Transmission products and systems for utilities of the future – IoT connected, digital twin based, intelligent

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SUMMARY

Our power systems and grids are transforming rapidly, driven to achieve a sustainable CO_2 neutral world and society. How will the future grid of a CO_2 neutral world look like? Cigre technical brochure "Future grids" describes the main drivers: Reduction of CO_2 emissions, network availability, public acceptance, economic transmission and distribution and increasing electrical energy consumption.

In this paper a completely new approach for digitalization of all new transmission equipment in a substation of the future is described: Power transformers, gas-insulated switchgear, circuit breakers, surge arresters, instrument transformers and coil products will henceforth be equipped with connectivity. The connectivity is done with a smart and robust IoT connectivity device securely transmitting a minimum amount of required information to a cloud-based storage and visualization platform. All devices will be delivered pre-equipped with all necessary hardware. The IoT connectivity device will be pre-configured and pre-installed on the equipment as part of the product manufacturing process. It comes with GPS and local weather information as well as the most relevant measurement signals per default: Apps create operational value of the data in the cloud.

Value and benefit for grid operation is transparency, enhanced productivity and intelligence. Central element is the connection of the digital twin with the operational data. This creates a completely new type of functionality for value-add applications, like active overload management to manage temporary overloads without compromising on lifetime or the indications on the residual lifetime of the asset. This paper describes functionality, operational values and benefits, testing procedures and results, installations and experience of the new generation of intelligent transmission products "Sensformer" and "Sensgear". It additionally describes the latest developments on digital twins for transmission products, the combination of data between the different products in transmission systems and the application of artificial intelligence to support the grid operation.

KEYWORDS

Digitalization, digital twin, artificial intelligence, transmission equipment, power transformer, reactor, coil, gas-insulated switchgear, circuit breaker, instrument transformer, substation

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1 INTRODUCTION

1.1 Why – The grids of the future require flexible equipment

How will the grid of the future look like and what are the new requirements for high-voltage substation equipment in the grid of the future? Cigre technical brochure "Future grids" describes main characteristics [1]:

- Reduction of CO_2 emissions,
- network availability,
- public acceptance,
- economic transmission and distribution and
- increasing electrical energy consumption.

The main challenge for substation equipment, described as "managing the loadings and ratings of the different substation components", is flexibility. Merging reliable primary equipment with digital technologies and integrated intelligence enables grid operation to become more flexible and effective, **Figure 1.**

Figure 1 Trends and challenges for future grid operation and digital opportunities for flexibilization

1.2 How – Flexible equipment merging reliable hardware with digitalization

In this paper a completely new approach for digitalization of all new transmission equipment in a substation is described: Power transformers, gas-insulated switchgear, circuit breakers, surge arresters, instrument transformers and coil products will henceforth be equipped with connectivity. The connectivity is realized with a smart and robust IoT connectivity device securely transmitting a minimum amount of relevant information to a cloud-based storage & visualization platform, **Figure 2**.

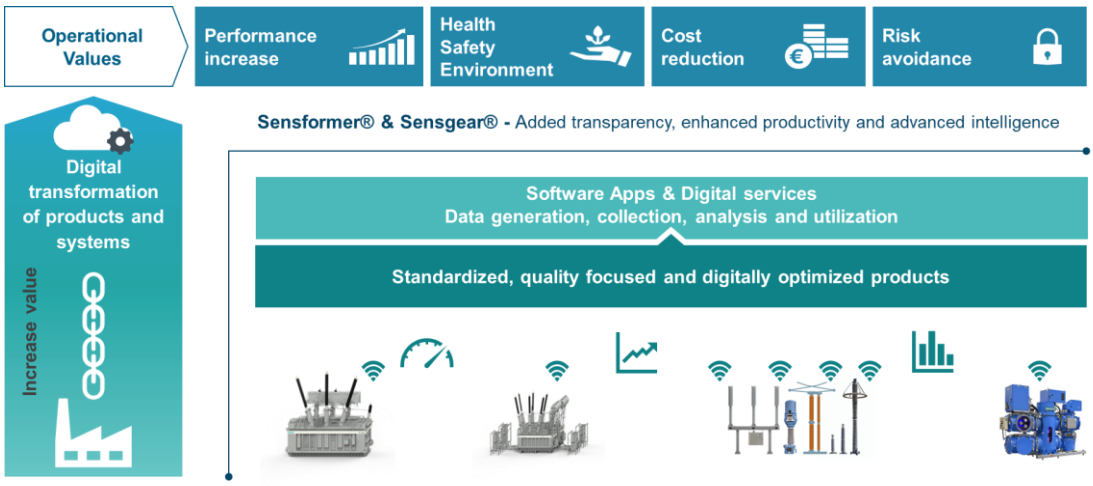

Figure 2 Operational values by connecting reliable equipment with the new digital functionalities

All transmission products are equipped with GPS and local weather information as well as most relevant product-specific signals according reliability statistics [2-5]:

- Power Transformers: Oil level alarm, top oil temperature, low-voltage winding current
- Gas-insulated switchgear and circuit breaker: gas density, temperature, circuit breaker counter, position & readiness
- Surge arrester: Surge counter, leakage current
- Instrument transformer: gas density or oil level alarm
- Arc suppression coils: Oil level indication, top oil temperature, zero sequence voltage, coil setpoint

Grid operators, asset management and service have various benefits of merging reliable hardware with digital technologies, **Figure 3**.

