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LOAD CONDITIONS AND EVALUATION OF THE RISE OF TEMPERATURE IN AN ENCLOSED CONDUCTOR

František Janíček * — Justín Murín ** — Jaroslav Lelák ***

Reliability of drives and electric systems in the auxiliaries of a power plant strongly affects the safety and operation reliability of the power plant blocks as well as the reliability of electric power delivery. The reliability of electric systems is affected — to a large extent — by the reliability of their supplying and by the overall design of the main electric scheme of the power plant. This contribution is concerned with a check computation of the load conditions in special busbars of reserve transformers in nuclear power plants. Additionally, evaluation of the rise of temperature of an enclosed conductor caused by Joule losses has been carried out by analytical and finite element methods.

Keywords: auxiliaries, nuclear power plant, load condition, enclosed conductor, heat transfer, finite element methods

Abbreviations: ASSU — Automatic Standby Start Up, TS — Trip Signal, CASSU — Collective Automatic Standby Start Up, EPSS — External Power Supply Sources, AX — Auxiliaries, RCP — Reactor Coolant Pump, EC — Enclosed Conductor, FEM — Finite Element Methods

1 INTRODUCTION

After the decision was adopted in 1995 to complete the 1st and 2nd blocks of the Nuclear Power Plant of Mochovce (JEMO) and after changing the supplier of the control system, the design had to be modified for the nuclear power plant to reach an internationally acceptable level. Within the project of completion of the 1st and 2nd blocks, a programme for improving the nuclear safety of JEMO was worked out in 1996. This programme led to additional changes and measures made to increase the operation safety and reliability.

In particular, an increased level of reliability of external supplying of the auxiliaries is supposed. The first design of the JEMO assumed one reserve transformer for two neighbouring blocks (1st and 2nd blocks, and for 3rd and 4th blocks). The new solution assumes one independent transformer for each of the blocks, which widens the operation possibilities of the two blocks in non-standard operation modes such as inspections of electrical systems, outages of the blocks of the nuclear power plant, faults of one of the reserve transformers. Non-standard modes of plant operation impose also increased requirements on the transmission of the required power through the 6 kV reserve busbars, through which the two blocks are interconnected [1], [2], [8].

The calculation of the current loading of the supplies and busbars of the reserve supplying anomalous modes is the basis for verification of the permissible current loading [9].

2 CHANGES IN THE SOLUTION OF RESERVE SUPPLYING OF THE AUXILIARIES

The original solution assumed one stand-by transformer 7BCT 1 common to the two blocks, located between the first and second blocks, and the reserve busbars between the blocks were supposed to be connected normally. The main drawback of such a solution is the fact that in the course of an inspection of this transformer and of its supplying 110 kV line which is to be carried out during a planned outage (roughly 5 days) of one of the two blocks, the neighbouring working block had no reserve supplying. A single reserve transformer was not rated sufficiently to secure a simultaneous self-acting start of the drives after CASSU on both of the blocks. In the case of a failure of working supplying of some of the 6 kV switching stations this would lead to an outage of the working block and to starting the emergency diesel generators.

The new solution proposes to implement a second transformer 7BCT 2 (110/6.3/6.3 kV) for the first two blocks and its placement between the second and third blocks (Fig. 1). At the same time, the reserve busbars between the 1st and 2nd blocks are disconnected. The transformer is supplied by a separate 110 kV line from the switching station Velký Ďur. This solution allows using the reserve supply of the 2nd block also for the 1st block, and vice versa. In this way, a better solution has been achieved but a problem has been encountered with dimensioning the reserve busbars. As busbars of the reserve supplying of the auxiliaries in JEMO, EC with a nominal current of 2.5 kA are used, produced by EGE České Budějovice [9].

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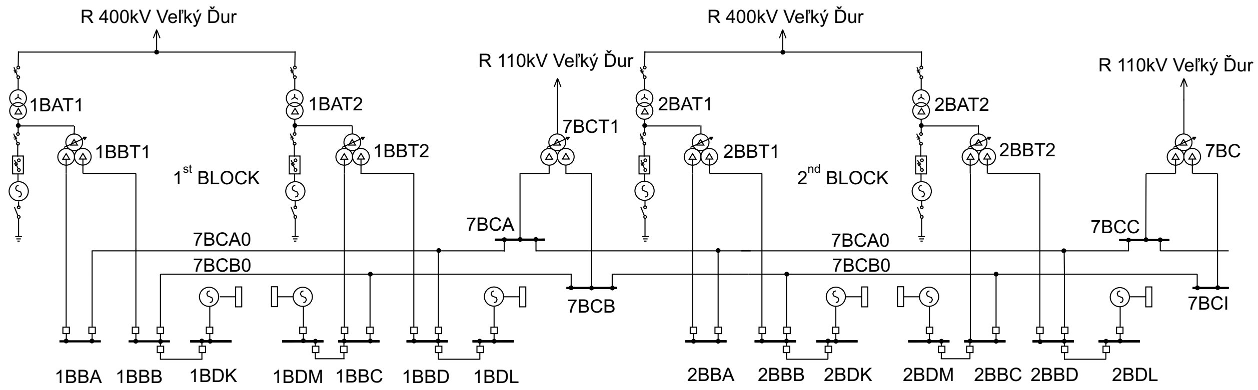

