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PS1 - Experience and new requirements for transformers for renewable generation

Design challenges for large offshore wind turbine transformers

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SUMMARY

Power transformers designed for offshore wind turbine applications need to be able to operate for a minimum of 25 years in harsh atmospheric conditions while being subjected to extreme, ever changing environmental conditions. Saline and humid atmosphere as well as continuous mechanical vibrations from the wind create increase challenges for the mechanical designers of such transformers. The high current and voltage harmonics coming from the converters installed inside the nacelle which supply the power transformer creates significant challenges to the electrical designer who has to balance size, performance, winding hot spots and ageing. Lastly, tight space restrictions mean that a compact design and the internal arrangement optimisation of each components of such transformers is of prime importance.

Other key components of such transformers are the insulation liquid as well as the cooling system. These need to be carefully selected and designed to ensure the safest and most compact design possible. Maintenance in offshore wind turbine transformers is a very complicated procedure. It can only be carried out by personnel who is not only competent on the task at hand but also have special clearance and training to operate in such offshore structures and conditions. Lastly, the life cycle assessment (LCA) of offshore wind turbine power transformers is by definition of great importance. It considers environmental incoming and outgoing flows, including carbon emissions in air, water and land, as well as the consumption of energy and other material resources. Special software utilized to carry out the life cycle assessment of transformers.

This paper presents the different challenges faced by the transformer manufacturer when designing power transformers for offshore applications. It investigates the electrical and mechanical design challenges and proposes solutions. It also discusses the most optimum solution for the insulation liquid and gives a brief summary of the maintenance and monitoring of such transformers.

KEYWORDS
power transformer, electrical and mechanical design, harmonics, vibration, maintenance, offshore application, wind turbine, ester oil, life cycle assessment

1. Introduction

Strict governmental environmental policies and commitments towards a carbon free energy generation is creating a shift from conventional energy sources to renewable energy generation. The offshore wind generation market is estimated to grow at a significant rate in this decade alone. Offshore wind farms are becoming increasingly larger in energy production capacity which leads to larger wind turbines being deployed and, as a result, larger power transformers which are housed inside the nacelle of the wind turbines. Such a transformer is GE's Mistral-14 power transformer, (14 MVA, 66 kV power transformer) housed inside the nacelle of GE's Haliade-X 13 MW, capable of producing 71 GWh of gross annual energy production.

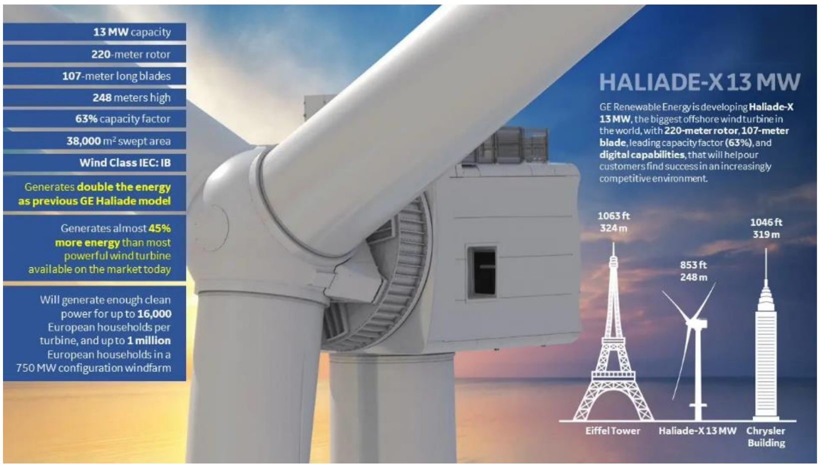


Figure 1- Comparative size of the Haliade-X wind turbine [1]

Figure 2 - 14 MVA, 66 kV power transformer

In large offshore wind turbines, the power transformer is placed inside the nacelle of the wind turbine. This enables the efficient transmission of generated power while minimising the underwater cable losses between the wind turbines and the offshore collector and converter platforms which can be several hundreds of kilometres apart. However, this arrangement also leaves the transformers exposed to harsh environments, such as humid and saline environments, with high vibrations, due to wind and the rotating blades. Specific solutions should therefore be defined and implemented to adapt standard technology to offshore application.

2. Electrical design – Impact, evaluation and mitigation of harmonics

Development of the power electronic equipment and turbine blade technology in the last decades allowed wind turbine manufacturers to reach higher power ratings with more efficient solutions. Converters are essential parts of wind turbines as well as power transformers. In general, in an electrical wind turbine system, a converter receives the energy at a variable frequency (depending on the wind speed) from a wind turbine generator and convert the energy into AC form at rated frequency to supply transformer and transfer the energy to the offshore substation before it is transferred on shore and on to the grid as shown in Figure 3. Transformers are vital parts of wind turbines and their overall dimensions play an important role in wind turbine design. Converters are a major source of harmonics which have a detrimental impact on all the devices connected in the grid. While the magnetic circuit design is similar for both onshore and offshore power transformers, an enhanced evaluation of harmonics at the design stage enables winding optimization thanks to a better control of the winding losses, hotspot and ageing and as a consequence helps to limit transformers overall dimensions as well as nacelle's ones.