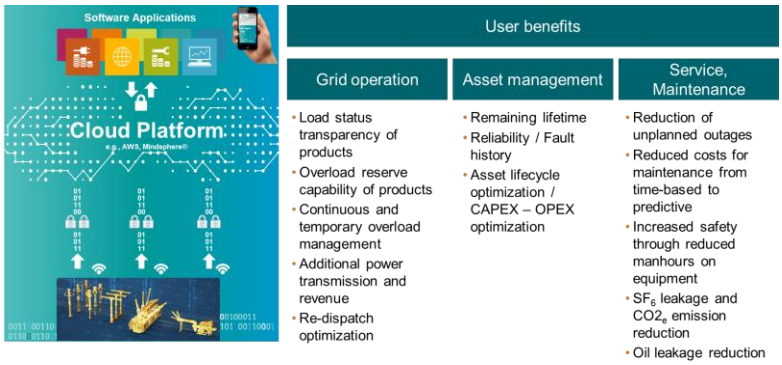

Figure 3 Born connected architecture and user benefits for operation, asset management and service

1.3 How – Digital twins merging real and virtual operation

The grid and operators of the 21st century face new challenges: fluctuating power generation by renewables and increasing and fluctuating electricity demand, require a grid and products which are flexible to avoid congestions. Current and voltage are the key physics to be managed. Current causes conductor temperature rise depending on the resistance of the material. The limiting factor is the absolute temperature of the used materials. Therefore, the knowledge and influencing of the material temperatures are key. Mechanical, electrical, and thermal digital twins are used to optimize product design, testing, production and operation. Until today, those digital twins are not actively used in operation. Sensformer and Sensgear advanced now combine operational data with the digital twin operation, which is generated and used during development and simulation to manage congestions actively. This enables grid operators to transmit additional power through higher current for a certain period of time depending on ambient temperature, **Figure 4**.

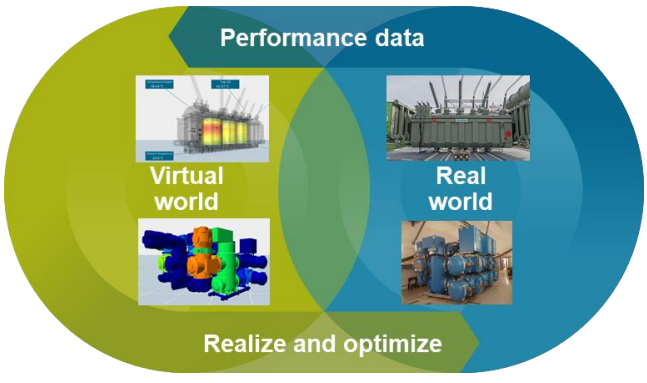

Figure 4 Performance / Load increase based on digital twins combining real operation with virtual operation: Example Sensformer and Sensgear GIS

Substation management in future grids requires managing the loadings and ratings of the different substation components. Consequently, the digital twin operation will be available for all Sensformer and Sensgear products, like power transformers. gas-insulated switchgear, circuit breakers, instrument transformers and arc-suppression coils. Two examples, Sensformer and Sensgear GIS are described in detail in the next chapters.

2 SENSFORMER – IoT connected, digital twin operated & intelligent transformers

2.1 Sensformer

In 2018, Sensformer was launched - the digitalized transformer portfolio [10]. With the starter functionality the following basic data are provided: Oil Level Alarm, Top Oil Temperature, LV Winding Current, GPS Location and local weather information. To ensure reliable and safe functionality of the IoT connectivity device, comprehensive tests according IEC were performed, in particular:

- Electrical safety: IP20 IEC 60529, relays insulation IEC 60255 and general req. IEC 61010
- EMC immunity and emission: IEC 61000 and IEC 55011
- Environmental cycle tests: IEC 60068 for temperatures – 25°C - + 70°C and humidity up to 95%

One year after market introduction, more than 500 Sensformers were delivered and commissioned worldwide, accompanied by simple installation. The operating experience confirms the functionality, the first user and operator feedback are very positive. Some users are very actively using the functionality and are consuming benefits of it.

