Transformer innovation in a changing energy landscape – Part I

ABSTRACT

We are in a changing energy landscape, transitioning to the future of energy on waves of innovation that respond to the economic, demographic, and environmental challenges of today. Electricity is becoming an important contributor to the energy transition in a connected and data driven society with rising electrical mobility. The future of energy will be electrical, digital, intelligent and sustainable supported by innovation, making significant progress in the way that electricity is generated, distributed, managed and consumed.

Transformers are part of this energy transition contributing to current megatrends like renewable energy, digitalization, sustainability, energy efficiency, circular economy etc. They are preparing for the future with developments in materials, design, manufacturing processes, components and services. Digitalization is becoming a pivotal element, that will not only help operation and maintenance during the transformer lifecycle (i.e., with artificial intelligence powered by relevant data and machine learning algorithms), but will also reshape relationships between the user, manufacturer and service providers with new business models. At the same time, the industry is experiencing a paradigm shift – immersed in a transformation process, becoming faster and more efficient, optimizing operations – with companies restructuring themselves to enhance profitability or in some cases simply looking to survive.

Transformer innovations are instrumental in addressing all those challenges, not just with pure R&D or technology developments but encompassing processes and operations across the whole value chain from design till transformer operation and maintenance.

This article presents different cases of transformer innovation, to illustrate how the industry is contributing to the future of energy, through digitalization; pushing into new boundaries; helping the development and integration of renewables; supporting other growing segments and industries; pursuing new frontiers of reliability and resilience; enhancing sustainability and energy efficiency, and readying for the future with new developments and innovations to come.

KEYWORDS

transformers, innovation, energy, renewables, data centers, digitalization, energy efficiency, ultra-high voltage, generator transformers, dry transformers, power transformers, HVDC, FACTS, STATCOM, machine learning, nanomaterials, additive manufacturing, 3D printing, asset management, traction transformers

Figure 1. Seven 600 kV HVDC transformers as a paradigm of transformer innovation

1. Introduction: Transitioning to the future of energy

Energy is an important part of human development, driving economic and welfare progress. In this journey, the energy industry has been evolving gradually and, sometimes, leapfrogging in disruptive waves of innovation. We are now transitioning to the future of energy, riding a new wave, with megatrends addressing today's economic, demographic and environmental challenges.

We are in a changing energy landscape, transitioning to the future of energy on waves of innovation that respond to the economic, demographic, and environmental challenges of today