In practice, from a transformer design engineer perspective, current harmonics mainly cause higher winding losses and as a result, higher winding temperatures and impact directly the transformer windings design. International Standards [2, 3] give guidance to assess the impact of current harmonics. However, publications [4,5] demonstrate that the methodology developed in the Standards is pessimistic and remains valid only if the conductor dimensions are low compared to the skin depth. For conductors with larger dimensions, it leads to conservative results as detailed by Y. Liu et al. [5] and consequently has an impact on the transformers size. Because of that, transformer manufacturers generally use electromagnetic Finite Element Method (FEM) and engineering tools to estimate the real harmonic impact on the transformer windings. Besides FEM, IEC 61378-1 [2] and IEEE C57-110 [3] standards propose alternative methods to calculate the correction for harmonic enhancement factors (FEW).

In addition, the effect of the geometrical winding arrangement and magnetic coupling of the transformer winding which affect the harmonic impact and transformer size should be considered during the wind turbine design stage. The selection of the winding configuration also depends on the converter design. IEC 61378-1 [2] gives the details for the different configurations for three winding core-type transformers. Loose coupling structures like double concentric and two-line parallel designs are preferred for such applications. Harmonics have various impact on both arrangements, and each arrangement has its own advantages and drawbacks with respect to electrical design perspective.

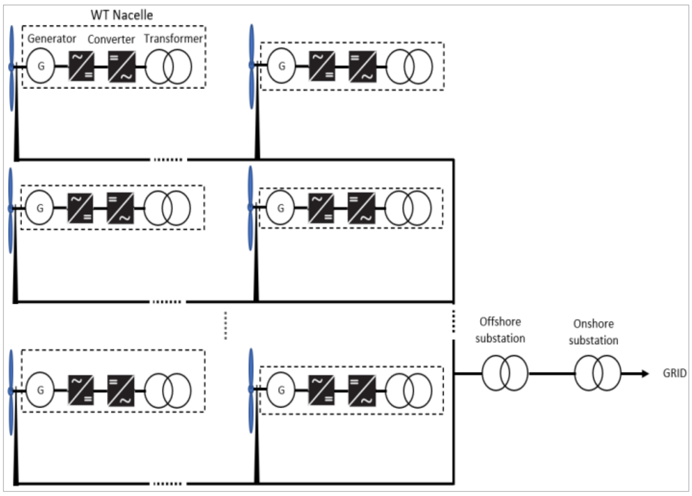
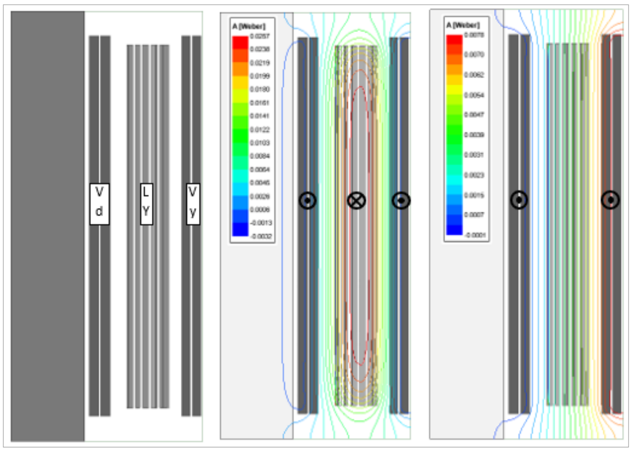


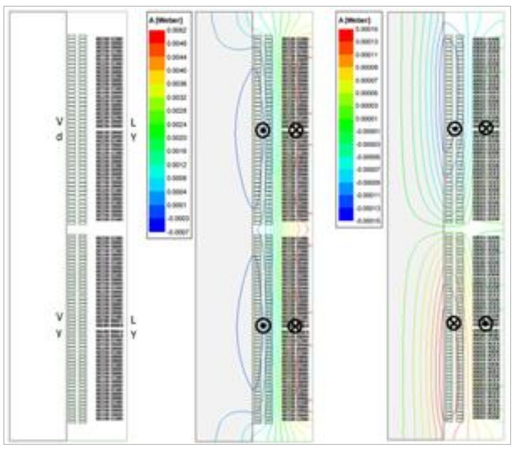
Figure 3 - Common layout of wind farm energy transmission

In double concentric winding arrangement, the line winding needs to be positioned between the two valve windings as described in Figure 4. In-phase harmonics, which have no phase displacement in between, flow from the valve winding, they add up and appear on the line side. However, in-phase opposition harmonics, which have 180° phase displacement between valves, the harmonics cancel in between the valve windings and do not appear on the line winding [2]. Double concentric winding design has an advantage in terms of short circuit forces because leakage flux distribution is uniform throughout the winding height and even when a short circuit event is faced by only one primary winding. In addition, local loss distribution is more uniform compared to other design options because flux corresponding to phase opposition and in-phase harmonics are oriented in the same direction. The disadvantage of this structure is that larger active parts are necessary compared to alternative solutions.



(a) (b) (c)

Figure 4 - Leakage flux of 3-winding double concentric design (a): harmonics in-phase (b) in phase opposition (c)



(a) (b) (c)

Figure 5 - Leakage flux of 3-winding axially stacked design (a): harmonics in-phase (b) in phase opposition (c)

In two-line parallel winding arrangement, the line windings and valve windings are axially split as described in Figure 5. Two-line windings, connected in parallel, are positioned with the valve windings arranged in the same radial direction. Similar to the double-concentric arrangement, in-phase harmonics flow from valve windings to line windings but in phase opposition harmonics cancel between valve-line windings and are not induced in the line windings. In this arrangement, local loss distribution may be non-uniform due to the presence of leakage flux distribution caused by harmonics being in phase opposition, as mentioned in [2]. In comparison to the double-concentric structure, the short circuit forces present in two-line parallel arrangement are higher. Indeed, this structure leads to considerable leakage field distortion, which in turn produces high axial short-circuit forces and end thrusts in the windings under short circuit, if a short circuit event is faced by only one primary winding, as discussed in [6]. The main advantage for such topology is to limit transformer size compared to other alternatives, which is one of the key drivers for wind turbine nacelle design transformers. However two-line parallel winding arrangement is the preferred solution for the wind turbine transformers as it is presenting optimized cost-effectiveness.