2.2 Sensformer advanced – Digital twin operated & intelligent

In 2019, Sensformer advanced was launched on the market as the next step supported by a digital twin operation solution [10]. Since the status of a transformer is continuously known from the moment of energization, the digital twin operation offers extended possibilities and advantages. In general, the digital twin operation provides a real time image of the transformer by simulation of thermal processes based on input data gained by already used conventional sensors. Simulation results provide virtual sensors used to determine the asset's condition. The main functionalities of Sensformer advanced are virtual sensors, active load and overload prediction, lifetime prediction and advanced intelligence.

Virtual sensors

Virtual sensors enable more insights of the transformer's inner life and condition. They are used to create a real time image of the transformer's active part. This includes an 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 user about the status of the asset anywhere and anytime. Hence, users gain better insight about their assets, for example a more detailed picture about the status of the single components. The evaluation is simplified by correlating signals and events out of historical data. **Figure 5** illustrates the operators Sensformer Advanced cockpit, providing all relevant operational data gained via the Sensformer Advanced functionality.

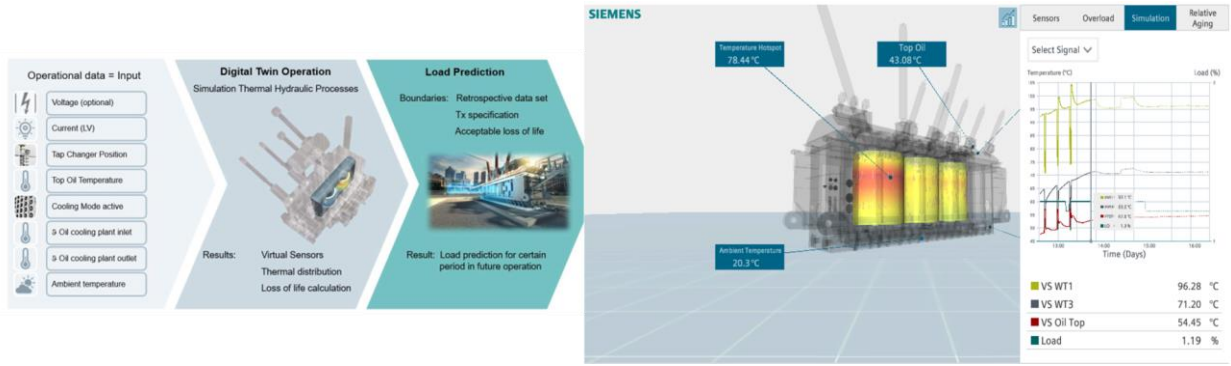

Figure 5 Sensformer Advanced structure and user cockpit, here active part thermal image is provided

Lifetime prediction

The calculation of actual lifetime loss is possible based on a retrospective evaluation of the operating mode of an asset. This enables absolute and relative lifetime loss forecasts. Continuous lifetime evaluation for a longer period based on IEC loading guidelines is also possible. A pre-condition for load prediction is flexible parametrization for aging. With lifetime prediction based on estimation of insulation aging, users can evaluate the age profile or their assets at any time. They get full transparency about actual aging of the transformer – information that is also useful for future CAPEX planning.

Active load and overload prediction

Overload prediction is based on a real time thermal profile of the transformer using historical operational data of the unit. With the help of the digital twin the real time thermal image of the transformer can be calculated anytime during operation. Different load scenarios can be calculated and simulated before stressing the physical asset, so the level and duration of loading and overloading that the transformer can withstand is known to the user at any time. The operating parameters are adjustable according to the user's requirements, and overload prediction is possible up to two hours into the future. Thus, transmission capacity can be increased based on an accurate forecast. The load prediction is provided based on the given and adjustable limits like maximum allowable hot spot and top oil temperature as well as loss of lifetime for a certain period. Thus, Digital Twin Operation enables load and overload operation of the transformer without touching any given operational limit and in consideration of ambient conditions. I.e. load performance of a transformer can be enhanced by using Sensformer Advanced Digital Twin Operation functionality. **Figure 6** illustrates a comparison of a given transformer load cycle according to the transformer specification (left side), against a transformer load predicted load cycle based on Digital Twin Operation functionality using retrospective transformer operation data (right side). The transformer operation condition is limited due to transformer specification. I.e. an overload period of 1.25 is permitted for 7 hours only, afterwards transformer must be operated at 0.6 p.u. only for 23 hours in order to keep loss of life to nominal figure. A permanent maximum ambient temperature is defined and used for transformer load and temperature design. But real life differs. In most cases loads are less than 1.0 p.u. and ambient temperatures are fluctuating, most likely below the specified maximum. **Figure 6** right picture illustrates the real-life case and the enhanced load capability by using Digital Twin Operation. The upper right picture shows the real ambient temperature (green line) vs. specified maximum ambient temperature. The bottom right picture shows the real load (green line before t = 0 min) and the predicted load by Digital Twin Operation (green line for t > 0 min). The load capability is enhanced of approximately 28 % for a GSU 588 MVA transformer by using Digital Twin Operation load prediction.

