The reconsideration of how best to generate electrical energy has seen an increase in the number of alternative energy supply systems – including wind farms. Wind turbine transformers, of course, have a completely different operating environment from standard power transformers.

Design and material selection of wind turbine generator transformers

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It is important to consider the different operating conditions and influences – as well as the different electrical, mechanical and material requirements – to which wind turbine generator transformers are subjected, compared to distribution and power transformers. All should be taken into account when designing a wind turbine generator transformer for optimal performance and cost.

Wind turbine generator transformers are subject to different operating conditions from distribution and power transformers. In the electrical design, there are different fast transients, harmonics and non-sinusoidal loadings, and different loading factors that need to be considered. From a mechanical design perspective, the dynamic load and losses result in a different drive for the design and testing criteria. These changes, in turn, bring about the need to re-examine the materials used, such as the insulation paper for thermal hot-spots, cooling oil for environmental reasons, or the core steel to optimise losses.

Design considerations

Electrical design

The operating conditions of wind step-up transformers are distinct from those of distribution and power transformers. Their designs should be such that they withstand amongst others: very fast transients, harmonics and non-sinusoidal current loading, loading factors and frequency variations [1, 3]. This section explores electrical design considerations when taking into account a few of these aspects.

Very fast transients

Wind generator step-up transformers are installed in network layouts consisting of cables that are connected to the breaker. During the switching process, very fast transients yield a rise time that is approximately 50 times shorter than that of a conventional full wave lightning impulse test (FWLI). These transient characteristics influence the voltage withstand of the internal insulation of the transformer. The reason for this phenomenon is given as: 'In systems with oil insulated transformers and reactors, transients are about 10 times slower due to a 10 times larger stray capacitance' [2].

The study in [2] found that the turn-to-turn voltage withstand reduces significantly with reduced rise time. A reduction as low as 0,4 pu of the turn-to-turn voltage withstand was recorded. In a separate investigation [4], it was concluded that in the case of oil, the breakdown voltage influence is 12% and 35 - 40% lower for impulses of front times 0,7 µs and 0,044 µs respectively, compared with that of the 1,2 µs full wave lightning impulse. Transformer internal insulation structures should be designed to withstand these very fast transients.

Harmonics and non-sinusoidal loading

Transformers for wind applications will frequently be subjected to non-sinusoidal load currents and harmonics. IEC 60076-16 [1] highlights this risk and specifies that customers shall provide the harmonic spectrum. The effect on transformer load losses is widely reported in literature. A detailed calculation of the K-factors that amplify the individual loss components appears in [5]. The reduction of the conductor sizes is a commonly applied effort to reduce the winding eddy losses. Subsequently, the cooling design should take into account increased winding losses and winding hot-spot rise. However, the overall temperature rise is not exactly proportional to total winding losses [6]. Similarly, the stray losses in metal parts will be enhanced according to the K-factor [8]. Stray loss reduction techniques should be applied, including increased yoke distances, tank shunts and copper shielding.

Dynamic loading factors

The speed of wind determines the output of the wind turbines; consequently the average loading factor of 35% is common [9]. The low level of transformer loading will directly impact on the requirements for the no-load losses. The low no-load losses required become even more stringent to reduce running or long term costs of the units. This inherently affects the selection of the core material that is used for the transformer. The varying load also affects the thermal performance of the metal part structures in a transformer and should be considered at the design stages to prevent localised hot-spot heating.

From the factors described, it is clear that a slightly different set of design considerations is necessary for wind generator step-up transformers. The International Electrotechnical Committee (IEC) provides important considerations to assist customers and Original Equipment Manufacturers (OEMs) to specify, design and manufacture more durable transformers.

Mechanical design

Structural considerations

Transformer performance, as prescribed by global standards and customer specifications, can only be achieved if there is perfect harmony between the electrical and mechanical designs. The mechanical design complements the electrical design by means of design concept and material choices, to achieve the most cost effective design to suit customer specifications, and reduce the carbon footprint (losses).