In the transformer design practices, the eddy loss enhancement factor for windings FWE is defined [2] as the ratio of the winding eddy loss due to the harmonics divided by the winding eddy loss due to the fundamental:

$$\text{FWE} = \frac{\sum_{h=1}^{N} P_{WEh}}{P_{WEh1}} \quad (1)$$

With P_{WEh} the winding eddy loss with the current at the nth harmonic, and P_{WEh1} the winding eddy loss with the current at the fundamental.

Methodologies described in standards are pessimistic as they rely on the assumption that strand dimensions are lower or comparable to skin depth, as detailed in [5]. This assumption becomes erroneous over a certain frequency range, and the well-known "h^2" rule (h being the harmonic rank) for estimating the harmonic enhancement factor is no longer appropriate to assess the impact of high frequency harmonics. However, alternative methods are proposed in standards appendices which suggest taking into account the conductors' skin depth to calculate more accurate results while considering the high frequency harmonics. With an explicit modelling of strands in the winding, it is possible to assess the high frequency eddy loss by FEM and perform a benchmark of four different methodologies. Table 1 presents results obtained by the authors for a fixed wind turbine transformer design and harmonic spectrum. A, B and C are the harmonic enhancement factors which are found by "h^2" rule given in International Standards. According to the FEM calculation results, the authors consider that the IEC correction method gives a more accurate estimation than the IEEE one.

Winding eddy loss enhancement factors			
Considered winding	Valve (star)	Valve (delta)	Line (star)
FWE calculated by "h^2" rule	A	B	C
FEW with IEC correction	0.74 x A	0.65 x B	0.79 x C
FEW with IEEE correction	0.58 x A	0.54 x B	0.53 x C
FEW calculated by FEM	Not modelled with acceptable accuracy		0.75 x C

Table 1 – Comparison study between different harmonic evaluation methodologies

Wind farm operators must comply with grid code requirements in terms of total harmonic distortion levels injected into the grid. Different harmonic elimination methodologies need to be considered during the wind farm electrical system design stage. In a two-winding transformer, ampere-turns are balanced, and the harmonic levels are the same between the valve winding and the line winding. For three-winding designs, specific vector coupling e. g. Yyd11 is efficient in eliminating, in principle, some specific harmonic components on the line side but not others. In phase opposition harmonics the circulating currents are not induced on the line. In current harmonics flow, the flux distribution allows a higher radial component than in-phase harmonics. This leads to higher eddy losses as the strand dimensions increase axially, and their sensitivity to radial flux in terms of eddy loss increases. In such winding layout of three-winding converter transformer, this aspect should be properly addressed so that harmonic eddy loss could be assessed more accurately.

Risks of overheating and/or derating due to these harmonics can be mitigated by using passive filtering devices (tuned on specific ranks), as well as active ones, to dynamically counteract the disturbances. Considering the prohibitive cost of civil engineering, volume and weight restrictions and stability constraints of the whole assembly, these filters might be quite expensive and therefore not suitable for offshore application. For this reason, the wind turbine transformer should be able to cope with the harmonics spectrum stated by the converter manufacturers. As a result, adequate care must be taken by the transformer manufacturer during the transformer electrical design to ensure that the transformer meets stringent restrictions on space, cooling and intermitted lower loading.

3. Mechanical design – Evaluation of external vibration withstand

Power transformers for large offshore wind turbines are installed inside the nacelle at the top of the tower and are designed to withstand transport loads [7], and when required earthquake excitation energy [8]. In addition, the turbine transformers will be also subjected to an unusually harsh vibratory environment due to the aeroelastic loads generated by offshore winds and the presence of other vibrating devices installed in nacelle (such as generators, gears or pumps). The overall dimensions and mass of the transformers installed inside the nacelles are restricted to a minimum so as to simplify installation and maintenance operations and to limit total costs. These strict and critical requirements make the mechanical design of such transformers much more complex compared to land-installed transformers.

The vibration withstand criteria defined by large wind turbine manufacturers for all devices installed in the nacelle are based on International and National Standards such as [9], [10] and [11] dealing with the classification of environmental conditions. IEC 60068-2-6 Standard [10] discusses for instance the type of experimental endurance tests that devices shall be subjected to. However, very few vibration endurance laboratories are able to excite heavy objects such as a twenty tonne transformer, and low frequency vibration amplitudes representative of wind and turbine excitations can’t be experimentally reproduced.

An effective alternative way to evaluate structural vibration withstand is to use calculation approach based on mechanical FEM. This offers solutions for modelling both static and dynamic behaviour of the structure under various excitation modes and enables analysing mechanical stress and fatigue levels in all transformers’ components. For power transformers installed in nacelles, three main verifications are performed by manufacturers:

(i) the absence of coincidence between wind turbine (tower, blades, and rear frame) and transformer main eigenfrequencies,
(ii) the structural withstand under harsh transport conditions, as offshore transformers can be shipped by a combination of road or rail and sea transport inside the nacelle,
(iii) the structural withstand under service conditions, for a duration of twenty-five years.