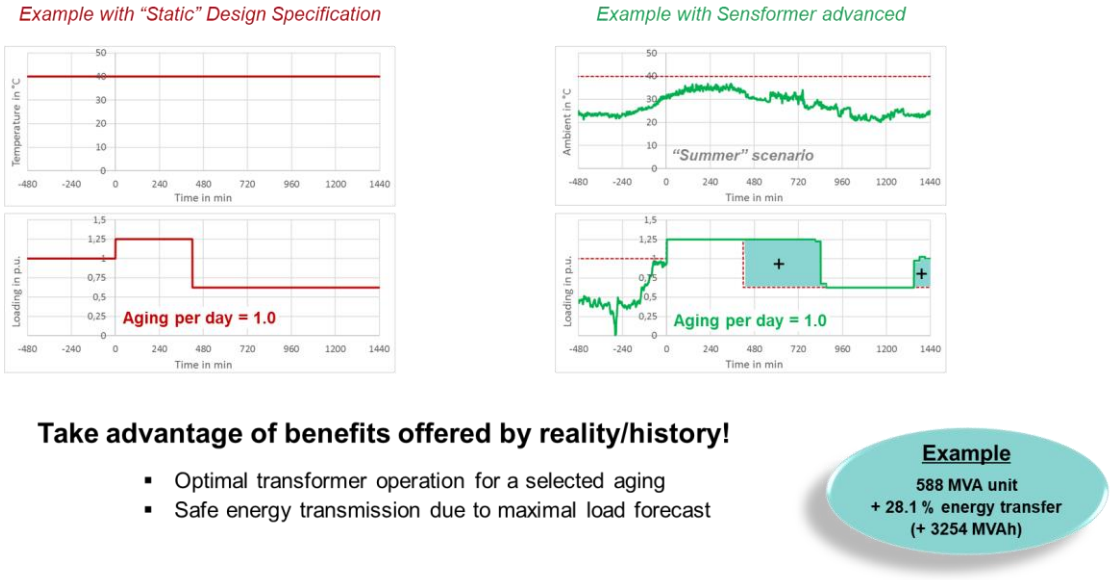

Figure 6 Digital twin operation: Performance increase by temporary overload optimization

Advanced intelligence

The Sensformer® advanced module provides several optional indicative measurements like bushing observation, gas in oil observation, moisture measurement, DC bias measurement, etc. These sensors will be used for further indicational monitoring of the transformer itself and for predictive maintenance guidance.

Pilot application

The Digital Twin Pilot was applied in an HVDC transmission link in operation for 10 years in Australia. Sensors for measurement, like ambient temperature, and cooler in- and outlet, had been retrofitted. The pilot had been operated for more than 1 year in order to investigate different operational conditions and to verify the accuracy of the simulation model itself.

3 SENSGEAR – IoT connected, digital twin operated & intelligent switchgear

3.1 Sensgear

In 2019, in addition to Sensformers, the connectivity concept was also realized and introduced for all other Siemens transmission products, so-called Sensgear [6]. Besides the GPS-signal and local weather information, relevant product related data are measured and securely transferred to the cloud:

- Gas-insulated switchgear (GIS) and circuit breaker (CB): gas density, temperature, breaker counter, breaker switching position & breaker readiness
- Surge arrester: surge counter, leakage current
- Disconnector: drive current
- Instrument transformer: gas density or oil level alarm
- Arc suppression coil: Oil level alarm, top oil temperature, zero sequence voltage, coil setpoint

The IoT connectivity device and sensors are an integral part of the equipment, **figure 7**. The hardware and sensors are well-proven, integrated and focus on the most relevant signals. Intensive performance tests demonstrate the IoT device reliability, **figure 8**.

