MECHANICAL STRESS OF THE GAS TURBINE SHAFT AT GENERATOR FAILURE STATES

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SUMMARY

This paper deals with the calculation of the short circuit moment synchronous machine and the influence on reliable operation of the set turbine-generator.

Keywords: *d,q,0 model of synchronous generator, voltage equations, magnetic fluxes equations, short circuit, sensitivity and toleration analyse*

1. INTRODUCTION

Synchronous machine have a privileged position among the sources of power energy for whole electricity supply system. Their failure-free work is therefore necessary for guaranteeing a rising demand on consumption and quality of power energy. One of the problem of failure-free work is the effect of the moment in short-circuits. The short-circuit moment exceeds several fold the nominal moment and causes the torsion oscillations of the shaft of whole aggregate turbine–alternator–exciter. How puts forth an influence of saturation the magnetic circuit into that is necessary to calculate by mathematical model. The solution comes out from the description of electromagnetic effects in the particular winding. We make up the stator's winding and exciter's winding as coils, whose electrical characteristics respond to the real windings. A damper is replaced according to his unbalance by two spare windings [1,2,3].

A part of each mathematic simulation should have to be an analyse of the form of this system not only at the nominal values its parameters, but also at different deviations. In accordance to it, the sensitivity and toleration analyse of the appropriate mathematical model usually makes. Its application' may be for example the optimizing of the design of the concrete machine.

2. MACHINE MODEL

A synchronous model is respected by six windings, according to figure 1. The stator contains three phase windings: a, b, c. Rotor contains exciter winding F and two spare damper circuits in lenght and diagonal axes D, Q. Mathematical model is consumptional, i.e. the output and the moment of generator is negative and that of motor positive.

Due to the symmetrical failures modelling only, the stator of the machine was transformed by means of Park's transformation into axes d,q,0. Respecting the three phase system symmetry assumption supposition, the 0 component is identically zero. Park's transformation was used with coefficients for moments and outputs invariation.

Further, a relative values system was used, namely the system of equal mutual reactance. A detailed descriptions of the model used is given in [8].

Direction of rotation

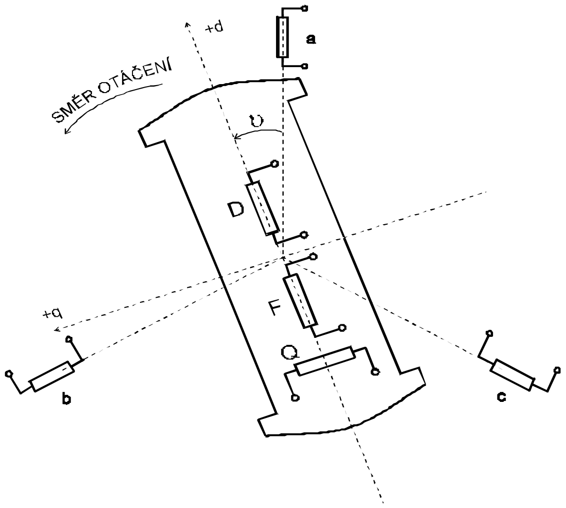

Fig. 1 Equivalent diagram of synchronous machine

where:

D	– spare damper circuit in lenght axis d
Q	– spare damper circuit in diagonal axis q
F	– spare exciter circuit in lenght axis d
a,b,c	– spare circuit of phase a,b,c
ϑ	– angle between axis of rotor and axis of phase a

Below in text is worked with these input parameters:

T_j	– time factor of accelerating
x_{hd}	– main reactance in axis d
x_{hq}	– main reactance in axis q
$x_{a\sigma}$	– stator leakage reactance
r_a	– stator windings resistance
$x_{F\sigma}$	– exciter leakage reactance

r_F – exciter winding resistance
$x_{D\sigma}$ – damper lenght axis leakage reactance
$x_{Q\sigma}$ – damper diagonal axis leakage reactance
r_D – damper lenght axis resistance
r_Q – damper diagonal axis resistance