Dynamic compatibility between wind turbine and power transformer (i) is validated by the determination of the main vibration modes resulting from a modal analysis and by checking that related frequency ranges are not overlapping. Transformer structural withstand under transport conditions (ii) is verified by a harmonic analysis (integrating modal behaviour) and fatigue analysis to assess stress and damage levels. These levels are then compared with withstand criteria of the different material, including specific structural components such as welds. The effect of potential shocks happening during transport is determined by computing time-domain strength analysis with the excitation spectrum and amplitude defined in [8] and [10]. Finally, transformer withstand under service conditions (iii) is evaluated using the same analysis as for transport conditions, but with different acceleration amplitude spectrum and including static strength analysis for very low frequency range (below 4 Hz).

Several challenges and difficulties were resolved during the large offshore wind transformer mechanical design study. Beyond classical modelling and meshing strategies defined to build optimized models' size without compromising results accuracy, specific calculation methodologies were adapted to notably assess fatigue withstand in frequency domain, to demonstrate the ultimate fatigue life capability of welds (use of interpolation method required to solve stress concentration regions) and to evaluate the bolts withstand, with reference to defined methodology in standard [12].

Vibration amplitudes seen for nacelle-installed transformers are at least one hundred times higher compared to typical land-installed power transformers, and the most severe acceleration levels are concentrated well below 50 Hz. This frequency range approximately corresponds to the first global vibration modes of the transformer, leading to an amplification of stress levels (resulting from imposed low-frequency accelerations) and then leading to large displacements of heavy components such as the active part and tank walls. Consequently, the higher stress levels are calculated at the fixation parts – for instance, the interface between the active part and the tank cover – and at the accessories attachment points, for instance the conservator, pipes, heat exchanger or control cabinet.

As mechanical design margins in terms of mass, overall dimensions as well as location of the fixation interfaces with the nacelle framework are very tight, the transformer manufacturer has to adapt the design strategy to overcome numerous challenges. With offshore constraints, designers need to find the balance between stiffening the structure in weak locations and avoiding concentration of stress in the most fragile parts. This equilibrium can only be met by finely adjusting local stiffness to smoothly distribute constraints in large areas, or by introducing deformable components dampening vibration excitations. This strategy was applied around the fixations of the transformer to the nacelle, at the conservator fixations level and at the active part fixations to the tank cover. Figures 6 and 7 illustrate the type of results obtained during the mechanical finite element method design study.

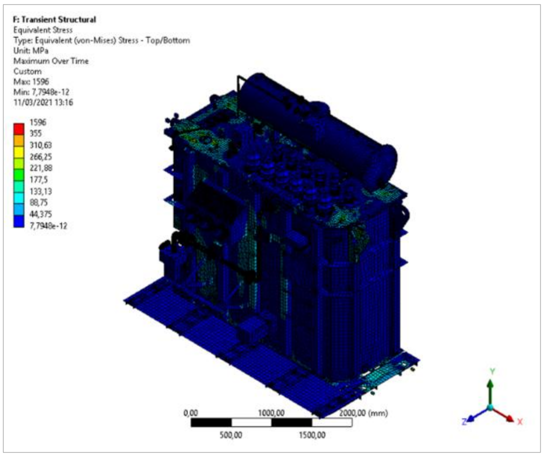
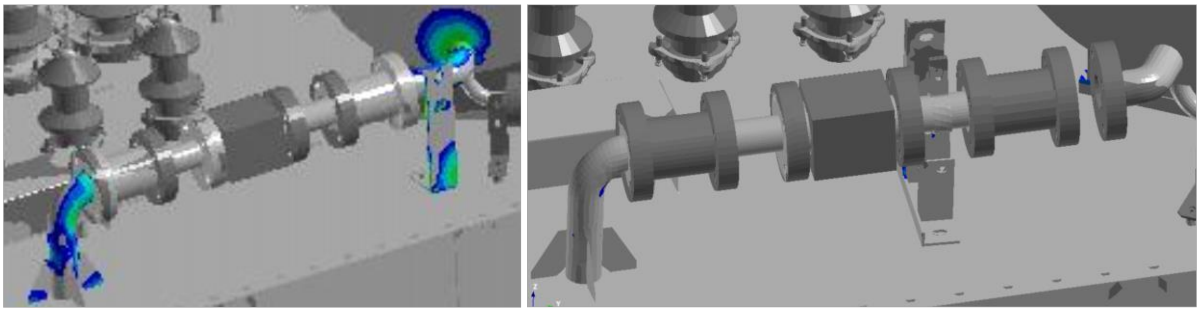


Figure 6 - Example of mechanical stress map resulting from shock excitation along vertical axis