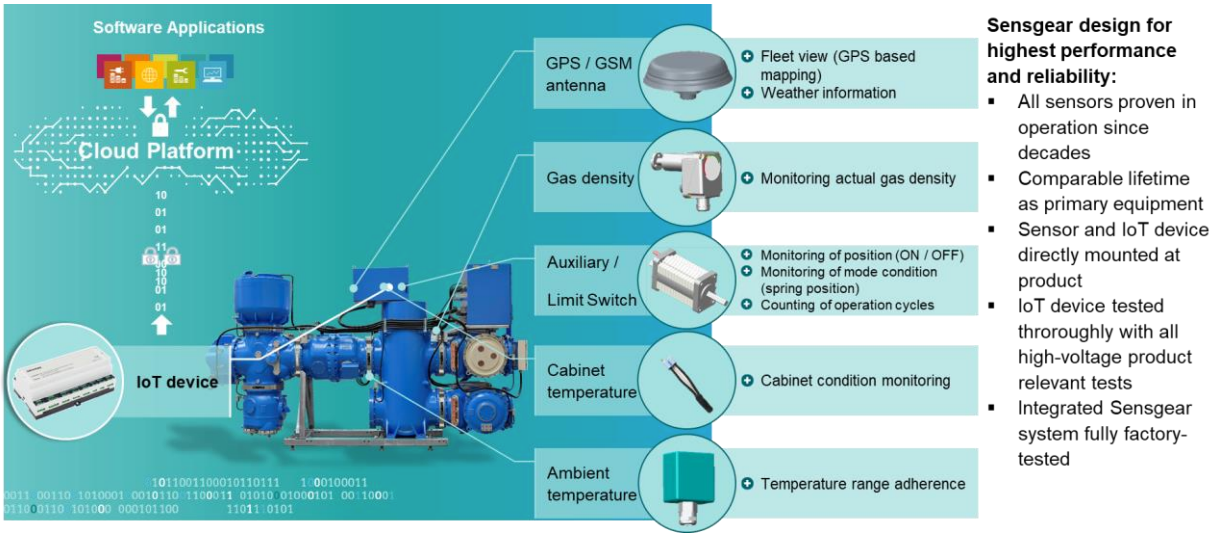

Figure 7 Sensgear integrated equipment with reliable sensors and IoT connectivity device, example GIS

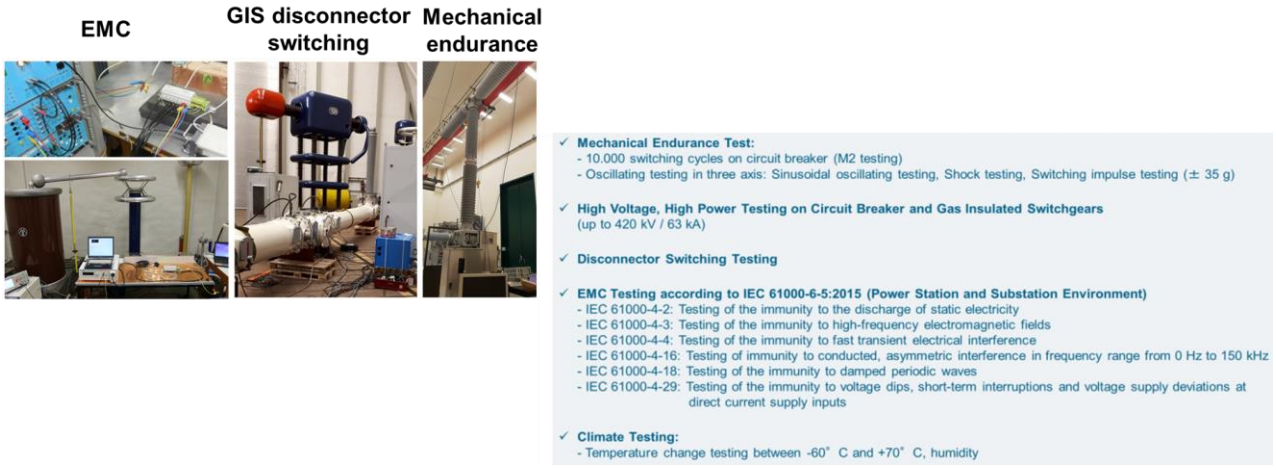

Figure 8 Test impressions Sensproducts and overview sensproducts qualification tests

As with the Sensformer the connectivity is based on a “read-only” concept without any influence or control on the device’s operation. The first installations fully demonstrate the reliability and quick uncomplicated installation. **Figure 9**

Figure 9 Sensgear installations for a CO_2 neutral / blue Circuit Breaker (left) [7] and a blue GIS (right) [8]

3.2 Sensgear advanced – Digital twin operated & intelligent

In 2020, Sensgear advanced has been introduced as the next step supported by a digital twin operation. **Figure 10** shows the principal interaction of Digital Twins to increase performance of real operation. The main functionalities of Sensgear advanced are active load and overload prediction based on real and virtual sensors advanced intelligence.