The diagram in figure 1 is described by:

a) voltage equations

$$U_k = R_k I_k + \frac{d\Psi_k}{dt} \qquad (k=a,b,c,F,D,Q) \tag{1}$$

b) equations for linkage magnetic fluxes

$$\begin{bmatrix} \Psi_a \\ \Psi_b \\ \Psi_c \\ \Psi_F \\ \Psi_D \\ \Psi_Q \end{bmatrix} = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} & L_{aF} & L_{aD} & L_{aQ} \\ L_{ba} & L_{bb} & L_{bc} & L_{bF} & L_{bD} & L_{bQ} \\ L_{ca} & L_{cb} & L_{cc} & L_{cF} & L_{cD} & L_{cQ} \\ L_{Fa} & L_{Fb} & L_{Fc} & L_{FF} & L_{FD} & 0 \\ L_{Da} & L_{Db} & L_{Dc} & L_{DF} & L_{DD} & 0 \\ L_{Qa} & L_{Qb} & L_{Qc} & 0 & 0 & L_{QQ} \end{bmatrix} \times \begin{bmatrix} I_a \\ I_b \\ I_c \\ I_F \\ I_D \\ I_Q \end{bmatrix} \tag{2}$$

For the linear transformation to the d, q, 0 coordinates is used a transformation matrix T

$$\begin{bmatrix} x_d \\ x_q \\ x_0 \end{bmatrix} = \underbrace{\begin{bmatrix} +k_d\cos\vartheta & +k_d\cos(\vartheta - 2/3\pi) & +k_d\cos(\vartheta + 2/3\pi) \\ -k_q\sin\vartheta & -k_q\sin(\vartheta - 2/3\pi) & -k_q\sin(\vartheta + 2/3\pi) \\ k_0 & k_0 & k_0 \end{bmatrix}}_{T} \times \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \tag{3}$$

After transformation the voltage equations will be:

$$\begin{aligned} U_d &= RI_d + \frac{d\Psi_d}{dt} - \Omega\Psi_q \\ U_q &= RI_q + \frac{d\Psi_q}{dt} + \Omega\Psi_d \\ U_0 &= RI_0 + \frac{d\Psi_0}{dt} \\ U_F &= R_F I_F + \frac{d\Psi_F}{dt} \\ U_D &= R_D I_D + \frac{d\Psi_D}{dt} \\ U_Q &= R_Q I_Q + \frac{d\Psi_Q}{dt} \end{aligned} \tag{4}$$

and the linkage fluxes equations

$$\begin{aligned} \Psi_d &= L_d I_d + L_{dF} I_F + L_{dD} I_D \\ \Psi_q &= L_q I_q + L_{qQ} I_Q \\ \Psi_0 &= L_0 I_0 \\ \Psi_F &= L_{Fd} I_d + L_{FF} I_F + L_{FD} I_D \\ \Psi_D &= L_{Dd} I_d + L_{DF} I_F + L_{DD} I_D \\ \Psi_Q &= L_{Qq} I_q + L_{QQ} I_Q \end{aligned} \tag{5}$$

Completing the voltage equations (4) with the movement equations for ω and β:

$$\begin{aligned} \frac{d\psi_d}{dt} &= \psi_d A + \psi_F B + \psi_D C + \psi_q \omega + u_d \\ \frac{d\psi_q}{dt} &= \psi_q D + \psi_Q E - \psi_d \omega + u_q \\ \frac{d\psi_F}{dt} &= \psi_F F + \psi_d G + \psi_D H + u_F \\ \frac{d\psi_D}{dt} &= \psi_D I + \psi_d J + \psi_F K \\ \frac{d\psi_Q}{dt} &= \psi_Q L + \psi_q M \end{aligned} \tag{6}$$

The loading angle is after the modification defined in relative scale by the relation

$$\frac{d\beta}{dt} = \omega - 1 \tag{7}$$

The moment of the synchronous machine in relative scale

$$m_{e1} = \psi_d i_q - \psi_q i_d \tag{8}$$

The moment equation of the synchronous machine in relative scale

$$\frac{J}{M_n} \cdot \frac{d(\Omega_{mech} \cdot p / \Omega_n)}{dt \cdot \Omega_n} \cdot \frac{\Omega_n^2}{p} = \frac{M_{e1}}{M_n} + \frac{M_{mech}}{M_n} \tag{9}$$

where of after the modification results the relation

$$T_j \frac{d\omega}{dt} = m_{e1} + m_{mech} \tag{10}$$

Connecting the equations (8) and (10) it obtains

$$T_j \frac{d\omega}{dt} = \psi_d i_q - \psi_q i_d + m_{mech} \tag{11}$$

and after the substitution for the currents the equation is for the angular velocity

$$\frac{d\omega}{dt} = \frac{1}{T_j}\left(-\psi_d \psi_q N - \psi_d \psi_Q 0 + \psi_q \psi_F P + \psi_q \psi_D R + m_{mech}\right) \tag{12}$$

The course of the synchronous machine in dynamic operations is described with equations (6,12) by the relation

$$\frac{d\beta}{dt} = \omega - 1 \tag{13}$$

The constant from A to R are in [5,6].