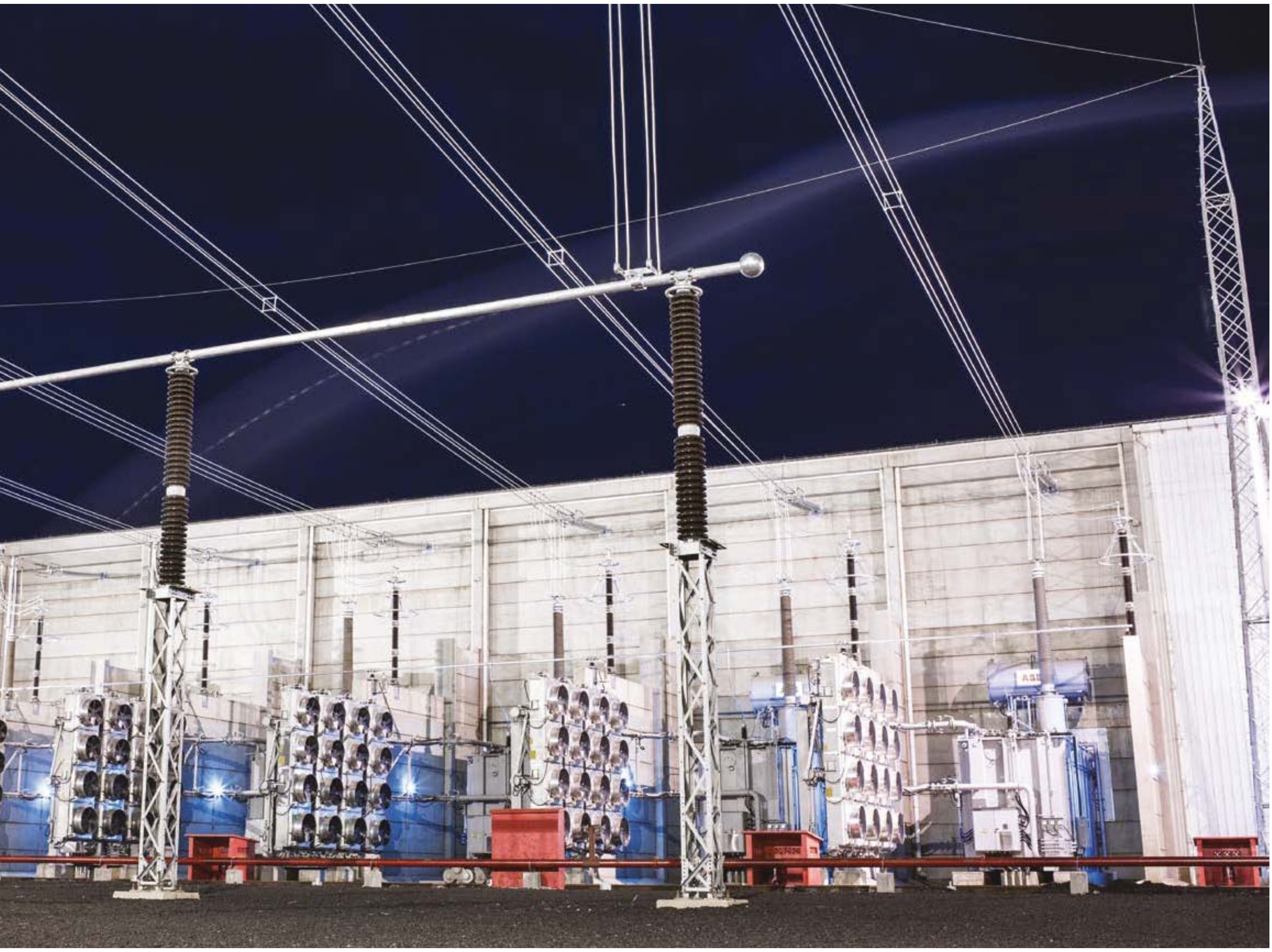
Global energy demand is expected to grow more than 25 % by 2040 with electricity becoming an increasingly relevant part of the energy mix – signalling the global move towards a more electrified world:

- The world population will keep growing and people will migrate increasingly to cities and other urban areas, especially in developing regions.
- A further connected and data driven society; with data centers becoming the brain behind progress; and intelligent devices and robotization helping people with their day-to-day activities and propelling companies to higher productivity.
- Electrical mobility will be predominant with the rise of all types of electrical vehicles: automobiles, and bicycles.

The industry is getting prepared to satisfy the increasing energy demand, while simultaneously pursuing sustainability and affordability for continued, long term development:

- Sustainability: Fighting climate change and global warming, improving energy efficiency and reducing environmental impacts and emissions, moving toward carbon neutrality.
- Affordability: Advancing with economic sense, reducing costs to keep driving progress, growth and employment.

This new wave of innovation is boosting technological progress, at a pace of change that is faster than ever:



Transformers are part of the energy transition contributing to current megatrends like renewable energy, digitalization, sustainability, energy efficiency, circular economy etc.