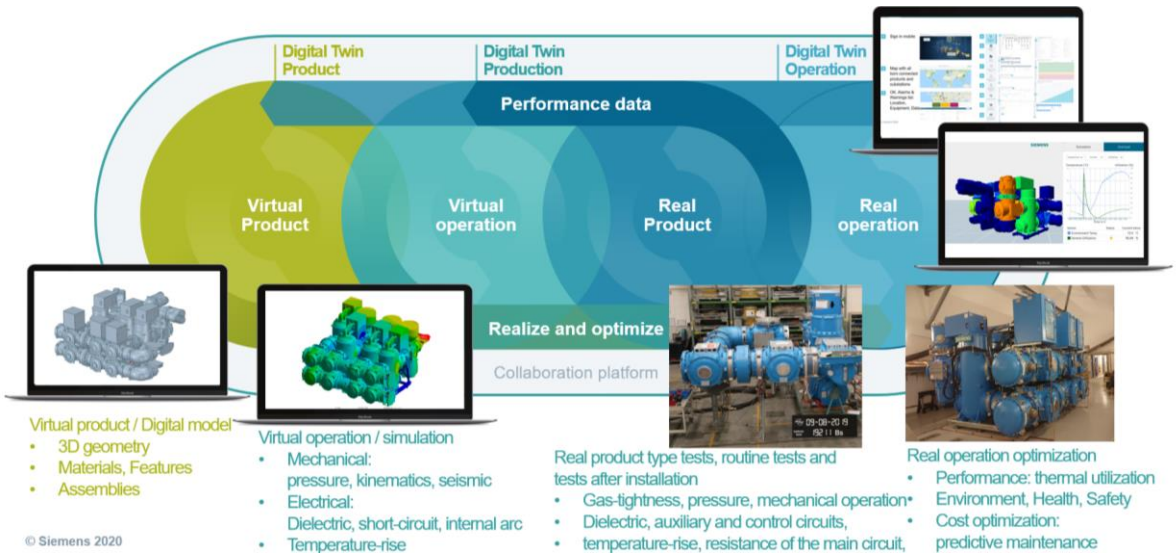

Figure 10 Sensgear Digital Twin Operation merging the real and virtual world – example Sensgear advanced GIS

Active load and overload prediction & management

For each GIS-module the original 3D digital twin with the respective geometrical, chemical / physical and thermodynamic properties is generated. A 3D power loss simulation is done for each module and combination of modules. The simulated module combinations are built in real and validated in temperature rise-type tests with temperature sensors on all critical parts. Additional short time overload tests are performed to validate the overload approximation of the thermal simulation model. The measurement and the simulation show high conformance. Benefits for the grid operators are higher performance and more transmitted power:

- Transparency on thermal utilization of the switchgear and its modules based on digital thermal twin and ambient temperature: virtual sensors
- Indication of continuous and temporary overload current capabilities without reducing reliability and lifetime, **Figure 11**
- Advice for additional power transmission potential through overload current
- Prediction of overload current capabilities based on ambient temperature prediction deducted from weather forecast
- Cost reduction potential through reduced re-dispatch

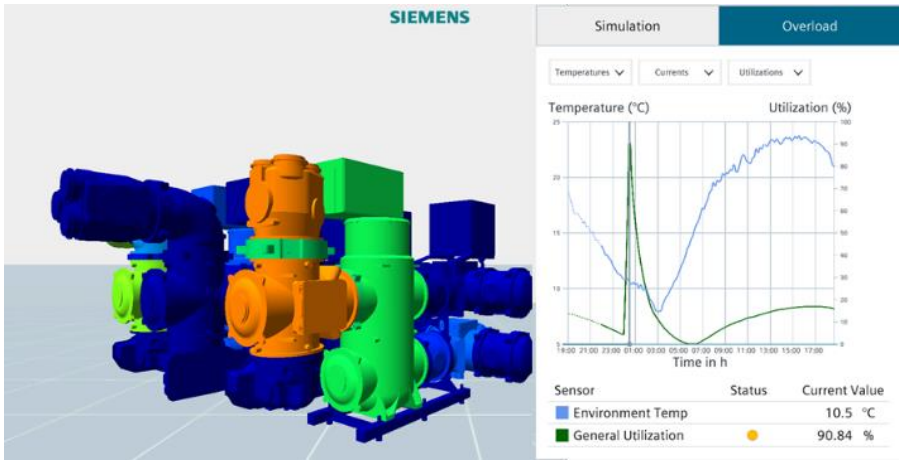

Figure 11 Example of Sensgear advanced GIS user cockpit

Advanced intelligence
Huge opportunities are possible by applying Artificial Intelligence (AI) to products and systems. From trending and prediction functionalities to complex decisions based on expert knowledge on product functionalities, behaviour, predictions and prescriptions. A first realized example is:

Gas Density Trending & Prediction -
Applying artificial intelligence to optimize gas monitoring
Conventional trending models require long data history (weeks) before performing linear interpolation. Faster and more accurate gas trending is achieved by applying neural networks to compensate sensor data with regard to weather influences. The AI model requires less historical data (days). Benefits for the grid operators are: Reduced SF_6 = CO_2e emissions, Cost savings for unplanned SF_6 leakage repairs and Less risk contingencies and penalties for SF_6 emissions

4 SENSFORMER AND SENSGEAR IN FLEXIBLE SUBSTATIONS OF THE FUTURE

Substation management in future grids requires managing the loadings and ratings of the different substation components [1]. Consequently, leading grid operators take actions and build flexible future substations: They consist of the full portfolio of Sensformer and Sensgear products, **Figure 12.**

Figure 12 Flexible Substation of the Future: Born connected and CO_2 neutral [11]
The additional benefit of the cloud connectivity of all Sensproducts is the combination of Sensgear and Sensformer data from all different Sensproducts to generate additional functionalities. Examples are the current data from AIS-instrument transformers and Power transformers used in the GIS for the overload simulation and management. The cloud architecture makes it easily possible to combine the data of all Sensproducts, tailor-made for operation, asset management or service.

