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RESIDUAL LIFE AND HEAT CONTROL OF A TURBOGENERATOR STATOR WINDING INSULATION

Abstract. Residual life and heat control method of a turbogenerator stator winding insulation based on the regular heat control data and the temperature excess regressive dependences for load conditions parameters is presented. It is shown, that the reliability for insulation residual life definition of a generator stator windings is higher when the calculated value of maximum temperature is taken for the insulation temperature, rather than the resistance thermometers readings installed in the slots.

Keywords: powerful turbogenerator, end zone, control, diagnostics, stator core, stator winding insulation, temperature.

Continuous state control of electrical machines windings insulation and the possibility of ensuring the parameters reliable prediction characterized its condition allow significantly improves the reliability and the safety of machine. Dependence of insulation defects development speed on the load conditions, structural and technological features, operating time of an electrical machine determines the probability of damage and excessive wear windings. The probability of winding insulation damage can be reliably estimated in case of analysis in three directions: continuous and periodic control data, trend of parameters, resource characteristics («life history» analysis).

The definition and prediction state of electrical machines windings insulation can be made with help the heuristic and statistical analysis based on deterministic methods. The heuristic analysis is mostly associated with the use of expert systems, when experts determines the insulation state based on intuitive knowledge with help the insulation parameters and according to the developed rules. Dependencies of residual life on the parameters of these processes, in particular, the so-called «life formulas» can be constructed on the basis of physical processes studies. The prediction state of electrical machines windings is also performed according to the trend of parameters. Moreover, the diagnosis is made at an arbitrary time interval.

The insulation life can also be determined by «life history» data, which determines the change tendency of diagnostic parameters and load characteristics in the presence of technological characteristics information, load and operating conditions of an electrical machine.

For powerful turbogenerators the most important parameter determines the winding insulation life is, first of all, temperature. Electrophysical and mechanical parameters significantly affect the windings insulation life. If the influence of the latter parameters is less studied and their control is practically not carried out, then the windings temperature control is carried out continuously with the installation of temperature sensors depending on a turbogenerator type at almost every winding bar.

The dependence of turbogenerator insulation life on the temperature θ is known [1] and can be represented as:

$$T = e^{\left(\frac{A+B}{(273+\theta)}\right)}, \qquad (1)$$

where A, B are the constants depends on the insulation properties. Expression (1) is the «life formula» of insulation, which taking into account «life history» data can be specified in the operation process. Such «life formulas» can give in a general form using some approximation methods for determine or specify of approximation coefficients.

However, it is necessary to solve a number of scientific and technical problems in order to these states realize in practice of turbogenerators in real time.

It is necessary to develop methodical means for temperature field definition along the all section of slot as the winding temperature sensors are only installed in possibility places. It should be emphasized that, as a rule, the maximum temperatures in the generator are not controlled. It is also important to develop methodical means and algorithms for winding residual life definition in real time of a certain point and fixed prediction period.

The first problem is solved on the basis of mathematical simulation for heat processes. At definite copper winding losses for a certain load condition the temperature field in section of winding bar can be found in the most approximate two-dimensional formulation when the steel temperature is set at the slot border. With specified calculation methods of steel losses this approximation may not have a place. Limit temperatures are experimental for well-equipped turbogenerators or calculated with help the other mathematical models.

The compound geometry of machine requires detailed calculation nodes when high load conditions. The use of triangular mesh or high-order elements in the finite element method allows makes this in the best way. The advantage of the finite element method is also the simplicity of boundary conditions install.

The interpretation of temperature function as a potential allows applying the basic equations of the finite element method and the general potential theory for calculation of stationary and non-stationary temperature fields [2].

When numerical calculation taken the following basic assumptions:

- the temperature field is plane-parallel;
- the homogeneous regions are isotropic, the thermo-physical characteristics of materials are independent on temperature;
- the heat conjugate on border interface of regions is ideal.

Fig. 1 shows the temperature field distribution in section of winding bar of a turbogenerator type TGV-200 from the turbine side for the load condition P = 160 MW, Q = -52 MVAr. The refrigerant temperature in elementary conductors is 60 °C. Fig. 1 shows that the temperature of stator winding insulation is unevenly distributed. The maximum temperature of stator winding bar is over nearly in 2 times than the minimum temperature.

