Thermischer Entwurf und Belastbarkeit von Leistungstransformatoren mit natürlicher Ölkühlung

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In elektrischen Energieübertragungssystemen gehören die Leistungstransformatoren zu den wichtigsten und teuersten Betriebsmitteln. Hinsichtlich ihrer Nutzungsdauer (Lebensdauer) werden daher von Seiten der Betreiber hohe Anforderungen gestellt. Um diese Anforderungen erfüllen zu können, müssen die Hersteller beim Entwurf und der Konstruktion des Transformators die auf die Lebensdauer am meisten Einfluss nehmenden Aspekte besonders berücksichtigen. Hierzu gehören die thermischen Verhältnisse im Transformator, da die Wicklungsleiter nach wie vor mit einer Öl-Papier-Isolation, deren Alterung sehr stark von der Temperatur abhängig ist, der elektrischen Festigkeit Rechnung tragen. An der Stelle der maximalen Temperatur (Heißpunkt) wird die Isolation am meisten beansprucht und altert daher am schnellsten. Die am Heißpunkt auftretende Temperatur wird als Heißpunkttemperatur bezeichnet. Sie bestimmt im Wesentlichen die Nutzungsdauer des Betriebsmittels und ist daher von vorrangigem Interesse, sowohl bei der Auslegung als auch im realen Betrieb des Transformators. Um die Heißpunkttemperatur zu erhalten, gibt es zwei Möglichkeiten: Die direkte Messung mittels optischer Sensoren und die Berechnung anhand eines thermischen Transformatormodells.

In der vorliegenden Arbeit wird die natürliche konvektive Kühlung (Kühlart ON) betrachtet. Zunächst werden einige dem Stand der Technik entsprechende Berechnungsmodelle vorgestellt. Eine herausragende Rolle spielt das auf physikalischen Grundlagen basierende thermische Mehrkörperersatzschaltbild des Transformators, dessen Modellparameter anhand einfacher Messungen in Erwärmungsversuchen bestimmt werden können.

In einem weiteren Kapitel wird auf die unterschiedlichen Wärmeübertragungsmechanismen eingegangen. Dabei stehen die für die praktische Anwendbarkeit wichtigen Formen im Vordergrund. Der Zusammenhang zwischen der Konstruktion des Transformators und den Wärmeübertragungsmechanismen wird beleuchtet.

Die im Transformator am meisten durch Stromwärme beanspruchten Komponenten werden anhand von Versuchsmodellen in Erwärmungsversuchen genauer untersucht. Neben den Wicklungen ist der Verbindungsleiter zwischen Wicklung und Durchführung von Interesse, da er stückweise unterschiedliche Isolationsstärken aufweist. Anhand der Messungen wird ein zweidimensionales Modell zur Berechnung der Temperaturverteilung aufgestellt. Der konvektive Wärmeübergang wird dabei auf unterschiedliche Weisen berücksichtigt. Ein Vergleich zwischen der bisherigen

Berechnungsmethode und der hier vorgestellten Methode zeigt das Einsparpotential bei der Bemessung des erforderlichen Leiterquerschnitts.

Der Vergleich der an einer Lagenwicklung anhand von Erwärmungsversuchen gewonnenen Ergebnisse mit einigen thermischen Modellen zeigt, dass die Modellparameter vielfach nicht beliebig universell verwendet werden können ohne dabei an Genauigkeit der Heißpunkttemperaturberechnung einzubüßen.

Am Modell einer Scheibenwicklung werden konstruktive und stoffspezifische Einflussfaktoren auf die thermischen Verhältnisse in der Wicklung untersucht. Dabei wird sowohl der konvektive Wärmeübergangskoeffizient als auch die vertikale Öltemperaturerhöhung in der Wicklung betrachtet. Die Ergebnisse zeigen, dass sowohl konstruktive Maßnahmen als auch Isolieröle mit unterschiedlichen Stoffwerten beide Auslegungsgrößen beeinflussen.

Ein Vergleich zwischen Erwärmungsmessungen an der Scheibenwicklung und einer thermischen FEM-Berechnung zeigt Erfolg versprechende Ergebnisse. Die Anwendung von numerischen Simulationen zur thermischen Berechnung von Teilkomponenten des Transformators sind von praktischer Bedeutung.