- All types of renewable energy sources are becoming prominent in the energy mix, driven by their technology advancement and significant cost reductions, with both large utility and smaller scale renewables being deployed across all regions, contributing to decarbonization.
- The extra renewables integrated into the system will keep changing the network topology and its operation, with decentralized power generation and virtual power plants adding flexibility and operability.
- New means of energy storage will contribute to manage the excess of renewable electricity that can be re-used at peak-demand times. Energy storage will not be limited to pumping hydro stations or larger scale batteries, but will also open up to other alternatives, like producing clean fuels (e.g., hydrogen via electrolysis) or the coordinated use of vehicles and home batteries.
  The introduction of battery-operated grid connected electrical vehicles and ultrafast chargers will require distribution networks to step up and cope with the extra demand and new consumption patterns.
  Charging could add significant peak electricity demand, but if coordinated with flexible charging, the vehicles may utilize the excess electricity: by solar charging during the day, varying the charge rate or with load balancing services.
- Challenges for the grid will be associated with power flow becoming increasingly complex and bi-directional, particularly when powering-back to the system, with the need to have a regulatory framework to govern those interchanges.
- Digitalization will continue to progress – to have more interconnected, intelligent, efficient and reliable grids; smarter power and distribution networks with data analytics enabled by artificial intelligence driving complex autonomous processes; and improving operability and efficiency. New business models, placing generation and consumption closer, will change the relationship between suppliers and consumers, that may become prosumers, with governments and regulatory bodies playing an important role.
- Energy efficiency and circular economy will further develop to support sustainability and enable better use of existing resources.
- Data centers will keep growing, claiming a more important share in the overall energy demand with some predictions indicating an overall consumption up to 20 % of the world's energy.
  Data center companies are already incorporating efficiency best practices, for example the use of artificial intelligence to directly control cooling systems or to reuse it for heat generated by the datacentres for heating. They are also increasingly sourcing green energy to reduce their carbon footprint and pursuing reliability to power all those servers. This is not only because of the costs, but also due to the social impact, as cloud computing gradually becomes critical to daily life.

Therefore, the efficient use of data and data austerity will become a topic of discussion equivalent to that of efficiency in appliances and electrical apparatus.

Preparations for the future include developments in materials, design, manufacturing processes, components and services

In summary, a disruptive wave of innovation will lead us to the future of energy that will be electrical, digital, intelligent and sustainable with significant progress in the way electricity is generated, distributed, managed and consumed.

2. Transformers, part of the energy transition and into a paradigm shift

Transformers are part of the energy transition, contributing to that new wave of innovation and facing the challenges of the evolving grid. They are getting ready for the future of energy with developments in materials, design, manufacturing processes, components and services. Digitalization is becoming a key element, opening the door to changes in the whole transformer lifecycle – how they are designed, operated, maintained or decommissioned, and reshaping the relationships between users and manufacturers with new business models.

At the same time, the industry is in a paradigm shift, immersed in a transformation process and subject to a different set of challenges that affect the whole value chain. For example: increased competitive pressure; globalization; consolidation; the rise and growth of new and existing players; overcapacity compared to demand; relevance of supply management or financial roles in corporate decisions; scrutiny and further complexity of large capital expenditures; requirement of shorter cycles and many others.

The industry is evolving and responding to these challenges, becoming faster, more efficient, and optimizing operations, with companies restructuring to enhance profitability or in some cases looking for survival.

Transformer innovation

All this pushes for innovation, not only to address the energy transition megatrends within the R&D or technology arena but also pertains to the whole value chain: looking at the business structure or the degree of vertical integration; how the industry is operating to fight commoditization; the optimization of business processes and operations to secure quality and enhance efficiency; challenging how the transformers are conceived by applying well-known concepts like design for manufacturability and other tools, like design-to-value; putting the user and their needs at the center to enhance collaboration and speed.

This article reviews different cases of transformer innovation, to illustrate how the industry is contributing to the future of energy, not only with digitalization but by pushing into new boundaries; helping the development and integration of renewables; supporting other growing segments and industries; pursuing new frontiers in reliability and resilience; enhancing sustainability and energy efficiency, and getting ready for the future with new developments and innovations to come.

3. New boundaries, keeping alive the pioneering spirit

Pushing up voltages and power ratings

Ultra High Voltage transformers

The race to reach and operate the grid at higher power and voltage ratings started with electricity pursuing economy and efficiency. Over the years, transformers have been part of that competitive race, pushing the limits, addressing the associated complexities and, at the same time, being efficient and sustainable, Fig. 2.

Ultra high voltage (UHV) power transformers today are reaching 1,100 kV DC and 1,200 kV AC, and are pushing power output to ever higher ratings, now largely exceeding 10,000 MW in the most powerful converter stations.