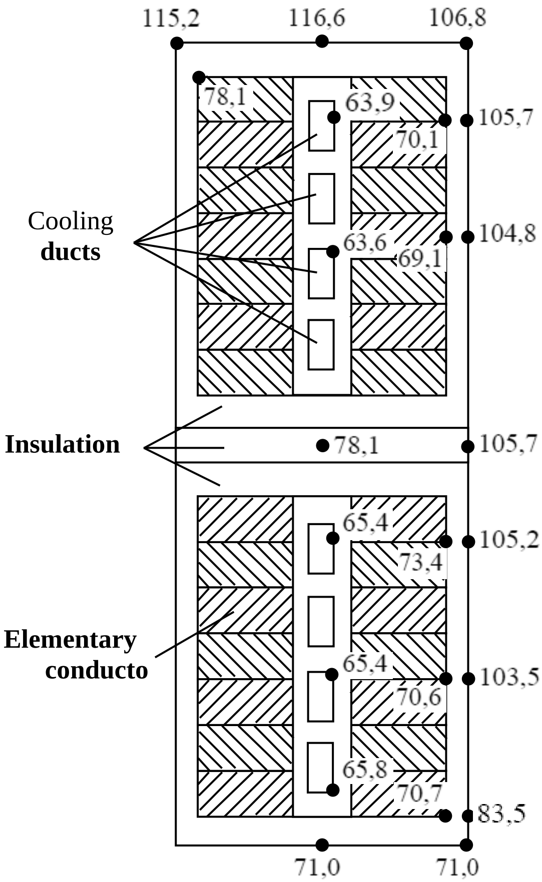

Fig. 1

This turbogenerator is well equipped with thermocouples and tested in many load conditions. The maximum temperature of winding bar insulation and the average maximum one for most critical zone in terms of aging and damage insulation were calculated for nine operating conditions of a generator with load and heat process parameters. This zone is decisive in determining the residual life.

Table 1 shows the temperature of cooling gas θ_{cg} in relation to which the excess temperature in the stator winding is determined, the average maximum temperature of isolation θ_{max} and its excess $\Delta\theta_{max}$.

Table 1

№ load	P, MW	Q, MVAr	U_s, kV	I_s, kA	cos φ	U_r, V	i_r, A	θ_{cg}, °C	θ_{max}, °C	$\Delta\theta_{max}$, °C	θ_i, °C
1	144	79,6	15,9	6,1	0,857	295	1421	34	70,4	36,4	33
2	142	46,3	15,67	5,5	0,95	251,5	1235	36	76,2	40,2	19,5
3	138	5,77	15,12	5,2	1,0	205,6	1024	34,5	82,5	48	19,5
4	138	-39	14,7	5,66	-0,985	171	848	35,5	99,3	63,8	30,2
5	158	6,8	15,45	5,92	~ 1,0	224	1110	33	92,1	59,1	24,4
6	157	-45,3	14,7	6,35	-0,965	187	929	37,25	117	79,8	23,5
7	185	106	16,65	7,56	0,845	379	1702	42	95,4	53,4	33,1
8	179	6,6	15,75	6,6	~ 1,0	245	1203	34	96,79	62,7	22,6
9	204	66	16	7,7	0,953	336,2	1549	42,5	109,6	67,1	31,5
10	206	118	16,65	8,48	0,845	417,4	1844	45	93,14	48,14	37
11	200	-55	15	7,977	-0,965	187	929	37,25	153	116	27
12	200	-83	14,7	8,5	-0,924	160	800	36	191	155	38

Using bulky mathematical software for the maximum temperature calculation at different load conditions of a turbogenerator in real time (with continuous control in operating conditions) is not quite convenient, so it is more advisable to obtain regressive dependences of the maximum temperature on the controlled parameters during the operate of generator. Such parameters are the load condition characteristics and the resistance thermometers signal installed in the stator winding and indirectly characterized its temperature. It is necessary that such regressive dependences can also be used for predict the maximum temperature of winding insulation in the stator end packets in the underexcitation load conditions of a turbogenerator with the maximum temperature of stator core [3, 4]. The input in dependences of resistance thermometers readings will also to estimate the insulation maximum temperature value with heat defects of the core steel and the stator winding. Studies of parameters optimum choice by the criterion of minimum temperature variation in the underexcitation load conditions were made for determine of exact regressive dependences.

Some of regressive dependences obtained according to load condition data 6 (see Table 1) and the relative errors of calculated and experimental data for this load condition are as following:

$$\Delta\theta s\ cos\ \varphi_{max},\ \delta = 21{,}2\%, \quad (2)$$

$$\Delta\theta s\ cos\ \varphi_{max},\ \delta = 17\%, \quad (3)$$

$$\Delta\theta s_{max},\ \delta = 11{,}5\%, \quad (4)$$

$$\Delta\theta s\ cos\ \varphi_{r\,s_{s}{}_{max}}^{\ 2},\ \delta = 2{,}6\%. \quad (5)$$

It can be seen from the above dependences that the last is the most accurate for underexcitation load conditions with such control parameters: the stator load conditions, the stator and the rotor currents, and cos φ. Taking into account this result the following regressive dependences for control and diagnostics of isolation state and its resource definition can be obtained:

$$\Delta\theta i_{s_{s}r_{max}}^{\ 2} \quad (6)$$

$$\Delta\theta i_{s_{s}r_{c_{max}}}^{\ 2}, \quad (7)$$

where $\Delta\theta_s$ and $\Delta\theta_c$ – excess temperature of steel and copper by the regular control system of a turbogenerator, respectively.