The premises, whereby is possible to describe the synchronous machine by the equation system (6) and (12), are:

1. a sinusoidal layout of the stator winding round the circumference of the machine
2. an implementation of one spare exciter winding in each axis
3. a symmetrical three phase system, i.e. the voltage of the net is sinusoidal with constant angular speed Ω_n
4. an unsaturated magnetic circuit
5. an implementation of stator relative scale
6. an implementation of rotor relative scale and the conversion from stator to rotor by the system of same mutual reactances

The main magnetic flux marked with the suffix h encloses through the stator and rotor magnetic circuit over the air gap. The leakage magnetic flux marked with suffix $\Phi_{F\sigma}$ encloses around of each stator and rotor winding.

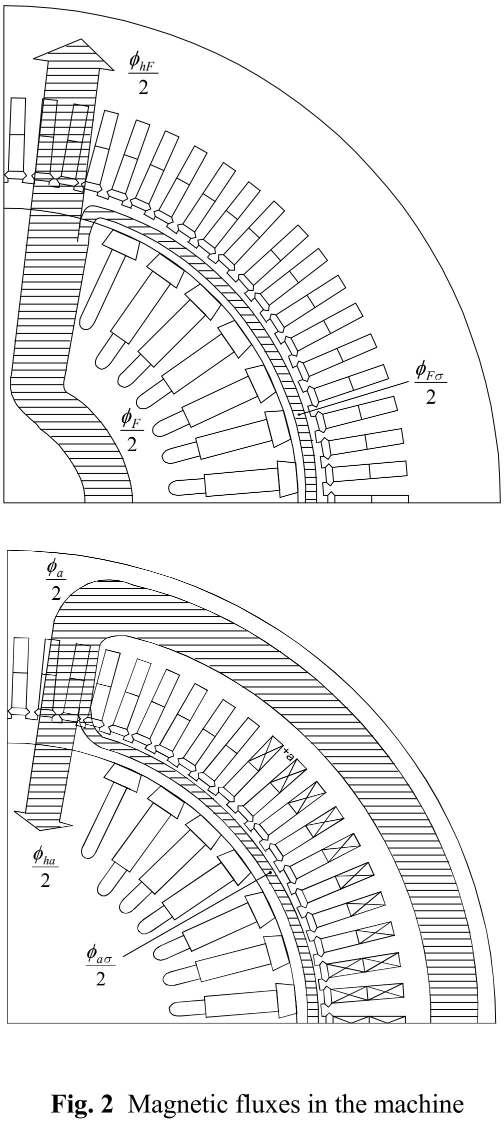

Fig. 2 Magnetic fluxes in the machine

3. USE OF MATHEMATICAL MODEL IN D,Q,0 COORDINATES

The aim of the calculation is to determine the influence of the saturation of magnetic circuit of the 35 MVA alternator on his short circuit moment at three-phase symmetrical short-circuit. The short circuit was simulated like short-circuit direct on the machine connections. The characteristics for the model described above were identified from the test measuring and from the calculation. Each other were in a very good harmony.

These four principle matters were further included in the model:

1) The influence of saturation can be respected in this model only approximately [4,7,8].
2) The linearization of magnetic circuit is made by time segments during the calculation. In every integrative step is the machine in fact solved as the machine with different magnetically conductive circuit. The conductivity of each part of magnetic circuit and then also the size of reactance is determined by the size of magnetic fluxes passing through appropriate part of magnetic circuit.
3) Considering of the transient process, it is necessary to determine the inductances and the reactances from the dynamic definition of inductance.
4) The main reactances in both axis d and q are not only the functions of magnetic fluxes ψ_{hd} and ψ_{hq}, but also of the total flux $\psi_c = \sqrt{\psi_{hd}^2 + \psi_{hq}^2}$, so that the real saturation of magnetic circuit was included [3].

Considering the magnetic characteristic for small saturations as a straight line according to figure 3a, the characteristic of inductive reactance on magnetic flux has approximately curve as at figure 3b.

