Study Committee A2

Power transformers & reactors

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DESIGN CHALLENGES FOR LARGE OFFSHORE WIND TURBINE TRANSFORMERS

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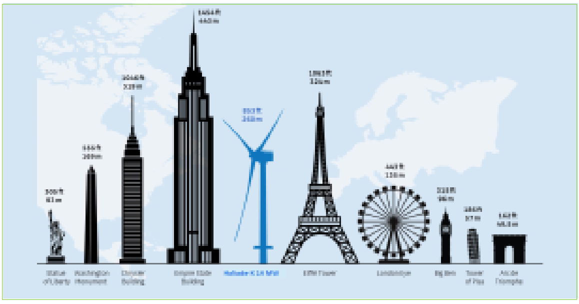


Motivation

- Numerous offshore wind farms projects are ongoing worldwide to support energy production decarbonization
- Large wind turbines, able to produce up to 15 MW, present a lot of design challenges caused by the enhancement in size and power of all its components
- This study aims at describing specific points under consideration when designing power transformers for large offshore wind turbine application

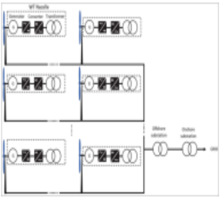
Method/Approach

- The present work focuses on main design challenges and solutions found by transformers manufacturer to provide reliable and efficient products for offshore wind farms application: <u>14MVA/66kV power transformer</u>

1. **Electrical design – Impact, evaluation and mitigation of harmonics**
2. **Mechanical design – Evaluation of external vibration withstand**
3. **Insulating liquids – Use of ester oils**
4. **Eco-design and life cycle analysis**
5. **Other design aspects**

1/ Electrical design - Impact, evaluation and mitigation of harmonics

- Electrical design of large wind turbine transformer is different from standard onshore products implemented on electrical network
- Presence of converter between generator and transformer implies important harmonic content to flow in transformer



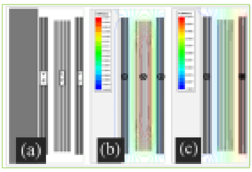
Common layout of wind farm energy

Identified challenges

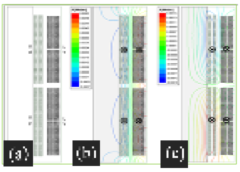
- Needs to deliver higher performances for various working points (active / reactive power, load profile, different coupling), with fluctuating THD
- Need to keep structure as compact/light as possible
- Avoid uncontrolled risks related to presence of harmonics (increase of losses, increase of hotspot temperature and impact on insulation lifetime)

Results/Discussion

- Authors propose to study the impact of harmonics on active part design using electromagnetic Finite Element Method (FEM) tools
- Selection of winding configuration is a key point: loose coupling structures such as double concentric and two-line parallel designs are preferred for such applications



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



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

Pros and cons for each design	Double concentric design	3 windings axially stacked
In-phase harmonics	-	+
In-phase opposition harmonics	+	-
Short circuit withstand	+	-
Local loss distribution	+	-
Compactness	-	+

- As both options lead to viable technology, **3 windings axially stacked** are preferred by manufacturer for weight and cost-effectiveness aspects

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continued

2/ Mechanical design – Evaluation of external vibration withstand

- Transformers installed in wind turbine nacelles are subjected to harsh vibratory environment during all lifetime
- Static and dynamic behavior of transformers needs to be assessed, for service conditions as well as for transport and maintenance operations specific to offshore environment

Identified challenges

- Qualify transformer for 25 years of use based on representative excitation (measured on a prototype) and integrating dynamical effects
- Avoid mechanical failure in all components, in particular for welds and bolted connections
- Keep structure as light and compact as possible

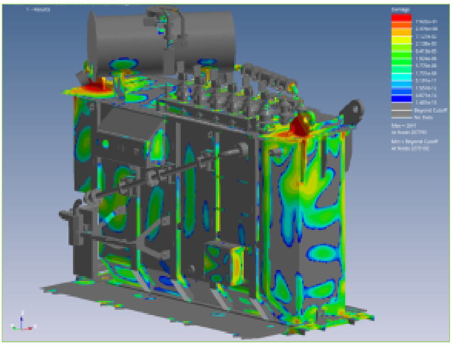
Results / Discussion

- Only available solution to evaluate mechanical withstand under external excitation is to perform mechanical FEM study
- 3 main verifications needs to be performed

✓ **Absence of coincidence between nacelle main vibration modes and transformer's ones**

✓ **Structural withstand under transport and maintenance operation** (short term)

✓ **Structural withstand under service conditions**



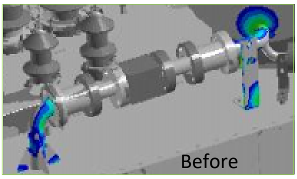
Example of fatigue damage distribution before optimization for a given material type