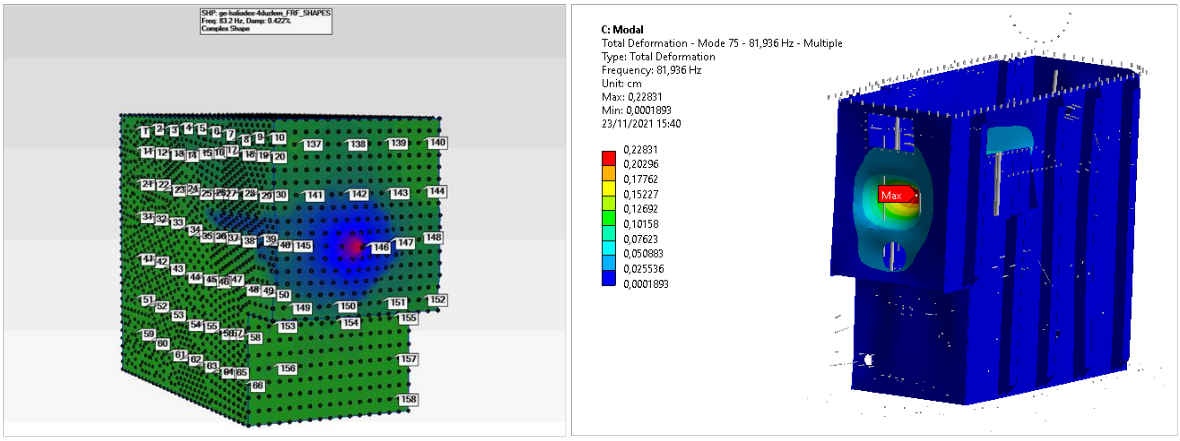


(a) *(b)*

Figure 7 - Fatigue damage plots of oil pipe at initial (a) and final (b) design stage (same colour scale)

Figure 6 shows typical stress distribution that can be obtained on the transformer external surfaces with finite element calculations. Figure 7 shows damage plots of the oil pipe connecting conservator to main tank at initial and final design stages for transport excitation. Important damage levels were found at initial stage, which was designed according to standard mechanical rules. After several calculation iterations assessing different structural modifications, a satisfactory design was obtained by changing the support location and stiffness and by introducing a flexible connector (not modelled as structural element on Figure 7 (b)).

The comprehensive calculation iterations of the transformer structure successfully comply with all the withstand criteria for storage, transport and at least twenty-five years of service. The results were obtained on numerical models and were validated by experimental investigations. However, endurance vibrations tests can't be performed on such large electrical devices. An alternative proposed solution is to assess the predictability of the finite element models results by comparing numerical modal analysis results with experimental modal analysis. Indeed, this kind of measurement campaign can be easily performed at transformer factories. If similar mode shapes and frequencies are determined between calculations and measurements, the finite element mechanical study is considered to be valid. Figure 8 presents a comparison between the measured and calculated results of one mode shape of the tank.



(a) *(b)*

Figure 8 - Representation of one vibration mode obtained by measurement (a) and calculation (b)

Figure 8 gives an example of a global vibration mode (first bending mode of upper short side plate) determined experimentally and numerically. This mode was computed at 81.9 Hz and measured at 83.2 Hz, giving a difference lower than 2 %. It is generally considered that the mechanical finite element models give a satisfactory predictability when the calculated frequency modes are within ±15 % of the measured values. For the transformer design studied by the authors, the obtained deviations between numerical and experimental results were less than ±10 % for all identified modes, thus validating the assumption that those mechanical models are representative of the transformer's real static and dynamic behaviours under various load cases.

4. Insulating liquids

Similar to conventional power transformers, the insulating liquid in offshore windfarm transformers works as an electrical insulation as well as a heat transfer medium. Nevertheless, one difference can be in the choice of the oil type. Indeed, for offshore applications, ester oils are preferred to the well-known mineral oil for two main reasons:

(i) ester oils have a better fire safety with a fire point twice higher (> 300°C) than mineral oil, decreasing therefore the risk of fire in critical areas such as offshore wind farms,
(ii) ester oils are biodegradable (OECD 301 tests), being less aggressive to the environment in case of leakage/spillage.

In addition to these two reasons, it is important to mention that ester oils have a better thermal class (130°C instead of 105°C for mineral oil) enabling therefore higher temperatures in combination with high temperature insulation (IEC 60076-14).

For the present project, synthetic ester (IEC 61099) was preferred over natural ester (IEC 62975) because of the higher oxidation stability, but also because of the better cooling performances in case of very cold climate (< -20°C). Indeed, the pour point of the synthetic ester is much better than the natural ester.

Nevertheless, product qualification has been achieved for natural ester recently and confirmed by experimental investigations [13] which have shown that vegetable oil with a sealed transformer could be used without any risk. In addition, the transformer is protected in a box inside the nacelle, as shown in Figure 9, reducing contact with the external environment and shielding it from the temperature decrease.

Due to the limited long-term experience in offshore environment, and synthetic ester having acceptable oxidation stability but very high hygroscopicity, a sealed system using a hydro compensator (rubber bag) inside the conservator (see Figure 10) with an automatic dehydrating breather (maintenance-free breather) is implemented. This concept was the result of a thorough risk assessment for synthetic ester, however natural ester will be implemented with the same design in the future.

Regarding the dielectric properties, the main differences between mineral oil and ester oil appear, under AC and LI, when the inhomogeneity of the field and the gap length increase [14, 15]. Dielectric design criteria were adapted accordingly.