Fig. 1. Characteristic of the protection against loss of stability.

Table 1. The current loads of the reserve busbars

Busbar	Preliminary load I(A)	Recooling 0.5h I(A)	2h I(A)	4.5h I(A)	5h I(A)	8h I(A)	9h I(A)	11h I(A)	14h I(A)	15h I(A)	16h I(A)
7BCA0	831.4	2474.7	2321	2321	1426	1426	1426	1439	1274	1274	1274
7BCB0	1307.2	3240.1	2795	2801	2293	2284	2286	2315	2005	1957	1915

In order to use the reserve transformer of the 2nd block to supply the "1.5th block" one has to verify the maximum transmission ability of the reserve busbars of the 2nd block from the point of view of transmitting a defined power to the 1st block while simultaneously loading the busbars by power take-offs of the 2nd block.

3 OPERATION MODES OF THE AUXILIARIES

The operation of the block is classified into these fundamental modes: R0 — block in hot reserve, R1 — start of the block, R2 — normal operation of the block with two working turbogenerators, R3 — anomalous operation of the block with one working turbogenerator, R4 — planned outage of the block, R5 — breakdown outage of the block caused by TS with CASSU, R6 — breakdown outage of the block caused by TS associated with a loss of working and reserve supplies, R7 — temporary abnormal operation of the block on AX. In modes R1, R2, R3, R4, and R7 the auxiliaries are supplied from working supplies. Part of the auxiliaries may be fed from a reserve supply. However, the feeding of the auxiliaries from the reserve supply can not be regarded as a normal state even though it may take several days till the working supplying is recovered. In modes R0 and R5 the auxiliaries are fed from the working or reserve supplies and in mode R6 from emergency supplies.

From the point of view of the requirements imposed upon the supplies of reserve feeding of the auxiliaries EPSS, the following situation can occur in a given block: A breakdown of the working supplying of one 6 kV switching station or a breakdown of the working supplying of two switching stations (*eg*, disconnection of the working transformer of the auxiliaries). If a fault occurs in three or four 6 kV switching stations, CASSU is signalled.

For checking the supplies and busbars of the reserve feeding of the auxiliaries in the second block we consider a state in which the reserve transformer 7BCT 1 is out of operation and the reserve supply for both of the blocks is provided by transformer 7BCT 2. In such a case the reserve busbars between the 1st and 2nd blocks are connected. Further, we suppose a situation that part of one block is fed from the reserve supply (permanent load) and in the neighbouring block one of those situations occurs which are described in part 3.

The most severe case of a permanent load from the point of view of current loading is the operation of the block in mode R2, the load being represented by two 6 kV sections fed from the reserve transformer.

4 EVALUATION OF THE CURRENT LOAD OF SUPPLIES AND BUSBARS

The load of EPSS is evaluated in steady states after the electromechanical transient phenomena accompanying automatic start up and restart have decayed. The basis determining these currents are the power balances for modes R2 and R5 [1]. A symmetrical load is considered.

For the purposes of computation we assume that the 2nd block operating in mode R2 loads the EPSS by a preliminary load represented by two 6 kV sections (two possible variants) and, at the same time, on the 1st block one of the situations described as a) to c) occurs.