As a reference, in HVDC transformers, higher voltages have been developed on both the DC and AC sides, with DC reaching 1100 kV and AC 800 kV voltage levels.

UHV transformers utilize advanced technology, especially relevant when associated to the dielectric performance. The transformer insulation structures must be prepared to cope with the increased voltage stresses, by using advanced solutions for winding insulation, leads design and turrets insulation. The nonlinear characteristics of the insulation strength result in other complexities required to meet the mechanical and thermal constraints that are exacerbated further by the larger size and dimensions that come with the higher power ratings.

Digitalization is becoming a pivotal element, that will help operation and maintenance during the transformer lifecycle, but also reshape relationships between the user, manufacturer and service providers with new business models

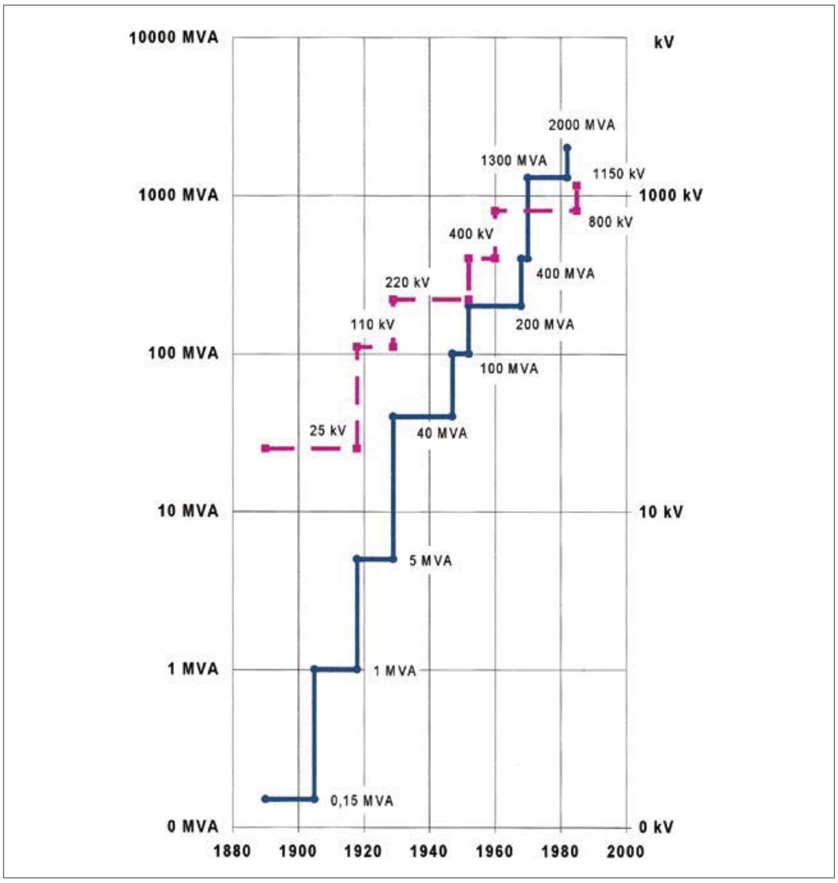


Figure 2. Overview of increase in transformer rated voltage and power [1]

Transport challenges come into play posing dimensional restrictions even after considering single-phase solutions with multi-wound cores.

The set of challenges are compounded on the manufacturing and production side where winding facilities, core stacking equipment, active part manufacturing, vapour phase drying equipment, lifting capacity and test room capabilities are needed to handle those increased dimensions, mass and test voltages.

To put it into context the power, weight and dimensions of the new generation UHV transformers are massive. The rating of one of the 1,100 kV HVDC transformers developed by ABB is 607 MVA single-phase with an installed weight of more than 800 metric tons and a total length of 32 meters.