The effect of saturation of the magnetic circuit was respected approximately:

- according to the total magnetic flux by changing the both main reactances:

$$\begin{aligned} x_{hd} &= f\left(\psi_c\right) \\ x_{hq} &= f\left(\psi_c\right) \end{aligned} \tag{14}$$

- according to the magnetic fluxes of the stator by changing the stator leakage reactance:

$$x_{a\sigma} = f\left(\psi_a\right) \tag{15}$$

- by changing the exciter leakage reactance:

$$x_{F\sigma} = f\left(\psi_F\right) \tag{16}$$

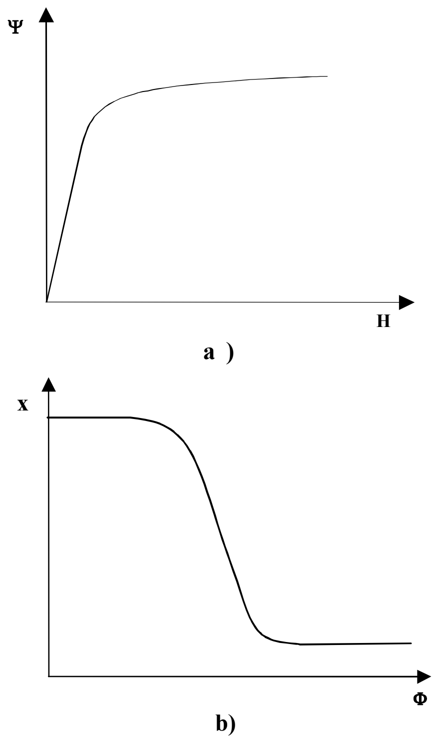

Fig. 3 Magnetic characteristic and characteristic of inductive reactance on magnetic flux

4. SENSITIVITY AND TOLERATION ANALYSE

The time course of short-circuit moment was determined from the calculation, figure (4):

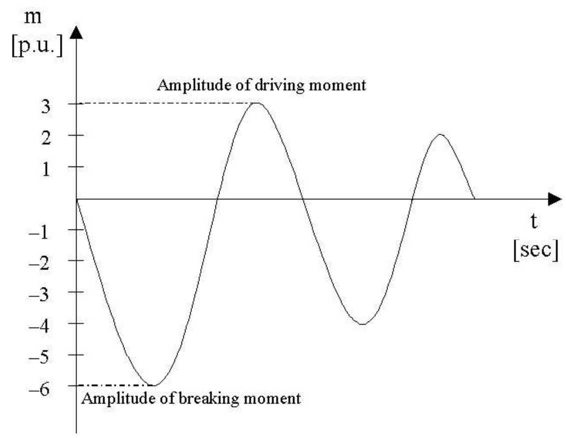

Fig. 4 Short-circuit moment curve

The functionality of the first two amplitudes on the input parameters (table 1) was recognized by sensitivity analyse, with the help of equations (6, 12).

According to the results of sensitivity analyse, figure (5), it is perceptible, that the system is most sensitive to the changes of the leakage reactances – the leakage reactance of stator $x_{a\sigma}$, of exciter winding $x_{F\sigma}$, of spare damper circuit in lenght axis $x_{D\sigma}$ and in diagonal axis $x_{Q\sigma}^{\sim}$.

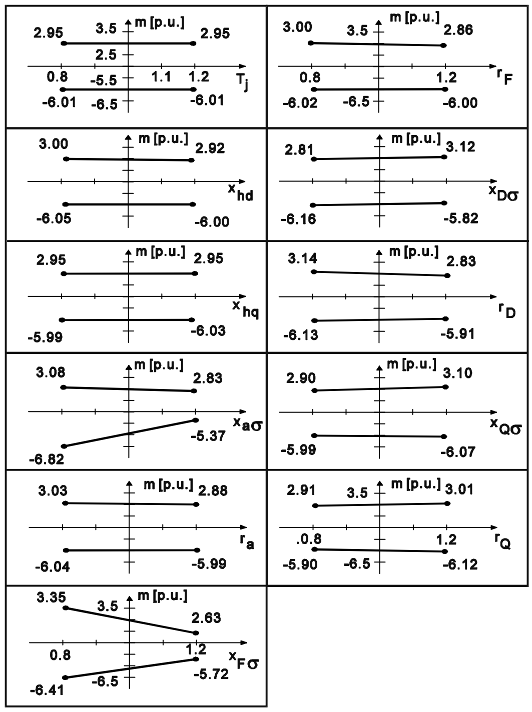

Fig. 5 Results of the sensitivity analyse

The leakage reactances of both spare damper circuit $x_{D\sigma}$ and $x_{Q\sigma}$ are charged by a biggest mistake and uncertainty at the identification of machine parameters, for these reasons:

a) The cage of the damper, which is created by the conductive wedges and the connective rings is replaced by two fictitious windings, mutually independent in axis d and q.

b) In case of the alternator the effect of eddy currents is not considerate. Otherwise these are enclosing in a massive rotor casing and the conductivity of this material is entirely comparable with the conductivity of the steel wedges.

c) One part of the wedges is from bronze, another part is from steel. Both parts are than cutted off by various number of the ventilating duct, picture (6).