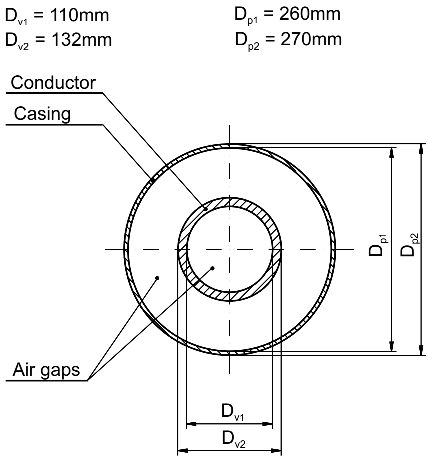

Fig. 2. The cross-sectional area of the EC

The first load case contains two variants of the preliminary load of the 2nd block:
Variant A: Outage of the operational feeding from the transformer AX 2BBT1. The load consists of two 6 kV sections 2BBA + 2BBB. The block continues operating in mode R2 with two sections, 2BBA and 2BBB, on the reserve supplying. In this case the current loads of the reserve busbars are 831 A (7BCA0) and 1307 A (7BCB0), see Table 1.
Variant B: Outage of the operational feeding from the transformer VS 2BBT2. The load consists of two 6 kV sections 2BBC + 2BBD. The block still operates in mode R2 with sections, 2BBXC and 2BBD, on the reserve supplying. In this case, the current loads of the reserve busbars are 1204 A (7BCA0) and 1109 A (7BCB0).

The second case of loading the EPSS for the reserve transformer is the occurrence of situations in the 1st block according to Variants a) to c):
Variant a): Outage of four 6 kV sections in mode R2 and transition into mode R0.
Variant b): Outage of four 6 kV sections in mode R2 and transition to the mode of recooling.
Variant c): Outage of four 6 kV sections in mode R5, the block continues in the mode of shutting down from reserve supplies. This is the most severe case because the block is recooled by means of circle II and the RCP operates.
The total load of the supply and of the four sections of the 1st block from operational to reserve feeding (R2 — R0/recooling, R5 — recooling). The discussed current load does not apply to the whole route of the reserve busbars.

The highest total busbar loading — from the point of view of dimensioning — presents CASSU in mode R5 connected with a transition of four 6 kV sections onto reserve feeding plus the preliminary load (two 6 kV sections of the neighbouring block on reserve feeding). In the most adverse case a current of 3.24 kA will flow through the busbar (7BCB0) for 30 minutes, followed by a decrease to 2 kA for 240 minutes and another rise to 2.3 kA. In the discussed case a not very likely state is assumed in which a technologic breakdown would occur (R5) of the working block followed by a failure of the whole operational feeding of auxiliaries. Additionally, the neighbouring block representing the preliminary load of two 6 kV sections on reserve would similarly have to be in an anomalous state whose occurrence during the whole lifetime of the power plant is relatively rare. The probability of such a situation is further lowered by the fact that the reserve transformer 7BCT 1 would have to be out of operation. It follows from the analysis that under combination of adverse conditions a current of approximately 3.24 kA may load a part of the route of EC. Therefore it is necessary to check if the route of busbars EC 2.5 kA can withstand the discussed overload [2]. In the next part of this contribution the evaluation of the temperature rise of the EC loaded by a current of 2.5 kA is made. Both analytical and numerical (by finite element method) evaluations of the temperature rise in the EC (caused by Joule losses) have been made.

5 EVALUATION OF THE RISE OF TEMPERATURE OF ENCLOSED CONDUCTORS IN STEADY STATE

The evaluation of the steady state temperature field of an enclosed conductor (EC) means solving a 2D-heat transfer problem with internal heat sources. The cross sectional area of the enclosed conductors contains the wire, casing, and air gaps inside the wire and between the wire and the casing (Fig. 2).

The heat produced by Joule losses in the wire and in the casing is transferred by conduction and by restricted convection to the casing surface from which it is subsequently transferred by free convection into the surroundings of the EC. One part of the heat is transferred by radiation between the wire and the casing and between the casing and the air surroundings. Both the wire and the casing are heated into the steady state by generated heat, but only partially transferred heat.

The temperature rise in the EC for a given load case will be evaluated analytically and numerically under the following assumptions:

- the heat sources in the wire and the casing are given by Joule losses, the magnitude of losses depends on the current in the wire I_v and in the casing I_p (we will suppose that $I_p = 0.2 I_v$) [3],
- the air inside the wire does not flow and it transfers the heat by conduction only (its heat conductivity factor $\lambda_1 = 0.029$ W/mK) [4],
- the heat is transferred across the wire and casing by conduction in the radial direction only (the heat conductivity factor $\lambda_2 = 229.1$ W/mK),

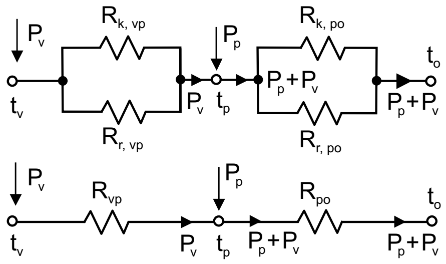

Fig. 3. Thermokinetical model of the EC

Fig. 4. FEM model of the EC

- across the air gap between the wire and the casing, the heat is conducted with the equivalent conductivity factor being λ_{ekv} in which restricted convection is accounted for (the evaluation of λ_{ekv} is iterative, depending on the mean temperature and air flow conditions), and the heat is radiated with emissivity constant $\varepsilon = 0.2$,
- the heat is transferred from the casing surface by free convection into the surroundings ($t_o = 28\,°\mathrm{C}$ is the bulk temperature), and by radiation with emissivity constant $\varepsilon = 0.2$.