Transformer bushings are also huge at those voltage levels and extra current ratings. To understand the order of magnitude, 1,100 kV DC bushings are approximately 40 % longer, three times heavier and 30 % larger in diameter than 800 kV DC bushings. The increase of overall diameter comes from using larger conductors to handle the current rating, with major design steps taken to meet the higher

Figure 3. 1100 kV DC Bushing

UHV power transformers today are reaching 1,100 kV DC and 1,200 kV AC, and are pushing power output to ever higher ratings, now largely exceeding 10,000 MW in the most powerful converter stations

operating requirements and test voltage levels for DC voltages. For example, air side corona shields are designed to match the bushing and reduce the stress in the high voltage side; and seismic requirements are evaluated together with the transformer and not individually.

Higher power generator transformers, new generation nuclear stations

Another example of pushing boundaries comes from the power generation sector where more powerful new generation nuclear reactors are coming into play with the EPR technology (European, also called Evolutionary, Pressurized Power Reactor).

The EPR is a third-generation pressurized water reactor, capable of achieving 1,650 MW of power output (compared to 1,450 MW for the most modern reactors) with a higher yield than previous models and requiring 17 % less fuel.

Current installations using EPR technology, under construction at different stages, are Olkiluoto in Finland with 1600 MW and two other new-generation nuclear power plants located at Flamanville in France (1650 MW) and at Hinkley Point in England (1630 MW) with three single-phase banks. In these cases, higher power rating transformers are needed to cope with the extra energy output coming from the generator.

The British power plant Generator Step Up (GSU) transformers are also combined with on load tap changer (OLTC) regulation. Single-phase transformers with 700 MVA output each, with a total 20 % regulation span, meaning 2,100 MVA of total power of the three-phase bank, are required for connection to the 400 kV system.

Multiple challenges are addressed in these types of large generator transformers, challenges that the higher power ratings impose on the thermal, magnetic and mechanical aspects of the design. This particular case is also prepared to operate at 15 degrees lower temperature than required by the standards to secure a longer life span and reliable operation which means additional size and weight, but which in turn entails detailed control of the hot spot temperatures and cooling requirements. In addition, the current in the high voltage side exceeds the range managed by any existing tap changer, requiring the use of two units in parallel, meaning increased total complexity, size and weight with the fully assembled transformer reaching 400 tons.

However, the development of large power stations is reduced worldwide with the advent of renewables. Very large generator transformers are also used less than in the past, posing challenges to the in-

Figure 4. 1200 kV AC Power transformer at the substation in India

dustry, specifically associated to knowledge management, considering the high level of expertise behind those type of units to secure a reliable and long operation.

Extending dry transformers to sub-transmission applications

The boundaries are also being pushed up in smaller size transformers with dry transformers today reaching voltage levels up to 145 kV.

For years, dry-type transformers have been associated with low and medium voltage applications, but that has changed to expand their environmental and risk mitigation benefits.

The traditional application is now extended to higher voltage and power ratings, incorporating oil-free on load tap changers, to cover (from the distribution side) buildings, hospitals, rail traction infrastructures like metro stations, till sub-transmission levels where they are increasingly used in metropolitan areas to step down three-phase medium-voltage to low-voltage for power distribution.

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Figure 5. 72 kV HiDry transformer with OLTC

Traction transformers are one of the cases where lighter weight and smaller dimensions are very important, to fit into locomotives of electric multiple units and high-speed trains

The challenges of increasing the ratings of dry transformers are not only associated with the insulation structure but also with their larger dimensions and weight and with transformer components like the dry tap changers to accommodate higher voltage classes.

Today, there are several installations around the world with dry transformers up to 72 kV, 63 MVA with good performance, for example in urban substations at city centers. A prototype of up to 145 kV is already tested by ABB with its power rating taken up to 63 MVA (Figure 5) to consider feeding main load centers.

Smaller size and dimensions

Traction transformers

Boundaries are also being pushed in the other direction, to make transformers more compact and smaller, keeping the same ratings and capabilities, or to use new technologies not applied before for a particular application.

Traction transformers are one of the cases where lighter weight and smaller dimensions are very important, to fit into locomotives of electric multiple units and high-speed trains. Efficiency becomes more important to help consume less power (energy costs might represent up to 10 percent of rail operator expenses) and support greener rail transportation in line with two of the main rail industry objectives.