Figure 9 – Transformer's position inside the nacelle, at the bottom right of the figure [16]

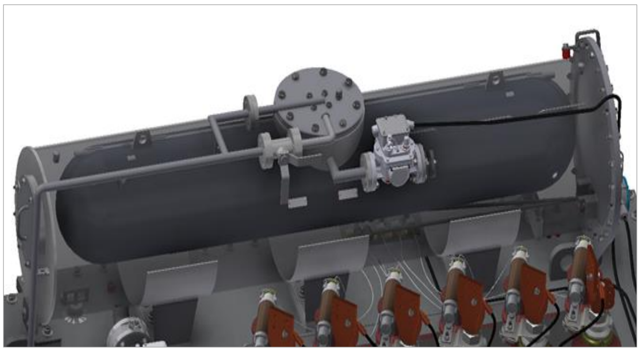


Figure 10 - Example of conservator equipped with rubber bag

5. Corrosion withstand capability

Any electrical apparatus operating in an open offshore environment must be specifically designed in terms of corrosion withstand due to combined effect of humidity and salt affecting all types of materials. The designers choose to install the power transformers inside the nacelle for different reasons. One of them being to protect it from harsh environment and consequently to reduce the risk of failures on long term. Transformers are installed in an enclosure inside nacelles (see Figure 9) during their assembly at the wind turbine factory and are shipped to site to their final destinations. Nacelle's atmosphere is controlled by applying positive pressure and desalting equipment, hence limiting drastically condensation during the whole life cycle. Therefore, a moderate corrosion protection regime can be used, such as corrosivity class "C4" with durability "very high" (VH) as per standard ISO 12944 series.

6. Cooling

Small liquid-immersed power transformers are generally air-cooled by natural oil flow in combination with radiators or corrugated walls directly attached to the tank for onshore applications. The indication is expressed in a four-letter code, e. g. ONAN (oil natural, air natural), as per IEC 60076-2 [17]. Specific temperature limits for the ambient temperature are defined regarding temperature rise requirements. The large wind turbine transformers need to meet the special demands required by the offshore wind turbine environment. As these transformers are housed inside of the nacelle in a closed environment, air-cooling option is not possible. Therefore, a water-cooled solution has been developed.

The oil-water cooler of the transformer is connected to an intermediate closed-circuit cooling system (deionised water) of the nacelle which is also dedicated for cooling other components of the wind turbine. A heat exchanger (air-blast cooler) located on top of the nacelle will release the heat to the environment. Utilizing KFWF (ester forced, water forced) cooling scheme presents the advantage that the transformer active part (made of core and windings) can be designed in the utmost compact way with the aim to minimize size and weight of the overall transformer. The performance can be further improved by using insulation materials with higher thermal performance such as thermally upgraded paper (TUP) or even using a high temperature insulation system.

7. Maintenance and monitoring

The power transformers installed in the nacelle operate in a harsh offshore environment at heights in excess of 100 m above sea level. Consequently, maintenance operations need to integrate related difficulties. The basic need for regular maintenance is minimized as much as possible for these transformers. Only the minimum necessary mandatory maintenance regime for protective devices and the pump connected to the oil-water cooler is basically necessary. It is recommended to consider annual maintenance interval while the necessary activities shall be planned very carefully in advance.

Above that, while conventional transformer documentation applies to normal onshore requirements, for offshore transformers additional aspects may be considered. The transformer manual typically defines e. g. functional checks (e. g. components including protection and control devices), leakage checks, electrical checks (e. g. transformer windings, bushings, protection devices or external components) or other checks such as oil sampling and analysis, correct valve positioning, absence of unusual noise, normal temperature readings, proper operation of the breather, etc. In addition to the maintenance guidelines provided with the transformer manual it shall be considered to apply maintenance on a regular basis as per standards [18], [19] and [20]. These standards provide guidance for any further details and to decide for task intervals applicable for strategic transformers with high constraint considering the offshore wind farm transformers harsh environment, load profile and consequences in case of unexpected failure. It is worth mentioning that the personnel used to carry out maintenance on offshore installations do not only need to be competent technically in their field, but also must be qualified to work in offshore locations.

In addition, the authors recommend considering online monitoring solutions to secure uninterrupted service of offshore transformers. Continuous development of electronics and data processing combined with a deep knowledge of power transformers and the successful implementation of transformer online monitoring systems on thousands of transformers have been achieved in recent decades. This allowed the development of highly sophisticated diagnostic and expert tools implemented into a state-of-the-art condition monitoring and expert system, as discussed in [21]. Experience in advanced monitoring and expert systems demonstrates that the application of these solutions allows continuous supervision of the transformer condition in operation, early detection of incipient failures, user-friendly fault tracking and lifetime management. Information can be accessed remotely which is a real benefit for offshore applications and can help to reduce planned as well as unplanned maintenance operations. Gas and moisture sensors should be considered as a minimum for equipping strategic transformers located in wind turbines nacelles.

8. Eco-design and life cycle assessment

While offshore wind turbine power transformers design activities admit numerous challenges as discussed in this paper, it becomes today necessary beyond international regulation to evaluate and minimize the impact of these equipment on the environment. Life cycle assessment (LCA) has been recently developed to quantify and interpret the impact of a given product or service throughout its entire life cycle: raw material extraction, processing, manufacturing, transport, use and end of life as it can be seen in Figure 11. LCA provides a comprehensive view of the environmental aspects of the product or process and a tool that provides a more accurate picture of the environmental trade-offs in comparing alternatives. Besides providing an assessment of environmental impact, LCA enables to perform true eco-design, in other words to try to minimize the environmental impact of the product at every stage of its lifecycle and to improve its environmental performance, while maintaining or improving its reliability and cost efficiency.

LCA considers environmental incoming and outgoing flows, including emissions in air, water and land, as well as the consumption of energy and other material resources. The analysis was performed with SimaPro LCA software version 9.0.0.40 and a set of impact assessment methods (CML-IA baseline, cumulative energy demand for energy and AWARE for water depletion). Secondary data are extracted from Ecoinvent version 3.5 life cycle inventory database [22]. Environmental impact evaluation is carried out on the whole life cycle of the product across and on each of the fifteen environmental indicators. One of the most popular is the climate change indicator (equivalent to carbon footprint) but other indicators are equally important.