5 USER INTERFACE, APP AND CYBER SECURITY

The visualization and analytics are performed in software applications. The platform is standardized and an integral part of Sensformer and Sensgear. For all products in a substation the same platform, application and user interface is used. Additionally, the fleet view enables the operators and asset owner of Sensformer and Sensgear to get transparency, productivity and intelligence of the whole installed fleet of Sensproducts. After logging in, the App offers via a secure mobile connectivity an instant overview about the asset status and near real-time data is accessible. The connected assets are visible with a general alarm overview. By clicking to an asset on the application map further details to the selected asset are shown. Moreover, the app enables for key KPIs push messages in case of alarms to simplify service and asset management essentially.

All transmission equipment will be delivered pre-equipped with the necessary hardware. The IoT connectivity device will be pre-configured and pre-installed on the transmission equipment as part of product manufacturing process in the factories. The transmission equipment is predominantly collecting and transmitting data to a secure storage and analytics tool. For safety and security reasons, there is only monitoring and no remote-control functionality that could actively influence a customer's operation. Data handling and security will be key for a reliable power transmission. State-of-the-art security and encryption technologies are the base. For data transmission to the cloud storage, an end-to-end encryption is used. Each transmission product has a unique ID, which is also used for encryption. The transmission is via HTTPS with a 256-bit TSL encryption. It complies with state-of-the-art data handling and management guidelines to ensure your data privacy and secure segregation in the cloud. IoT device and cloud services fulfil the highest cyber security standards, **Figure 13.**

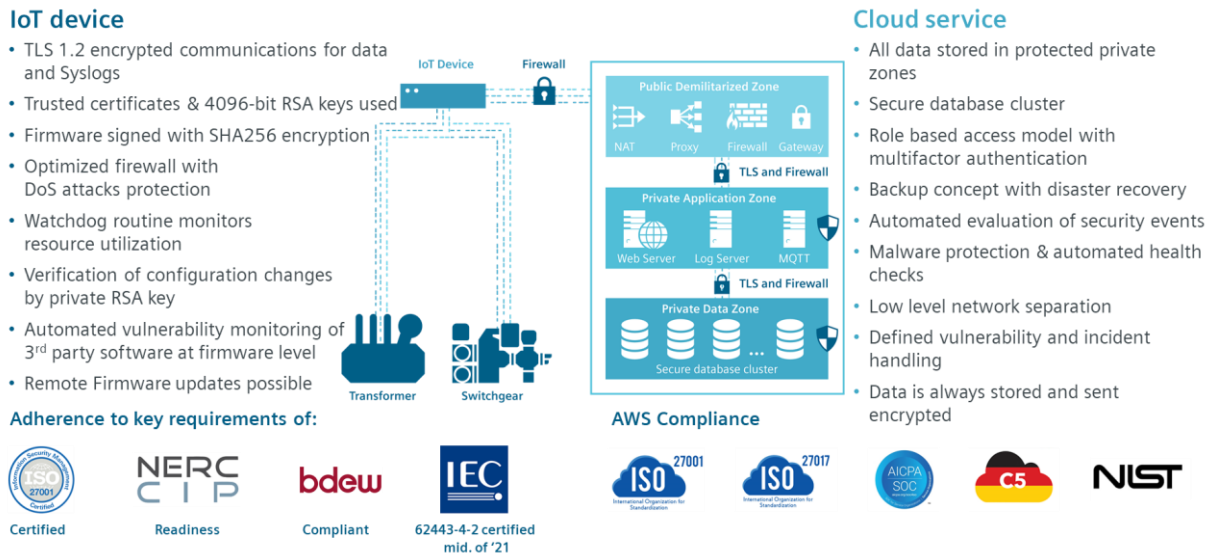

Figure 13 Customer data, IoT device and Cloud service safeguarded by latest cyber security standards

6 SUMMARY AND OUTLOOK

The new generation of Sens-Transmission products is installed globally, **Figure 14**. In the first year after market introduction, 500 units were delivered. Merging reliable hardware, cloud connectivity and digital twins enable operators to optimize performance, quality and speed of operational decisions as well as to become more flexible, act faster and more efficiently. Moreover, Sensgear and Sensformer provide an open platform that enables operation, asset management and service to combine substation data in the cloud easily according their requirements. The interaction of the connected Sensproducts in systems and substations will make operation more effective. Customers benefit from increasing their revenue by flexible equipment operation in controlled overload, lowering their OPEX and total expenditures while making use of the state-of-the-art digital capabilities built on high quality conventional transmission products