5.1 Analytical solution of the temperature rise

The thermokinetical scheme of the heating of EC is given in Fig. 3. P_v is the heat source in the wire [W/m], P_p is the heat source in the casing [W/m], R_{vp} is the heat resistor between the wire and the casing [mK/W], R_{po} is the heat resistor between the casing and its surroundings [mK/W], t_o is the bulk temperature.
Then we can write

$$P_v = \frac{t_v - t_p}{R_{vp}}\,, \qquad P_v + P_p = \frac{t_v - t_p}{R_{po}}\,, \tag{1}$$

After some manipulation we get the equations for deriving both the wire and casing temperatures in the steady state (t_v and t_p).

$$\begin{aligned} t_v &= P_p R_{vp} + (P_p + P_v) R_{po} + t_o\,,\\ t_p &= (P_v + P_p) R_{po} + t_o\,. \end{aligned} \tag{2}$$

The heat resistor R_{vp} contains two parallel resistors: the convection component $R_{k,vp}$ and the radiation term $R_{r,vp}$

$$\begin{aligned} R_{k,vp} &= \frac{1}{2\pi\lambda_{ekv}} \ln\frac{D_{p1}}{D_{v2}}\,,\\ R_{r,vp} &= \frac{t_v - t_p}{\pi D_{v2}\varepsilon_n c_0\left[(T_v/100)^4 - (T_p/100)^4\right]}\,, \end{aligned} \tag{3}$$

where $\lambda_{ekv} = \varepsilon_k\lambda$ is the equivalent heat conductivity of the air inside the gap between the wire and the casing (λ is the conductivity of air at corresponding mean temperature, ε_k is the restricted convection coefficient that must be evaluated from the criterial equations). T_p and T_v are absolute wire and casing temperatures, respectively, $c_0 = 5.67\,\mathrm{W/mK^4}$ is the Stefan-Boltzmann constant, ε_n is the replaced emissivity of the outer wire (ε_v) and the inner surface of the casing (ε_p)

$$\varepsilon_n = \frac{1}{(1/\varepsilon_v) + (D_{v2}/D_{p1})\big((1/\varepsilon_p) - 1\big)}\,. \tag{4}$$

The heat resistor R_{po} contains two parallel parts, the convection term $R_{k,po}$ and the radiation term $R_{r,po}$:

$$\begin{aligned} R_{k,po} &= \frac{1}{\pi D_{p2}\alpha}\,,\\ R_{r,po} &= \frac{t_v - t_o}{\pi D_{p2}\varepsilon_p c_0\left[(T_p/100)^4 - (T_o/100)^4\right]}\,, \end{aligned} \tag{5}$$

where α is the heat flux coefficient for free convection of heat from the casing surface to the surroundings with absolute bulk temperature T_o (α must be evaluated by an iterative algorithm from the criterial equations).

For the load case $I_v = 2.5\,\mathrm{kA}$ [5] (the wire heat source $\mathring{q}_v = P_v/S_v = 11314\,\mathrm{W/m^3}$ where S_v is the wire cross-section area, and the casing heat source, S_p $\mathring{q}_p = P_p/S_p = 4305\,\mathrm{W/m^3}$ where S_p is the casing cross-section area) we have received:

- the equivalent heat conductivity of the air inside the gap between the wire and the casing $\lambda_{ekv} = 0.149765\,\mathrm{W/mK}$,
- the heat flux coefficient of the free convection from the outer casing surface $\alpha = 3.948\,\mathrm{W/m^2K}$.

From equations (3) we have

- the wire temperature $t_v = 69.6\,°\mathrm{C}$,
- the casing temperature $t_p = 43.1\,°\mathrm{C}$,

In the case of negligible heat transfer by radiation in (3) we get

- the wire temperature $t_v = 81.5\,°\mathrm{C}$,
- the casing temperature $t_p = 47.4\,°\mathrm{C}$.