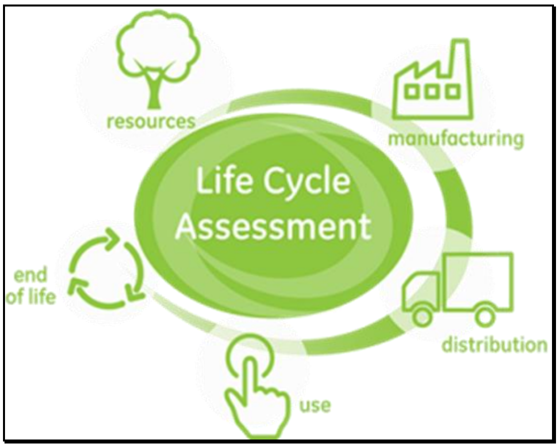


Figure 11: Diagram of the life cycle stages of a product

Figure 12 represents the LCA of the special power transformer filled with a synthetic ester (IEC 61099). As can be expected for transformers [23], the “use” phase (operation and maintenance) represents 90 % of the global environmental impact of the product. This phase is the most impacting due to the transformer losses, and this is the reason why European Regulation [24] has been implemented to limit the losses through the minimum Peak Efficiency Index (PEI). For the size optimization of the wind turbine for offshore applications, these special transformers were excluded from the regulation. Table 2 shows the PEI calculation of the transformer versus the European regulation.

Tier 2 requirement (2021)	PEI of 14 MVA
99.650 %	99.466 %

Table 2: PEI of the offshore transformer(excluded) versus EU regulation

In addition to the impact of “use” phase, two other impacts related to the materials production can be underlined:

(i) the significant parts of “Human toxicity” and “Freshwater ecotoxicity” indicators come from the treatment of slags generated in the steel production process (tank & core),
(ii) the significant part on “Resource depletion” is due to the use of high quantity of copper.

As demonstrated in a previous study for a larger transformer [24], even if the insulating liquid represents around 20% of the total mass of the transformer, results have shown that its impact on the material phase is low compared to the influence of copper or magnetic steel. In other words, the change of the conventional mineral oil by a biodegradable ester oil (natural ester or synthetic ester) won’t be significant in the LCA of the transformer. The effects will be more visible in the comparison between material production.

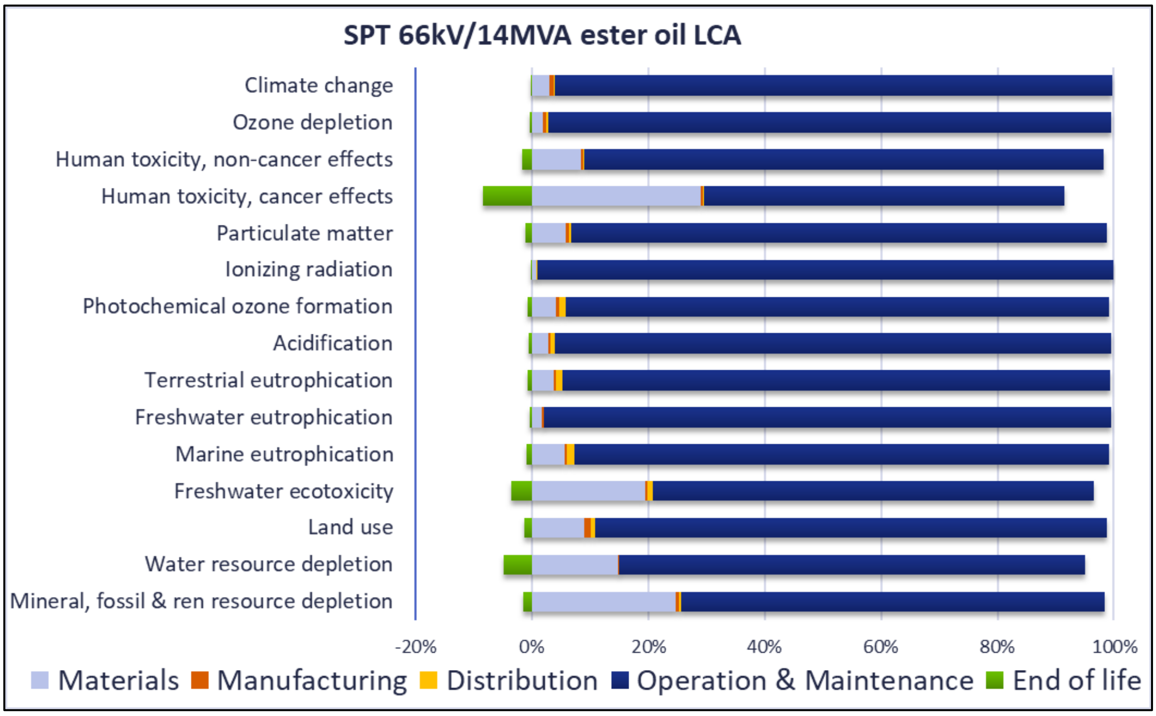


Figure 12: LCA result of the 66kV/14MVA transformer.

9. Conclusion

This paper highlights the different challenges related to the design of large wind turbine power transformers and presents solutions. While functionality of nacelle-installed transformers is similar to any other transformer, transformer manufacturers are forced to adapt their design to harsh offshore environment and difficult access. The spatial and mass restrictions strongly influence the design of all transformer components, sub-components and systems, directly or indirectly.