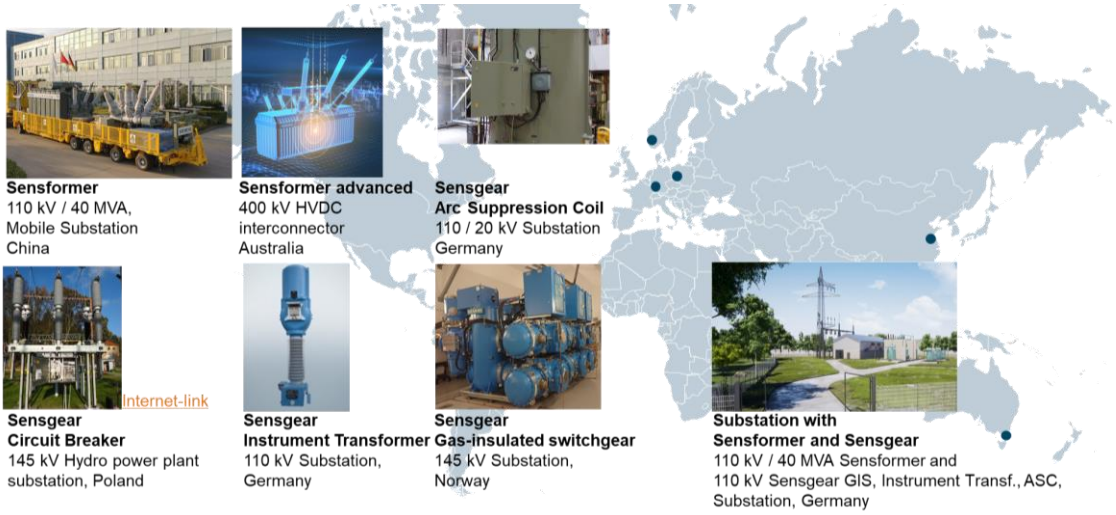

Figure 14 Selected Sensformer and Sensgear installations

Summary and Outlook:

1. Sensformer and Sensgear merge reliable products with cloud connectivity and digital twins without impacting the control & protection philosophy
2. Benefits are: Grid operation becomes more flexible, service predictive and prescriptive and asset management more effective
3. Digital twin operation available for Power transformers, will be available for GIS and AIS-switchgear and coil products starting end of 2020
4. Sensproducts will increasingly interact in substations and systems
5. Product intelligence will be further developed, from trending and prediction to complex decisions based on expert knowledge of operation, products and systems

BIBLIOGRAPHY

[1] Cigre Study Committee B3 Substations and electrical installations: Expected impact on substation management from future grids. Cigre Technical Brochure 764, 2019

[2] Cigre Study Committee A2 Power transformers and reactors: Condition assessment of power transformers. Cigre Technical Brochure 761, 2019

[3] Cigre Study Committee A2 Power transformers and reactors: Transformer bushing reliability. Cigre Technical Brochure 755, 2019

[4] Cigre Study Committee A3 Transmission and distribution equipment: Non-intrusive methods for condition assessment for distribution and transmission switchgear. Cigre TB 737, 2018

[5] Cigre Study Committee A3 Transmission and distribution equipment: Ageing high voltage substation equipment and possible mitigation techniques. Cigre Technical Brochure 725, 2018

[6] Kuschel, M.: Helbig, D.: Heinecke, M.: Singh, P.: Sensformer and Sensgear - Intelligent IoT-connected HV T&D Products. Proceedings of Internat. Conference on Condition Monitoring, Diagnosis & Maintenance; CMDM 2019; Bucharest, Romania; Sept. 9th–11th, 2019

[7] Sensformer® and Sensgear® info: https://new.siemens.com/global/en/products/energy/high-voltage/transmission-products/sensproducts.html

[8] Kuschel, M.: Albert, A.: Ehrlich, F.: Nesheim, N.: Pohlink, K.; Rank, T.; Skar, J.: „First 145 kV / 40 kA gas-insulated switchgear with climate-neutral insulating gas and vacuum interrupter as an alternative. to SF6 -Design, Manufacturing., Qualification and Operational Experience". CIGRE session, Paris, 2020

[9] Wold Economic Forum: Global Innovations from the Energy Sector 2010-2020. WEF White Paper, Geneva 2020

[10] Helbig, D., Fritsche, R., Heinecke, M., Singh, P.: Intelligent IoT-connected transmission equipment in sub-stations. Technical paper B3-305, Cigre Session 2020

[11] Engel, M.; Oechsle, F.; Helbig, D.; Kuschel, M.: Hochspannungsanlagen im 21. Jahrhundert. Fachtagung Hochspannungs-Schaltanlagen, TU Darmstadt 2020