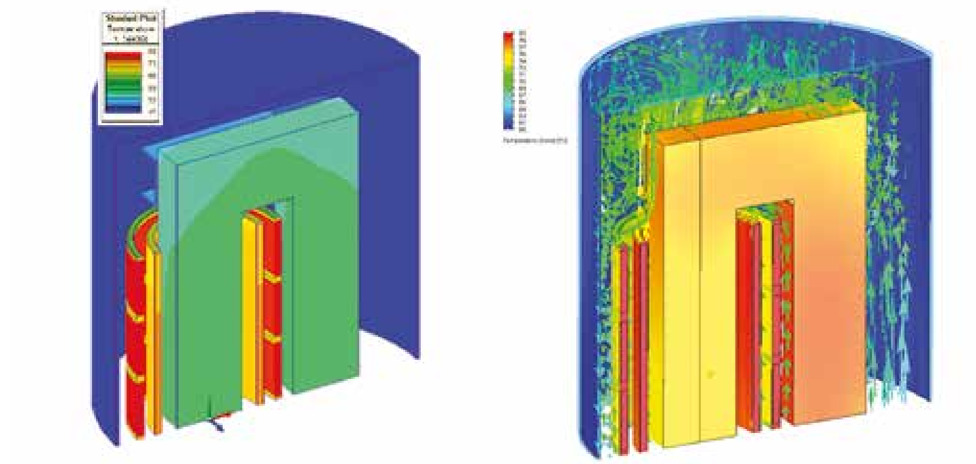
As seen in the EMAG-thermal FEA results of Fig. 5 a), the outer high-voltage winding has the highest temperature, as one would expect. This is in contrast with the CFD-thermal results of Fig. 5 b), where the hotspot is at the top of the inner low-voltage winding. This is because the outer winding is exposed to cooler oil, in contrast with the inner winding. In the thermal model, the two windings were encased by epoxy, forming two concentric cylinders around the left leg of the yoke, forming a flow channel between them. Therefore, thermally, the inner winding is sandwiched between the outer winding and the core heat sources. In contrast, the outer winding is in contact with cooler oil and the shared flow channel between it and the inner winding. This explains the difference in the results and serves to show the need for detailed thermal design.

**Digitalised transformers allow the real-time regulation of the hotspot temperature, optimising their life**

## Summary

The challenges the transformer industry is facing, such as disruption of supply chains, market pressure thanks to emerging low-cost players, and an ageing fleet with reduced maintenance budget, can be mitigated by leveraging the benefits of digital twins. However, the main challenge in applying digital twins is their long simulation time, affecting the turn-round time needed to yield actionable information. This makes it difficult to explore designs in development, and forecast scenarios during operation. Leveraging some unique techniques of Simcenter MAGNET™ a low-frequency electromagnetics solution [3], the simulation time needed in the design and probing of the digital twin is significantly reduced without foregoing accuracy.

In this article, a single-phase 100 kVA distribution transformer was used to generate various models that are leveraged in the creation of a digital twin for hotspots analysis ranging from losses (core, winding, and stray), dielectric, and temperature. For the no-load core losses, the solving time was reduced by 81 % (8.5 to 1.5 min), and the impact on the average loss was less than 1 %. For the winding load losses, it was reduced by 93 % (2.5 h to 11.5 min), with a 2.4 % underestimation of the average winding loss. The greatest impact was on the stray



a) FEA

b) CFD

Figure 5. Transformer temperature distribution in using a) an uncalibrated EMAG-thermal FEA and b) CFD-thermal models

load losses, where the solving time was reduced from 3 days to about half an hour.

In the dielectric hotspot assessment of the end-winding and the high-voltage inter-turn regions, the fast electrostatic solvers can be used, but the peak voltage has to be known.

From the thermal analysis, a reduced-order thermal FEA model of fast turn-around time can be realised by reducing the thermal model to only the hottest parts, and calibrating using CFD and / or test data.

Consequently, it is possible to generate relative fast transformer digital twins to ensure reliable and efficient designs and predict health and remaining life, in asset management.

**The challenges the transformer industry is facing, such as disruption of supply chains, market pressures, or an ageing fleet with reduced maintenance budget, can be mitigated by leveraging the benefits of digital twins**

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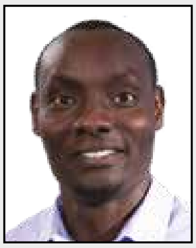

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