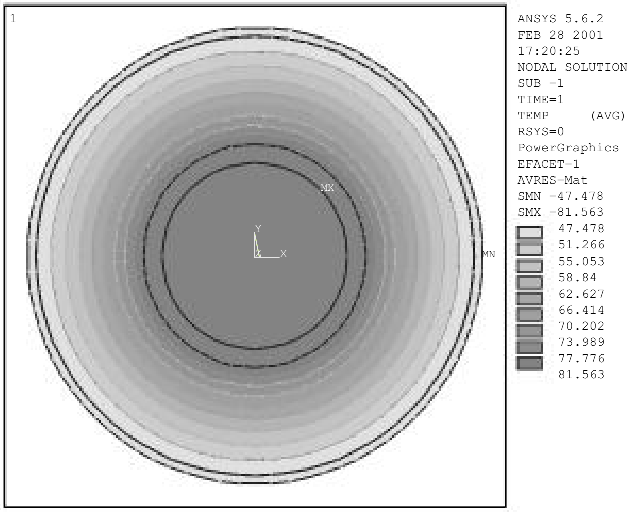

Fig. 5a Temperature field

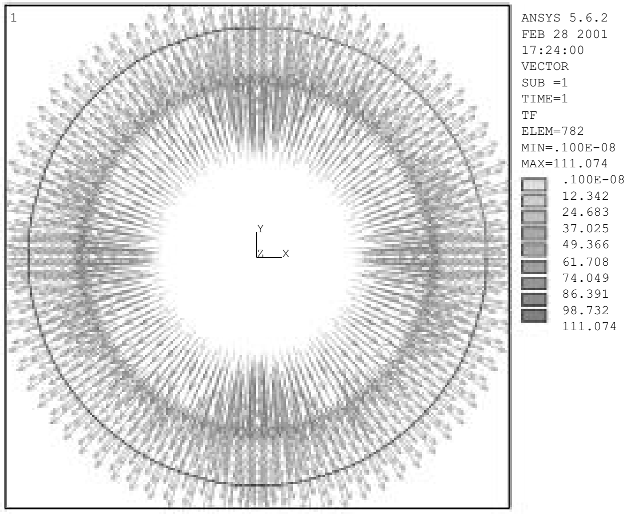

Fig. 5b Heat flux

5.2 Evaluation of the temperature rise by FEM

The problem of the steady state heat transfer is described by the functional [6]

$$\Pi\left[t(x,y,z)\right] = \frac{1}{2}\int\limits_V \left[\lambda_x\Big(\frac{\partial t}{\partial x}\Big)^2 + \lambda_y\Big(\frac{\partial t}{\partial y}\Big)^2 + \lambda_z\Big(\frac{\partial t}{\partial z}\Big)^2 - 2\dot{q}t\right]\mathrm{d}V + \int\limits_{S_2} qt\mathrm{d}S_2 + \frac{1}{2}\int\limits_{S_3}\alpha(t-t_\infty)^2\mathrm{d}S_3 \quad (6)$$

where: $t(x,y,z)$ is the unknown temperature field in points of the body (the volume of this body is V and the surface is S);
$\lambda_x, \lambda_y, \lambda_z$ are the heat conductivity factors of the material in directions x, y, z; $\dot{q}$ is the generated heat [W/m^3];
q is the conducted heat through the body surface S_2;
α is the flux coefficient of the heat convection [W/m^2] from the body surface S_3 into the surroundings (its temperature is t_∞ [°C]).

An algebraic system of equations will be achieved after implementation of the finite element methods into the equation (6):

$$\mathbf{K}\boldsymbol{t} = \mathbf{P} \quad (7)$$

$\mathbf{K}$ is the heat conduction matrix,
$\boldsymbol{t}$ is the vector of the element nodal points temperatures,
$\mathbf{P}$ is the heat loads matrix.

For modelling the EC cross-sectional area (the wire, the casing, and the air gaps), a 6-nodal triangle element of the program ANSYS [7] has been used (Fig. 4). The used geometric and material parameters were the same as in the analytical solution. The heat transfer by radiation has not been taken into account in this numerical solution.

The resultant temperature field and the temperature flux are given in Fig. 5. The wire has been heated to temperature $t_v = 81.5$ °C, the casing has been heated to temperature $t_p = 47.4$ °C.

Comparing the results of the analytical and numerical methods we can see good agreement of the obtained temperatures in the case of neglecting heat radiation. These results are situated on the safe site of the loading. Including the radiation in the solution diminishes the temperature rise of the wire.

6 CONCLUSION

The manufacturer states a nominal current of 2.5 kA for the nominal temperature 75 °C in the EC. Anyhow, this value was determined on the basis of an economical current density rather than limited by the maximum permissible temperature of the conductor. The results of our analytical and numerical solution of the temperature rise have approved the nominal operation conditions of the 2.5 kA EC.

For exact consideration of a safe operation of the 2.5 kA EC by overloading, additional analytical, numerical and experimental evaluations have to be performed. These evaluations will be the aim of our further work.

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