Abschließend werden wichtige Aspekte hinsichtlich der Heißpunkttemperaturberechnung und der Beeinflussung von Leistungstransformatoren im Betrieb erörtert.

▪ Thermal Design and Loading Capacity of Large Power Transformers with Natural Oil-Cooling

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Introduction

Large power transformers belong to the most important and valuable assets in power systems. With the liberalisation of the energy market utilities are constrained to adopt the exploitation and the life time of such operating resources close to the requirements of the modified energy market situation. Compared to the situation of recent years operation, the changes in electrical power flow can lead to increased load conditions and transformer loading beyond nameplate rating. It appears worthwhile to pay special attention to this key component to ensure stability and reliability of electrical power supply. Both - network operators and transformer manufacturers - are asked to predict the expected life time of the transformer under the “new” loading conditions. Due to the stressed situation on the world market the manufacturers are forced to increase the maximum utilisation of the transformer without any additional cost increase but at the same level of the transformer’s reliability.

The life time of the transformer mainly depends on the life time of its insulation. In most power transformers cellulose insulation is used until yet. Since the temperature is the dominant factor for the ageing rate of the cellulose molecules there is a strong interest in the solid oil-paper-insulation temperature determination. Due to the fact that the highest ageing rate appears at the point of maximum temperature there is a particular interest to determine the winding's hottest spot temperature. This temperature is not only important for long term ageing but it is also a limiting factor in real transformer operation. The hot-spot-temperature depends on the instantaneous load of the transformer, the loading prehistory (the dominant thermal time constant of a transformer amounts to few hours), the temperature of the external cooling medium, the winding design and the cooling mode. In general there are two possibilities for the hot-spot-temperature determination. The first possibility is to measure the temperature directly, the alternative one is to calculate it using a thermal model of the transformer.

For transformer manufacturers the calculation of the hot-spot temperature is important for the designing process, since in a short circuit heating experiment, carried out as a transformer type test, the manufacturer has to guarantee, that the allowed temperature limits are not exceeded.

In the present study the natural convection cooling mode is analysed. The main focus is the investigation of the factors taking affect on the internal heat transfer, e.g. the heat transfer from the winding to the surrounding transformer oil. The analysis is based on extensive experimental research on test arrangements. Since the interpretation of the results is based on the physical fundamentals a broad application to similar heat transfer problems, e.g. windings, is given.

Thermal modelling

The common practical solution of hot-spot-temperature determination is the calculation through a thermal transformer model. The input data for such a model is the transformer load and the external cooling medium temperature.

A number of papers have been published proposing improvements of the thermal model from the valid IEC standard [IEC, 1991]. The standard approach for hot-spot-temperature calculation is through using characteristic points temperatures. Such models have been published often. The model from Pierce (1992) is of special interest since it is given in the latest IEEE guide from 1995 as an alternative temperature calculation method.

The main problem is not only to establish the thermal model rather than to define its parameters. They can be defined from general heat transfer theory, from especially provided measurements on a test model or from easy measurements made as a transformer type test.

Since the heat transfer phenomena inside transformer windings are complex there is no universal thermal winding and transformer model available at present. Changing boundary conditions and manufacturing tolerances influence analytic and numerical heat transfer calculations strongly. Many winding types, each with different cooling duct designs, are in use to meet customer requirements and to reach competitive design solutions. Deviations of the oil streaming conditions in a real transformer and in a setting under which the formulas are established in heat transfer theory also lead to inaccuracies in temperature calculations. Almost each cooling mode requires its unique model. Especially the treatment of natural convection heat transfer phenomena is difficult.

Comparisons between measurements made on real transformers and results obtained from measurements made on test winding arrangements have shown, that thermal model parameters usually can not be applied for other arrangements without deterioration of calculation accuracy.

In order to guarantee a wide range of thermal model applicability the main aspects in the process of establishing the model should be the choice of easy measurable quantities for model parameter determination and the construction of a model which is based as close as possible on the physical heat transfer mechanisms.