Traction transformers are among the heavier components on a train and there are two innovations that are opening up new possibilities:

- Lightweight transformers: Changing the mechanical conception, reducing the quantity of oil. Supported on an innovative approach of mechanical integration, less oil is used, exactly where it is needed around the windings, reducing the oil weight up to 70 % and the total weight up to 20 %, adding design flexibility and less use of materials to combine the weight reduction with a significant reduction of losses (Figures 6 and 7).
- Rail dry transformers: This is an example of innovation used in existing technologies in fields not previously considered and exemplifies how their inherent benefits fit the needs of the application. For example, lower associated maintenance (no oil, no oil pumps, no air dryer to keep the oil dry…etc.) and higher fire resistance for improved safety. Dry transformers for this application also allow load losses reduction for higher efficiency levels.

Medium voltage, medium frequency transformers

Medium frequency transformers (MFTs) can be used for weight and dimension reduction purposes for converters and demanding power electronics applications.

In contrast with Low-frequency transformers (LFTs) that are directly connected to the grid [the operating frequency (fundamental frequency) being the grid frequency, i.e. 16.7, 50, 60 Hz], MFTs are connected to converters (DC/AC, AC/DC, DC/DC). The fundamental fre-

Figure 6. Effilight, an innovative solution to get lightweight traction transformers

Figure 7. Resibloc traction, dry transformers for railways traction

quency is then of several kHz or more and the waveform also often contains harmonics at much higher frequencies (tens of kHz).

The transformer size therefore reduces very significantly when the frequency increases. Since both the magnetic flux and the number of turns is inversely proportional to the frequency, increasing the frequency enables a reduction of the core cross-section and of the number of turns in the windings. The combination of reduced winding diameter and a lower number of turns also reduces the conductor length and the electrical resistance, which is the main reason why MFTs are more efficient than LFTs.

There are some key physical differences when comparing LFTs with MFTs, for example, the materials due to losses:

- The core losses caused by the flux at medium frequencies are much higher, meaning that standard core materials cannot be used. To limit core losses, much thinner steel sheets (down to a couple of microns thickness) or ferrites must be used.
- Similarly, the medium-frequency content in the current has a very strong impact on copper losses, and in the same way, the conductors have to be split into many parallel cables with a very small cross-section (so called Litz wire).

To better understand the order of magnitude, compact (less footprint, dimensions and weight) MFTs are being used for example at the CERN particle accelerator in Geneva, Switzerland – like the proton synchrotron required a well stabilized DC voltage of 25 kV using DC/DC converters with the following characteristics: 22 kHz operating frequency, 160 kVA rated power, ester oil insulated, KNAN cooling, two primary and 24 secondary windings, 580 × 480 × 400 mm dimensions and 90 kg weight (Figure 8).

Medium frequency transformers can be used for weight and dimension reduction purposes for converters and demanding power electronics applications