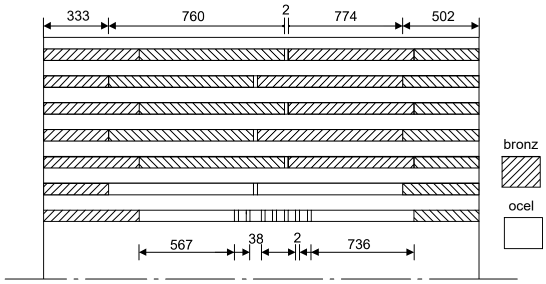

Fig. 6 The construction of damper

The damper is in generally a shortcage as by the asynchronous machine and has the same function too. If the machine runs synchronous, the voltage and current is not inducing in. The damper counteracts by his moment against the deviations of the rotor velocity from the synchronous velocity – it damps the oscillation of the rotor, figure (7).

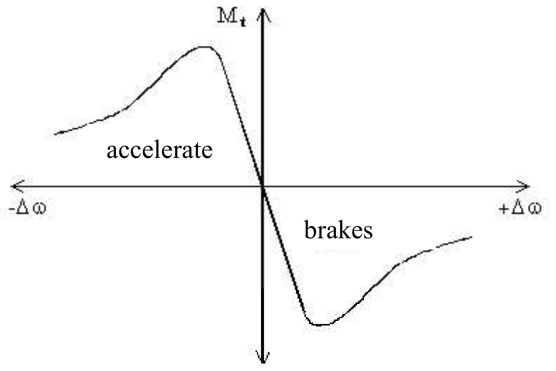

Fig. 7 The moment of damper at the deviation from the synchronous velocity

As the spare damper circuit parameters of every synchronous machine model are most liable to suffer from uncertainty and error, a toleration analysis has been calculated for these parameters at three different levels of two damper parameters input errors, x_{Ds} and x_{Qs}. The toleration analysis was performed by the Monte Carlo method. During the calculation both parameters were within the range:

a) 0.0984 - 0.1476 [p.u.]
b) 0.0615 - 0.1845 [p.u.]
c) 0.0246 - 0.2214 [p.u.]

The resulting short circuit moment at these entrance uncertainties is no more an explicit curve but it can be found within the area defined by the edge curves. Results for all three uncertainly grades are shown in figure 8. It can be stated that the model exhibits a very logical behaviour if the greater uncertainty of the resulting course.

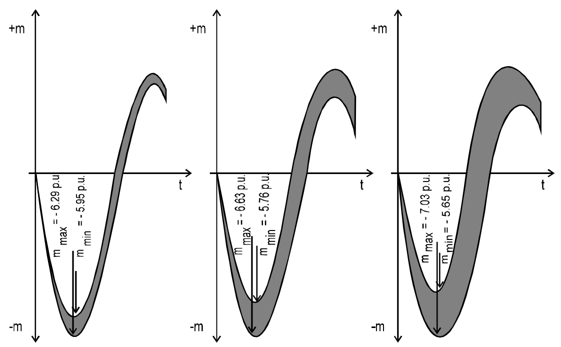

Fig. 8 Results of the toleration analyse

Concluding this chapter it can be stated:

a) the short circuit moment is most sensitive to the leakage reactance of the exciter and stator circuit.

b) the uncertainty in damper parameters will most bring about big error in the resulting course of short circuit moment.

5. THE INFLUENCE OF NONLINEARITY OF THE MAGNETIC CIRCUIT AT THE SHORT CIRCUIT MOMENT

To enable the assuming of the saturation influence at a synchronous machine short circuit moment at least approximately the changed of reactance value is necessary to be changed according to the degree of corresponding part of magnetic circuit saturation. The reactance dependence at the magnetic flux was defined by solution of two dimensional magnetic field in the section of the machine. Reactances x_{hd} , x_{hq} , $x_{F\sigma}$, $x_{a\sigma}$ were the magnetic flux functions in the model (14,15,16).