Electrical design is mainly driven by the presence of high harmonics generated by power electronic devices. This paper shows how the winding arrangement can be studied by FEM analysis, as well as with alternative methodologies, in order to evaluate the impact of the harmonics and select the most appropriate winding arrangement. In offshore wind turbines, power transformers are expected to operate in heights in excess of 100 m above sea level in the nacelle on top of the wind turbine tower many kilometres away from the shore. Consequently, they are subject to large dynamic excitation forces due to variable levels of wind and also transportation and erection operations. Mechanical finite element studies permit designers to accurately assess structure withstand including long term service and to overcome mechanical design challenges due to limited modification possibilities. The selection of insulating liquids is also discussed in this paper. The use of synthetic ester is the preferred choice for insulation liquid and necessary risk mitigation actions are presented. The use of natural ester has also been approved after a thorough risk assessment was performed and is ready for application in future projects. Other design aspects such as corrosion withstand, cooling method, maintenance and monitoring are discussed, even if the final solutions retained are driven by global wind turbine design strategy rather than by power transformer optimization. Finally, this paper presents the very important topic of life cycle assessment and gives an overview of the transformer impact on the environment and how that can influence the design choices since the transformer losses over its lifetime are the highest contributor to the environmental impact of the product. Today, European regulation on energy efficiency doesn't consider offshore wind turbine transformers however this may change in the future because these transformers are deployed in a large scale.

BIBLIOGRAPHY

[1] https://www.ge.com/renewableenergy/wind-energy/offshore-wind/haliade-x-offshore-turbine
[2] IEC 61378-1 “Converter transformers – Part 1: Transformers for industrial applications”, Edition 2.0, 2011.
[3] IEEE C57-110 “IEEE Recommended Practice for Establishing Liquid Immersed and Dry-Type Power and Distribution Transformer Capability when Supplying Non-sinusoidal Load Currents”, 2018.
[4] Sergey G. Makarow, Alexander E. Emanuel, “Corrected harmonic loss factor for transformers supplying non-sinusoidal load currents”, Ninth International Conference on Harmonics and Quality of Power. Proceedings, pp. 87-90, 2000.
[5] Yaqing Liu, Dandan Zhang, Zhenbiao Li, Qinqing Huang, Bin Li, Menghu Li, Jian Liu, “Calculation method of winding eddy-current losses for high-voltage direct current converter transformer”, The Institution of Engineering and Technology, pp. 448-497, 2016.
[6] G. B. Kumbhar and S. V. Kulkarni, “Analysis of Short-Circuit Performance of Split-Winding Transformer Using Coupled Field-Circuit Approach”, IEEE Transactions on Power Delivery, VOL. 22, NO. 2, pp. 936-943, 2007.
[7] CIGRE Technical Brochure N°673 - Guide on Transformer Transportation, December 2016, ISBN: 978-2-85873-376-7.
[8] IEEE Std 693:2018 IEEE Recommended Practice for Seismic Design of Substations.
[9] IEC 60721-3-2: 2018 - Classification of environmental conditions – Part 3-2: Classification of groups of environmental parameters and their severities – Transportation and handling.
[10] IEC 60068-2-6: 2017 - Environmental testing – Part 2-6: Tests – Test Fc: Vibration (sinusoidal).
[11] VDI 3834 Part 1:2015 - Measurement and evaluation of the mechanical vibration of wind turbines and their components - Wind turbines with gearbox.
[12] Eurocode EN 1993 1-8: Design of joints.
[13] A. Sbravati, K. Wirtz, L. Oliveira, “Insulating liquids at free breathing conditions”, Electrical Insulation Conference (EIC), Virtual event, June 7th to June 28th, 2021.
[14] Z.D. Wang & al., “Ester insulating liquids for power transformers”, CIGRE conference, paper n°A2-209, 2012.
[15] R. Frotscher & al., “Behaviour of ester liquids under dielectric and thermal stress – From laboratory testing to practical use” CIGRE conference, paper n°D1-105, 2012.
[16] Y. Kieffel, E. Laruelle, C. Perrier, C. Grillot-Zemmouri, B. Portal, R. Luscher, M. Kavuk, « Life cycle assessment of the 72.5kV GIS and 66kV/14MVA green transformer for integration into the 13MW offshore wind turbine”, CIRED conference, Paper n°0381, September 20-23rd 2021.
[17] IEC 60076-2: 2011 - Power transformers – Part 2: Temperature rise for liquid-immersed transformers.
[18] IEEE C57.93 “Guide for Installation and Maintenance of Liquid-Immersed Power Transformers”
[19] IEEE C57.152 “Guide for Diagnostic Field Testing of Fluid-Filled Power Transformers, Regulators and Reactors”.
[20] CIGRE Technical Brochure N°445 “Guide for Transformer Maintenance”.
[21] S. Coenen, B. Dolata, T. Chiulan, “Online condition monitoring becomes standard configuration of transformers - Practical application for optimized operation and maintenance and failure avoidance”, CIGRE CMDM conference, Bucharest, Romania, 2015.
[22] http://www.ecoinvent.org/database/database.html, Zurich, Switzerland.
[23] E. Laruelle, C. Perrier, F. Devaux, “Circularity design of power transformers” Proceedings MATPOST, Lyon, France, November 2019.
[24] Commission Regulation (EU) 2019/1783 of 1 October 2019 amending Regulation No 548/2014 on implementing Directive 2009/125/EC of the European parliament and of the Council with regard to small, medium and large power transformers.