- Initial mechanical design of transformer was found non-compliant with specified criteria
- Several evolutions were introduced considering FEM study results to improve the situation, notably:

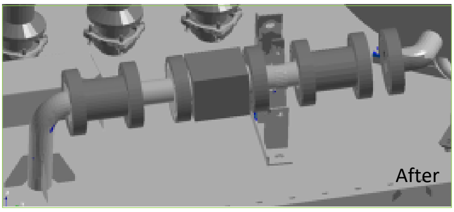
✓ **Reinforcements of all fixations** of accessories attached to tank and of active parts fixations (internal to tank)

✓ **Fine tuning of stiffness** around transformer fixation points, to smoothly distribute vibratory energy and avoid concentration of stress in fragile components

✓ **Adjustment of welds maps and bolted connections** design to prevent any failure related to fatigue



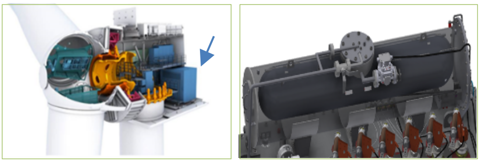
Damage plot in oil pipe and surroundings before and after implementation of corrective solution



- After several iteration, technical solutions were found to validate transformer mechanical design for 25 years
- Validation of FE models can be done thanks to comparison between FE modal analysis and experimental modal analysis

3/ Insulating liquids

- Both mineral and ester oils can be used for offshore wind turbines transformers
- Ester oils present several advantages as a higher fire point, a better biodegradability and a higher thermal class
- Oxidation stability of ester (especially natural ester) is lower but transformer is protected in a box inside the nacelle, and a sealed system with rubber bag is used
- Synthetic ester was preferred because of better cooling performances in case of very cold climate (<-20°C)



Transformer's position inside the nacelle, at the bottom right (left), and conservator equipped with rubber bag (right)

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continued

4/ Eco-design and life cycle analysis

- Life cycle analysis (LCA) permits to quantify impact of a product during its entire life cycle
- LCA is achieved by modelling transformer in dedicated tools, including all necessary aspects such as emissions in air, water and ground, energy consumption and materials resources
  - ✓ *SIMAPRO software + ISO 14040 + ISO 14044*
- Results are determined for 15 independent indicators

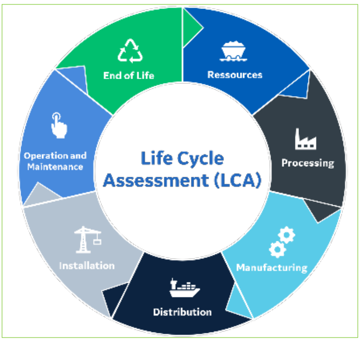
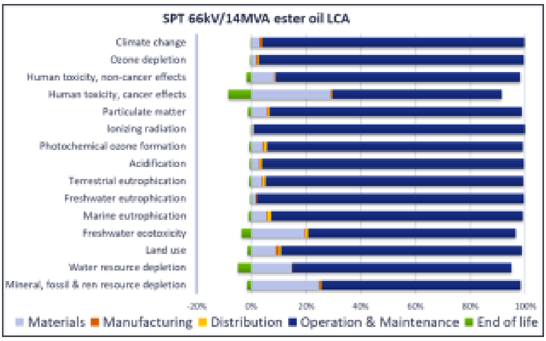


Diagram of the life cycle stage of a product

- As for standard power transformers, offshore wind turbine transformers are mostly impacting environment:
  - ✓ During the “use” phase due to **electrical losses** happening in core and windings
  - ✓ During the “material” phase, due to the **steel** production as tank and core (Human toxicity and the Freshwater ecotoxicity), and the use of high quantity of **copper** (Resource depletion)



LCA result of the 66kV/14MVA transformer

5/ Other design aspects

- **Transformer’s maintenance operations** are made complex in offshore application, in particular because it is installed at 150 m above sea level
- Transformer manufacturers need to reduce as much as possible the **frequency and scope of maintenance** operations
- Furthermore, the use of **online monitoring systems** allow continuous supervision of transformer health and permits to take quick decision without planning special control operation when an even occurs
- Transformer **corrosion withstand** has also to be considered during design stage. In Haliade-X project, choice has been made to install transformer in a **climate-controlled enclosure** inside the nacelle, reducing drastically the risk of corrosion due to humid and saline environment

Conclusion

- Design of nacelle-mounted transformers applied to offshore environment presents new challenges
- Use of finite element methodology analysis for both electrical and mechanical design activities is required
- Ester oil is the preferred option for better fire safety
- Strict limitation in dimensions and mass, in addition to harsh environment conditions is another challenge
- Other design aspects such as cooling means, corrosion withstand, maintenance operations or monitoring can be solved without major difficulty