Leakage reactances of damper spare circuits were let to be constant because of the minor dependence of the observed short circuit moment at them, and especially with a turbomachine, the place and density of damping fluxes can be very difficult to define. Figure 9 shows the resulting course of the short circuit moment of the machine with a cylindrical rotor 35 MVA considering the saturation effect. Regarding the measuring performed at the given machine during short circuit at 10% and 25% of the nominal voltage; calculations were done for the same values to enable the comparison of the measurement and resulting calculation. The result of measurement and short circuit moment calculation at the short circuit at 10% of nominal voltage was linearly recalculated to short circuit at 25% of voltage.

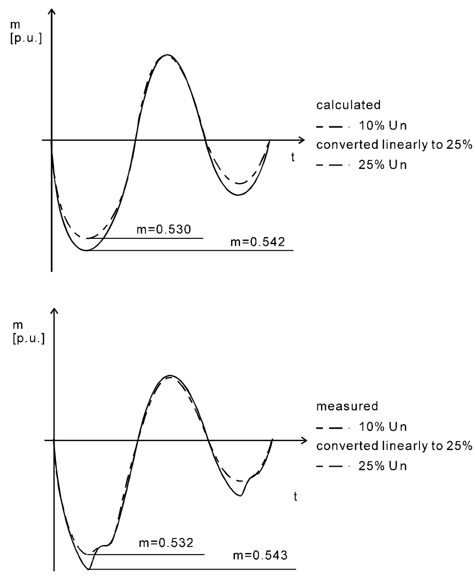

Fig. 9 Resulting course of the short circuit moment

In spite of low feeding voltage values and resulting relatively low influence of magnetic circuit nonlinearity the effect of saturation appears to be equal during the calculation and measurement.

The amplitude variable component of short circuit moment course extends and the aperiodic component shifts more toward negative, e.g. braking values. The explanation is as follows: reactances decrease due to the saturation effect which brings about the increase of fluxes and consequently active losses RI^2. Because of the fact that the machine is separated from the net by short circuit if has to cover the higher losses from the kinetic energy of its rotating masses and extends therefore moment braking amplitudes.

6. THE INTERPRETATION OF THE RESULTS

The short circuit moment is most effected by the change of exciter leakage reactance $x_{F\sigma}$ for these reasons:

1) The course of the short circuit moment depends almost not on the main reactances x_{hd} , x_{hq} , because the magnetic flux encloses mainly through the leakage ways during the short circuit.

2) The stator leakage reactance $x_{a\sigma}$ changes little according to the magnetic flux, because the leakage flux encloses across the stator claws and slots. The decisive is there naturally the reluctance of magnetically non-conducting slots.

3) On the contrary the exciter leakage reactance $x_{F\sigma}$ depends a lot on the magnetic flux of this circuit, especially in case of alternator. Usually the first two slots beside the wide claw are there sealed either in whole or in a part with the magnetically conductive wedges. The leakage magnetic flux encloses across these wedges. According to their small cross-section they oversaturate quickly and the exciter leakage reactance hardly slope down, (picture 3b).

The results are absolutely in a harmony with the physical reality, picture (4):

The growth of the amplitude is due to a serious growth of the currents on the reduced leakage reactances. The linkage magnetic fluxes stay in the first periods after the short circuit almost constant, because on the short circuited windings are valid the voltage equations:

$$0 = ri + \frac{d\psi}{dt} \tag{17}$$

and considering the matter, that the first member of the equation (the decrease on effective resistance) is possible to neglect, then

$$\frac{d\psi}{dt} \cong 0 \quad \Rightarrow \quad \psi \cong konst. \tag{18}$$

(so-coaled principle of the constant flux)

The stronger interaction of bigger currents with almost the same magnetic fluxes causes an increase of the short circuit amplitude.

The shift of the short circuit moment more to the braking half-waves. Owing to the increasing fluxes increase also the active losses $\Delta P = r.i^2$ (the effective resistance is in the first amplitudes constant and step by step rather increases by the heat effect of short circuit). This growth of the active losses owing to the saturation is necessary to reimburse from somewhere. It is impossible from net, because the machine is separated by it. So there is no choice than to reimburse these increasing losses from the kinetic energy of rotating masses, and therefore is the machine more breaked and the kinetic energy transforms faster to the heat energy.

7. CONCLUSION

It is obvious that the higher voltage at the beginning of short circuit the greater magnetic circuit saturation effect. During the short circuit from full voltage the linear calculation shows the maximal short circuit moment as a six multiple of nominal moment [12]. Considering the saturation effect according to the machine type it is, however, approximately 16 multiple. No wonder that the machine design performed linearly appears in real life situation to be under dimensioned with all accompanying negative effects on reliable operation of the set turbine-generator.

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BIOGRAPHY

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