Any architectural marvel is only as good as its foundation; with transformer design the foundation is laid by the magnetic core clamping structure. The clamping structure limits core lamination vibration,

so the noise impact on the environment is reduced, and is exclusively responsible for maintaining winding clamping forces. These structures must be well designed and constructed in order to withstand short-circuit forces resulting from abnormal service conditions without permanent deformation. Guaranteed losses as specified are achieved through the strategic use of non-magnetic material or special geometry, as this reduces possible financial penalties on the manufacturer and ensures the supply of a profitable asset to the customer.

Cooling influence and selection

With modern transformer life expectancies, it is essential to cool the windings sufficiently and effectively enough to ensure hot-spot temperatures below customer specified values. Research has shown a mechanical half-life breakdown in pulp cellulous insulation for every 6 - 7°C increase above the designed hot-spot temperature, which could lead to a breakdown in the insulation electrical stress withstand capability, and failures. Cooling can be achieved by various cooling methods ie ONAN (Oil Natural Air Natural), ONAF (Oil Natural Air Forced) and OFAF (Oil Forced Air Forced). Wind turbine step up transformers are usually specified with a rating equal to the generator [23] and therefore do not normally operate at full load, resulting in a potential long insulation lifetime. However, the higher localised losses at full load, due to the harmonics introduced by the wind turbine generator [23], need to be taken into account at the design and testing phases.

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Winding connections

Other important factors of the mechanical design are the winding connections or joints. The cable area choice is based on the current carrying capability of the material used and the effect of the insulation thickness on the cooling efficiency and the cable orientation when routed in a bundle of cables, ie horizontal or vertical. The dielectric clearances between winding leads and winding leads to earth are driven by the Design Insulation Levels (DILs), the cable diameters and the insulation thicknesses. The structure containing the cables should be designed with short-circuit, manufacturing and transport forces in mind.

Material requirements and selection

Transformer specifications such as IEC 60076 [10, 11 ,12 ,13, 14, 15, 16], usually omit specific material requirements, focusing rather on design and performance. Wise selection of materials can improve the design of the transformer in terms of performance and cost. The different materials that may be selected must be reviewed and the benefits of each selection weighed up with respect to the application in the transformer and the performance influences from the wind turbine generator.

With harmonics being present, the focus on conductor and insulation techniques and quality compliance, with specifications such as [17, 18, 19] is important. In all probability, the area of the conductors will be increased and insulation will be increased one class.

With the possibility that cooling could be a challenge in wind towers, it may be necessary to consider aramid [20] and ester oil-based [21] insulation systems. The added advantage of the ester oil is reduced risk in an oil spill.

The local humidity and possible high salinity of the tower may mean that polymeric open bushings or cable connections should be specified in accordance with the correct pollution class defined in IEC 60815 [22]. Bushings or cable terminations should, as a minimum, pass simulated salt fog testing, but should preferably pass long term natural ageing.

The losses for wind turbine transformers should be as low as possible. The two focus areas of materials are core steel, which affects the no-load loss, and conductors, which affect the load losses. For low loss cores, thinner domain refined core material is often used to reduce magnetic losses. The method for reducing load losses is to reduce the resistance of the conductor by increasing the active conductor area and reducing the dimensions that drive the eddy losses down. As this can be a costly exercise with copper conductors, aluminium could be considered as a cheaper alternative. Aluminium windings will generally be bigger than copper owing to the difference in density so conductor saving will need to be balanced against the extra costs needed owing to the dimensional growth of the tank and oil needed for the larger tank. The fact that the transformer may need to fit inside a tower may limit its size and may mean that copper has to be used.

Conclusion

Wind turbine generator transformers have different operating conditions from distribution and power transformers. The subsequent effects on the electrical and mechanical design have to be taken into account, and wise material selection can improve the cost and performance of the design. There are various techniques in the design and application of standard and alternative material selections to ensure a resilient transformer in the application of wind turbine electricity generation.

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