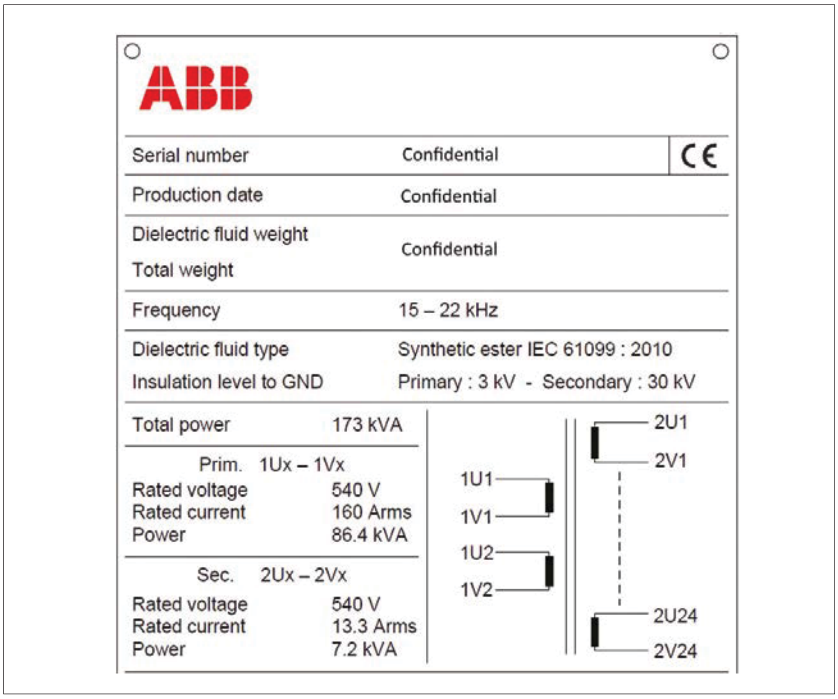

Figure 8. Nameplate of CERNS 173 kVAs MFT

Supporting the oil and gas industry, subsea transformers

The oil and gas industry are operating at deeper distances under the sea to get access to additional sources. They are also gaining efficiency and extending the economic lifetime of the fields by moving equipment from platforms to the sea bed (i.e. pumps, compressors, pipeline heating, distribution and frequency conversion equipment), envisioning to have a complete subsea factory.

Subsea transformers allow pumps and compressors to be placed away from the power supply on the platform. A typical system to power a motor on the seabed consists of a transformer and an inverter on the top, a submarine cable and a subsea transformer to adapt the voltage to feed the machinery at the bottom.

Higher transmission voltage reduces the load current and therefore the size and weight of the cables and the voltage-drop across them. The transformer challenges include managing the harmonic distortion, being prepared to withstand the high pressure from deep water and providing a maintenance-free operation.

Subsea power transformers may reach 100 MVA (Figure 9) with operation up to 3,000 meters below the surface. Two different solutions with oil technology are available, a single or double shell tank, without a conservator, equipped with a pressure compensation system to equal the internal and outside pressures, avoiding collapse. The low temperatures of the sea provide the necessary cooling.

Due to the advantages of the application, the use of subsea transformers and reactors may be extended in the future to grid connections of offshore wind generation, wave power or tidal turbines. Reactors will be used due to long submarine AC cables.

Subsea transformers allow pumps and compressors to be placed away from the power supply on the platform

Figure 9. Subsea transformer

Solar transformers are exposed to the harmonic components of the inverters, typically in 2-150 kHz frequency range

4. Renewables applications

The generation of renewable energy is one of the main drivers of the energy transition. There are multiple developments and innovations associated with the diverse types of renewable energy sources and their applications, that in general have different types of challenges and requirements.

For example, solar transformers are exposed to the harmonic components of the inverters, typically in 2-150 kHz frequency range. Wind turbine transformers are following the trend of increased power ratings of turbines with higher voltages while kept efficient and dimensionally compact; and offshore wind transformers are prepared for a salty corrosive environment and vibrations, installed in offshore substations with demanding size and weight restrictions.

Solar

In solar applications, some of the developments of the recent years have been devoted to address the need for shorter design, development and construction lead cycles, to deliver the transformers and get them ready faster for installation and operation.

A good understanding of the application requirements is the enabler – by developing standardized concepts that can be quickly implemented in customized solutions for a particular project; providing economies of scale and process efficiency to support the short cycles and cost reductions demanded by the industry.

Containerized solutions are an example: adapted to any required power output, with liquid-filled or dry transformers, i.e., from central inverters with output voltage of 1,000 V DC for high efficiency to multi-winding solutions for 1,500 V DC up to several MVA, those are available inside a conventional container for installation and logistical savings.

The use of ester fluids in liquid-filled transformers, their operation at higher-temperature or energy-efficient designs based on different inverter power and voltage ratings are also alternatives to optimize the total cost of ownership and reduce the environmental impact in this type of application.

Wind

The wind turbine transformers connect the turbines to the distribution system, stepping up the output voltage from the generator while power collection transformers are installed downstream for connection to the high voltage grid.

The manufacturers of wind turbines are competing to grow their size (in the way to reach 12-14 MW each), and that is helping to reduce the levelized cost of energy. The transformers are following that trend, growing in power and voltage ratings, with voltage outputs up to 66 kV at transformer exit, being compact and efficient while contributing to overall efficiency gains.