Fundamentals of heat transfer and transformer construction

Temperature gradients inside a transformer are the consequence of power losses. In the state of thermal equilibrium in every moment the produced heat, e.g. power losses, has to be transferred from the active parts of the transformer (internal cooling) to the surrounding cooling medium (external cooling). On this way the heat flux has to pass miscellaneous materials and different heat transfer mechanisms occur: heat transfer through conduction (in the solid parts), heat transfer through convection (heat transfer between a solid surface and a liquid in motion and vice versa) and heat transfer through radiation. In most cases of power transformers the heat transfer through radiation is negligible (because of low surface temperatures and small surface area available for radiation compared to the surface area responsible for convection). Whereas the treatment of heat transfer through conduction is easy the case for convection heat transfer is the most complicated one, especially when the fluid motion is caused only by buoyancy forces. This occurs for all cooling modes denoted with ON and AN. Fundamental differences can be found between natural and forced convection heat transfer. A general theory dealing with the determination of natural convection heat transfer coefficients (HTC) a between surface and fluid is given in the boundary layer similarity theory. The fundamental approach is the correlation between dimensionless numbers and the HTC a. To describe the natural convection mechanism two dimensionless numbers are relevant: the Rayleigh number (Ra) and the Nusselt number (Nu). Finally from the Nusselt number the HTC a can be calculated. The advantage of the dimensionless numbers is the applicability of the results to other similar thermal heat transfer problems. The solution of a special natural convection heat transfer problem is given if the functional dependence between the Nusselt number Nu and the Rayleigh number Ra is known. In order to obtain the functional dependency measurements (heat run tests) on appropriate test facilities are necessary.

Since the temperature gradients depend on geometrical data the construction of the transformer is a significant factor taking influence on the HTC a. The thickness of solid insulation, the condition of the heat transferring surfaces, cooling duct arrangements and additional insulation assembly are responsible for the temperature gradients quantity. Hydraulic resistances in the oil circulation loop are slowing down the oil motion and thus reduces the HTC a. Since the physical properties of the liquid cooling medium are involved in the calculation of the dimensionless numbers their influence on the thermal behaviour of the transformer is obvious.

From a simplified analytical examination of an oil circulating loop (through the winding, transformer tank and the radiator) two expressions are derived showing the dependencies of the HTC a and the vertical oil temperature gradient inside the winding (Joil,top - Joil,bottom). Based on this results the main influence factors are experimentally analysed with heat run tests on a test winding.

Investigations on a single conductor with different insulation thickness

Conductors used for transformer winding bushing interconnections usually need higher insulation levels compared with the insulation inside the windings. In practice the insulation on short segments of the connecting conductor is several times thicker than the insulation inside the windings. This leads to increased conductor temperature rises. To avoid unacceptable high temperatures, conductors with an increased cross section are used to decrease power losses inside parts with additional insulation.

The normally used design rules assume an infinity length of the additionally insulated conductor. In a number of cases the conductor length equipped with an additional insulation is less than half a meter. In such short conductor segments the heat flow along the conductor is not negligible compared with the heat flow through the conductor insulation. With a two-dimensional thermal model the temperature can be calculated precisely. In such a way, it is possible to determine the minimum cross section leading to acceptable values of local hottest insulation temperature. Due to the convection heat transfer from the surface of the conductor to the surrounding oil the thermal model is non-linear.

The thermal model established is verified in laboratory experiments on a conductor with a cross section of 263 mm^2 and loaded with currents up to 1450 A. Based on the measurements it is possible to improve the formula for the convection HTC a calculation. For the higher insulated part of the conductor the thermal resistance of the additional manually wrapped paper layer has to be increased due to thermal contact resistances and oil layers inside the paper by adoption to the measuring results by introducing an insulation thickness correction factor greater than 1.

A comparison between the results obtained from the one-dimensional and the two-dimensional thermal model of the conductor shows that the simplified calculation is too vague and leads to large cross sections. With the more sophisticated model the required cross section is much smaller. For an adopted conductor hot-spot minus average oil temperature of 23 K according to IEC (1991) a reduced cross-section of the interconnections to 72 % (of the cross-section calculated with the one-dimensional model) is sufficient.

The provided calculation method represents an improvement in design practice and leads to an economical optimal construction of the interconnections.

Measurement technique and calculation of the HTC α of transformer windings

To investigate the thermal behaviour of transformer windings it is necessary to know the average winding copper temperature. The determination of the average copper temperature by measuring local temperatures requires a high amount of sensors installed inside the winding. In order to avoid an expensive installation of a large number of local temperature measuring sensors inside the winding the continuous average copper temperature on-load measurement method for a mono phase winding is applied. In the literature this method was originally developed for measurements on real transformers during the short-circuit heating test.