The maximum relative error of dependence (6) for all load conditions not exceeds 3,5 %. For dependence (7) this value is slightly higher (5 – 7 %). That is, taking into account the resistance thermometers readings installed between the winding bars worsens the convergence of obtained regressive dependences. The coefficient at $\Delta\theta_c$ of dependence (7) is insignificant. This indicates that the load condition parameters and resistance thermometers readings installed at the slot bottom have a more influence on the maximum temperature for the present turbogenerator. This corresponds to the peculiarities of heat processes in such machines in the underexcitation load conditions.

Taking into account the method of resistance thermometers install at the slot bottom area (from the third packet of stator core end zone), it can be expected that their readings will not show the peculiarities of heat processes in end packets under load conditions of reactive power consumption (increase of heating with decrease of excitation current). This can also be seen from Table 1. The magnitude of resistance thermometers readings installed between the winding bars and at the slot bottom area is directly proportional to active power and stator current and almost does not respond to reactive power. Therefore, regressive dependences of type (6), (7) advisable to obtain only for load conditions of reactive power consumption. These dependences are as following:

$$\Delta\theta i_{s_{s_{c_{max}}}}^{2} \quad (8)$$

$$\Delta\theta i_{s_{s_r}}^{2} \cos\varphi_{max}. \quad (9)$$

These expressions allow predicting the readings $\Delta\theta_i$ i $\Delta\theta_c$ for the specified load conditions diapasons after $\Delta\theta_{max}$ is found from (5). **It is necessary to note the** removal from a regression parameters number of current excitation makes significant the regression coefficient to θ_c.

It is possible to predict the maximum temperature for load conditions 11 and 12 (the reactive power consumption at nominal active power) using the obtained regressive dependences. It can be seen from Table 1 that for these load conditions the maximum temperature insulation exceeds the allowable value.

The resistance thermometers readings are as follows: for load 11: $\Delta\theta_i$ = 27 °C, for load 12: $\Delta\theta_i$ = 38 °C.

The resistance thermometers readings do not exceed 40 °C for all of these load conditions. The resistance thermometers do not respond at all to increase of insulation temperature in the end packets zone in the underexcitation load conditions. This causes the need for a specified temperature control of winding insulation on the basis of above methodical foundations.

The above method for maximum temperature definition of a turbogenerator stator winding insulation to calculate of its residual life in real time will use.

It is known the residual life insulation calculates for the nominal load temperature θ_n when an electrical machine designs. Thus, find the calculated residual life insulation θ_{cal}. The temperature θ differs significantly from one θ_n in the process of turbogenerator work. It is advisable therefore to find the actual lifetime insulation for any temperature by the formula:

$$T_i = t_i\left(\frac{T_{\mathrm{cal}}}{e^{\left(\frac{A+B}{(273+\theta)}\right)}}\right), \quad (10)$$

where t_i are the intervals of the present operation time in which the temperature deviates from some average value by a small quantity. Thus, the actual lifetime isolation will increase when $\theta > \theta_n$ and decrease when $\theta < \theta_n$ in separate intervals of operation time as compared with the present time. For time moment

$$t = \sum_{i=0}^{n} t_i,$$

where t_0 – the operation beginning of new insulation,

the residual life is

$$T_{\mathrm{res}} = T_{\mathrm{cal}} - \sum_{i=0}^{n} T_i^{*}. \quad (11)$$

It is clear the insulation part at the maximum temperature wears out much faster than the others its areas.

How much the residual life insulation decreases in consideration of high heat zones will show.

According to [1] B = 1020, A = -15,5 for stator winding insulation of a turbogenerator under consideration. When winding temperature T_{max} for the nominal load condition is 97,4 °C the calculated insulation life T_{cal} = 28; and T_{cal} = 79 years when θ is the temperature determined by means of resistance thermometer.

It is assumed that a turbogenerator for year works 6000 hours. Let a turbogenerator for 28 years in load condition 12 have worked 1008 hours. Then by (10) the insulation part of stator winding at the maximum temperature actually will live 26000 hours. The residual life is T_{res} = 23,8 hours. The insulation part that will be determined at the average temperature (~ 60 °C), will live during this time only 57 hours, and the residual life will be reduced by these 57 hours. In case the winding insulation temperature is the resistance thermometers value that the residual life will be even greater.

Conclusions

1. The reliability for residual life definition of generator stator windings insulation is higher when the calculated value of the maximum temperature is taken as the insulation temperature.
2. The given methodical means can be applied in the control and diagnostics systems of a turbogenerators in real time.

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