The main challenges of turbine transformers are the intermittency of wind with variable output and thermal cycles; the interface with the drive train and other electricals (harmonics); mechanical (like vibrations) and corrosion related problems. All these may be addressed with compact and lightweight designs with minimal footprint using (in the case of liquid-filled transformers) forced oil and forced water cooling methods, sealed and vacuum-proof moisture-free tanks and ester fluids.

Their installation could be at the nacelle or on the ground floor, inside or outside the tower. To optimize costs, transformers locations are defined by reducing the length of the connection to the lower voltage side which means placing the wind generator and the transformer as close as possible. In onshore applications near the tower base, or within the tower or nacelle in offshore – with the nacelle being the most demanding location.

Power collection transformers complete the connection to the high voltage grid, with typical high voltage substations in the case of onshore wind.

Transformers on the platform ideally need to be light weight, small, low maintenance and reliable for reducing the system, platform and operational and maintenance costs

Offshore wind

In offshore wind farm locations, the collection transformers have typical ratings of several hundred MVA (up to 500 MVA nowadays) and up to 345 / 400 / 550 kV, and are installed in an offshore substation and connected through power cables to an onshore substation (the average distance to shore is about 50 km) where power transformers step the voltage further. The power output of offshore wind farms is increasing, and power rating of the cables depends on the configuration. Shunt reactors and other reactive compensation systems are used for power compensation and system stabilization.

There are multiple challenges for the transformers used in this application:

- Performance and reliability in the wider sense, from the main active part till the tiniest accessory, since any operation in an offshore environment is complex and involves a significant cost.
  Fire safety plus operation and maintenance are key aspects to address, with some of those, like the avoidance of electrical motors for cooling equipment being considered.
  Oil leaks from transformers may result in environmental pollution, this, together with other health and safety issues, may be a driver for change in the type of liquid insulation (i.e. ester fluid).
- Collection transformers have some kind of redundancy, typically following a n-1 approach, with demanding overload capabilities to keep the wind farm operating in case of a transformer malfunction or during maintenance periods.
- The dimensions and weight are an important restriction, as the cost of the platform is highly dependent on that, influencing the total cost of ownership, with specifications generally including weight and size related capitalization, on top of losses.
  Transformers are typically three

Figure 10. 66 kV WindSTAR transformer for installation in wind turbine towers or nacelles

Transformer innovations are instrumental in addressing the challenges, not just with pure R&D or technology developments but encompassing processes and operations across the whole value chain from design till transformer operation and maintenance

phase units, stepping the voltage up to 132 kV – 230 kV, with power ratings in the region of 100 MVA – 600 MVA, two or three windings configurations (i.e. double secondary) and an on-load tap changer.

Single-phase units are also associated with the alternative modular concept of offshore substations, where smaller size modules may reduce the total costs.

A lot of potential innovation is open for the future in this field, but we may expect a more generalized use of single-phase transformers as the power and voltages keep increasing.

- The mechanical aspects are also worth highlighting. With the transformers typically installed in the offshore substation at the construction yard, the whole substation is then shipped floating till the final destination.

  The transformers are sea fastened for transport and prepared to withstand the sea accelerations (worst case scenarios would be 6-3-2 g - longitudinal, vertical transversal direction), pitch and roll values and lateral and vertical accelerations for both transport and operation.

  Vibrations and platform movements can also happen during long-term operations with fatigue analysis performed for the defined design lifetime. Seismic conditions at the place of installation shall also be taken into consideration with the ground acceleration translated into platform acceleration.
- Corrosion protection for the harsh offshore environmental conditions complete the set of main challenges, with special surface treatments, severe service coatings or stainless-steel parts being used. Additional considerations include methods to avoid galvanic bimetallic corrosion.

Transformers on the platform ideally need to be light weight, small, low maintenance and reliable for reducing the system, platform and operational and maintenance costs. The collaboration between the user, system integrator, platform builder and manufacturer is very important to coordinate and solve all those challenges.

Note: This article was first presented at ARWtr19, the 6th International Advanced Research Workshop on transformers held in September 2019 in Cordoba, Spain.

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