The method is based on a superimposed direct measuring current to an alternating load current. The winding is loaded with the alternating load current in the main circuit. The measuring direct current is provided from a DC current source. The DC circuit is coupled to the main circuit by a coupling resistance which is continuously loaded by the required alternating load current and the direct current component. Reactive power compensation has to be applied in order to reduce the load of the alternating power supply and the load of the coupling resistance.

The winding's resistance is equal to the ratio of DC voltage drop and DC current through the winding. It is measured using a power-analyser. Consequently the actual copper temperature of the winding is computable from the initially measured winding resistance in the cold state before starting the heating experiment and the actual winding resistance. The average HTC a of the winding depends on the temperature difference between the winding surface (paper-insulation surface) and the average oil temperature in the winding and the heat flux density. The temperature on the winding surface is equal to the average copper temperature reduced by the amount of temperature drop through the paper-insulation due to thermal heat conduction.

The measurement of local temperatures on the winding and in the oil close to the winding and inside the tank is easy to perform with resistance temperature detectors (RTD's) because the experiments are carried out with voltages less than 500 V.

Investigations on a test winding

The thermal behaviour of natural convection oil cooled transformer windings is investigated on a test winding arrangement. Investigated is a layer winding and a disc type winding. With a number of heat run tests the following results have been obtained:

<u>Layer winding</u>

The heat run tests made with the layer winding are used for two analyses. The evaluation of the HTC a shows the dependency of the heat flux density – with increasing heat flux the average HTC a increases. For the maximum heat flux density of 220 W/m^2 the HTC a amounts to a = 27 W/m^{2}K.

Since this winding design is comparable with the investigated types discussed in literature, the thermal model parameters can be analysed and compared. From local characteristic temperature measurements at dedicated points on the winding surface and inside the vertical cooling ducts the individual model parameters are calculated.

The comparison of the results obtained from the measurements and those calculated with the parameters shows, that it is not possible to define a unique set of parameters which delivers a high precision of temperature gradient calculation. An other influence is caused by different oil streaming conditions between windings inside a real transformer and test windings positioned autonomously in a tank.

<u>Disc winding</u>

Extensive measurements on a disc winding type are performed to investigate the influence of the following factors to the average windings HTC a and the vertical oil temperature gradient (Joil,top - Joil,bottom) inside the winding:

- the heat flux density
- hydraulic resistances in the oil circulating loop
- physical properties of the transformer oil
- vertical radiator position

With increasing heat flux densities also the average HTC a increases. This result is based on the temperature dependency of the oil driving force responsible for the convective heat transfer expressed by the Rayleigh number. The general applicable result is given by the relation between the Rayleigh number and the Nusselt number wherewith the HTC a is calculable for other similar windings.

It is known from design and manufacturing practice that the thermal behaviour of similar windings installed in different transformers may be different. This phenomenon especially appears in natural oil cooled (ON) windings of high voltage transformers. One reason is the difference in the windings insulation level and thus consequently higher hydraulic resistances in the oil circulating paths. It is obvious that for the same heat flux density but increased hydraulic resistance the HTC a is reduced. This result is caused by a minor oil velocity in the cooling ducts due to an increased hydraulic resistance leading to reduced oil mass and heat transfer through the entire winding. Since the oil retention time in the winding is increased with higher hydraulic resistances also the vertical oil temperature gradient (Joil,top - Joil,bottom) increases. A comparison of the vertical temperature gradient between the results obtained from different top oil temperature determination are obvious since the directly measured one represents a mixed temperature of the hot oil streaming out of the winding and the surrounding top tank oil of lower temperature.

The impact of different transformer oil parameters on the windings heat transfer capability is analysed with two transformer oil types having significantly different oil viscosity. As the values representative for the thermal phenomena in transformers, the following characteristic temperature differences are analysed: average winding minus average oil temperature difference (Δqwo), the vertical oil temperature gradient (Joil,top - Joil,bottom) and the oil in the radiator logarithmic mean temperature difference (LMTD). The clearest differences appear in the vertical oil temperature gradient whereas only slight differences appear in the temperature rise of the radiator logarithmic mean temperature difference. Comparing the temperature gradients of the oil inside the winding and the oil inside the radiators it can be seen that the increasing difference (with increasing heat flux density) is the consequence of an increasing oil by-pass – the cold oil exiting from the radiator flows near the winding directly to the top of the tank.

Thermal calculations using finite element method based software

The thermal behaviour of the natural oil cooled transformer disc type winding is investigated by means of the finite element method (FEM) software ANSYS. In order to avoid unrealistic boundary conditions the simulations describe the experimental set-up as close as possible. For that purpose it is necessary to model the test winding and the complete test set-up (tank with radiators). The external heat transfer from the oil to the ambient air through the heat exchangers is simplified modelled by an uniform heat transfer coefficient on the radiator surface. In order to hold the size of the simulation model in a manageable range some simplifications are introduced: two-dimensional axisymmetric coordinate system, the winding disks are modelled as a solid body, all spacers and the steel walls of the tank and the radiators are omitted.

The applied heat flux density (load) of the winding is assumed to be homogeneous. The simulations are carried out with two different heat flux densities according to the correspondent experiments. The evaluation of the simulations are made by a comparison of calculated and measured temperature values, such as top oil and bottom oil temperature in the tank, the vertical oil temperature gradient in the winding and the average winding copper temperature. The deviations in almost all of the calculated and measured temperatures are in the range of less than 3 K, only for the case of higher applied heat flux density the deviation in the bottom oil temperature amounts 5 K. The pragmatic procedure of total arrangement modelling shows that in respect of the computational time nowadays the applicability for total transformer modelling is not reasonable. To establish designing rules for small parts of transformer assembly like winding cooling duct arrangements and heat exchangers the method is of trend-setting interest.

Hot-spot-temperature calculation under real transformer operation

During real transformer operation with variable load and variable cooling medium temperature it is very rare that the transformer resides in thermal steady state. Since for the transient hot-spot-temperature calculation there also exists no exact thermal model the attempt to calculate it by simplified assumptions is commonly made. In [IEC, 1991] the calculation is treated by approximating any load diagram by step functions. Another attempt is made in the new IEC 60076-7 committee draft 14/403/CD, where the transient temperature calculation is based on an introduced time dependent function which is assumed to be constant for a certain transformer construction, e.g. transformer type. Since the character of heat transfer is non-linear it is obvious that this function is not constant. With the model from Radakovic (1997) it is possible to calculate the temperature in discrete time steps. For that purpose it is necessary to know the initial temperature value.

Transformer long-term operation strategies

To take influence on the operation of a transformer under real conditions the only possibility is through the external heat exchangers operation mode. Through an intelligent fan control system the heat exchangers heat transfer capability can be controlled in such a way that actual temperature values, especially the top oil temperature, are kept constant. Additionally other criteria like overload capability and long-term ageing can be considered in order to guarantee an economical operation of the transformer. A FUZZY-Logic based control algorithm is convenient to fulfil this requirements.

Conclusions

Based on extensive measurements on arrangements examined in laboratory heat run tests the thermal behaviour of thermally high stressed assembly in large power transformers was detailed analysed for the natural oil cooling mode. For a common problem of the winding bushing interconnection design a two-dimensional thermal model for the connecting conductor was established. The model allows to determine the techno-economical optimal conductor cross section so that the temperature limit in the critical parts of higher insulation level will not be exceeded. Considerable measurements have been performed on a test winding facility. For the layer winding the measurements have been used twofold. With a number of local measured copper and oil temperatures the results have been compared with two state-of-the-art thermal models. As a main result it can be concluded that the model parameters can not be universally used without deterioration of temperature calculation precision. Another evaluation of the results deliver the average heat transfer coefficient of the winding, using the fundamental correlation of heat transfer theory expressed by the Nusselt number. For the disc winding numerous factors influencing the heat transfer capability of the winding are analysed successively. The results show the impact of each of the factor to the average heat transfer coefficient and the vertical oil temperature gradient. The comparison of results obtained from heat run tests and the appropriate numerical simulations demonstrate the advantage using such calculation methods. The main advantage is given for certain transformer parts simulation, e.g. winding parts and cooling duct arrangements. The use for practical industrial transformer winding construction procedure is not of high relevance so far since the simulation time of total complex arrangements is still too high. Finally important aspects for a real transformer operation have been analysed: online calculation of the hot-spot-temperature, limitations during a transformer operation and long-term operation strategies. Associated with long-term operation strategies a multi-criteria Fuzzy-logic based heat exchanger fan control algorithm was presented.