TURBINE-GENERATOR SET TRANSIENTS CAUSED BY UNBALANCED SHORT-CIRCUITS

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ABSTRACT

In the paper transient phenomena at unbalanced short circuits are analyzed. The emphasis is given to the analysis of torsional torques in the shafts of a turbogenerator set. Measurements on a laboratory model of a turbine-generator including a 4-pole synchronous generator and a DC motor drive connected by a torque transducer and a flexible joint are carried out. Adding a flexible joint natural frequencies similar to those of large turbogenerator sets are obtained. The results of the measurements are compared to the results of calculation by a mathematical model of a synchronous generator completed with the equations of motion of the partial masses of the turbine-generator set. Measured and calculated results show that significant torsional strains are present at unbalanced short circuits close to the generator.

1. INTRODUCTION

Transient phenomena in a turbine-generator set are a function of the occurrences in the complex system of the turbine-generator-power system. Faults in the power system can cause torsional oscillations and eventually fatigue life expenditure of the shaft of the turbine-generator set. As the power of the generator units tends to increase, more attention is paid to the problems of monitoring and calculation of torsional torques in the shafts of a turbine-generator set. The shafts of turbogenerator sets are susceptible to low-frequency excitation torques because of the large inertial masses of the rotors of the generator and turbines and their poor ability to damp low-frequency oscillations. These problems are smaller in hydrogenerator sets because of greater shaft stiffness and relatively small inertia of a turbine comparing to the inertia of a generator.

Subsynchronous oscillations have been intensively investigated in the past twenty years because they have caused several severe damages of turbogenerator-set shafts. Subsynchronous oscillations are the topic of a number of papers classified by IEEE Working Group [1]. Special attention is given to the subsynchronous resonance in series-capacity compensated systems [2].

Most of the published papers dealing with the problems of torsional oscillations analyze symmetrical faults, predominantly a three-phase short circuit, either simple or combined with the fault clearing and high-speed reclosing. Most frequently analysis is carried out for a turbogenerator [3], and rarely for a hydrogenerator set.

According to [4], strains in the coupling zones of the turbine-generator shaft, are the largest at subsynchronous resonance, then at the out-of-phase synchronization and three-phase fast reclosing after a two-phase short circuit. Strains caused by generator terminal short circuits are in sixth place by severity. Although not the most severe from the standpoint of shaft fatigue per incident, they occur more often than some more severe disturbances.

In the past few decades efforts have been made to develop a different mathematical model for calculation of electrical and mechanical transients of a turbine-generator set caused by electrical disturbances. However, there still exists a need for more practical measurements of mechanical transients which could contribute to the evaluation of different mathematical models. Field measurement of mechanical transients caused by such severe disturbances, which could confirm the results obtained by mathematical modelling, is quite impossible to carry out on a large generator-set. What remains is measurement on a smaller generator-set or on a laboratory model.

In the paper transients in a turbine-generator set during unbalanced short circuits are analyzed. Measuring of electrical and mechanical transients has been carried out on a laboratory model of an isolated synchronous generator. The results of measuring are compared to the results of calculations by the mathematical model and by analytical expressions for calculating transients in synchronous machines.

2. ANALYTICAL EXPRESSIONS FOR CURRENT AND ELECTRICAL TORQUE

Approximate expressions for calculating steady-state and maximum short circuit current of an unloaded synchronous generator are well-known. It is also known that the largest steady-state armature current occurs at phase-to-neutral short circuits, somewhat smaller at two-phase short circuits and the smallest at three-phase short circuits. The situation with maximum current, interesting because of large mechanical strains in windings which they cause, is somewhat different. The maximum value of the alternating component of an armature current can be theoretically calculated (for short circuit from no-load condition) as:

$$I''_{kmax3} = \sqrt{2}\cdot\frac{U}{X''_d} \quad (A) \qquad (1)$$

for three-phase short circuit;

$$I''_{kmax2} = \sqrt{6}\cdot\frac{U}{X''_d + X_2} \quad (A) \qquad (2)$$

for two-phase short circuit and

$$I''_{kmax1} = 3\sqrt{2}\cdot\frac{U}{X''_d + X_2 + X_0} \quad (A) \qquad (3)$$

for phase-to-neutral short circuit where:

U - generator's phase voltage before short circuit (V);

X''_d, X_2, X_0 - generator's subtransient, inverse and zero-sequence reactance per phase (Ω).

Maximum current arises at phase coinciding to the position of the rotor axis in the moment of short circuit, and can be calculated for all short circuits approximately as:

$$I''_{kmax\Sigma} = 1.8\cdot I''_{kmax} \qquad (4)$$

According to above expressions the largest maximum armature current occurs at phase-to-neutral short circuits, somewhat smaller at three-phase short circuits and smallest at two-phase short circuits.

In some specialized literature [6,7] comprehensive analytical expressions for calculating armature currents, with electrical damping included, are given. These expressions enable time response of the current from the moment of short circuit to be calculated with relatively good precision if constant rotational speed is supposed.

The largest field current (for independent excitation) can be expected at three-phase short circuits, somewhat smaller at two-phase short circuits and smallest at phase-to-neutral short circuit, which can be shown by comprehensive expressions, from [7] for example.

Maximum value of the alternating component of electrical torque can also be calculated from expressions:

$$m_{k3\sim} = \frac{u^2}{x''_d} \quad (pu) \qquad (5)$$

for three-phase short circuit;

$$m_{k2\sim} = 2.6\cdot\frac{u^2}{x''_d + x_2} \quad (pu) \qquad (6)$$

for two-phase short circuit and

$$m_{k1\sim} = 2.6\cdot\frac{u^2}{x''_d + x_2 + x_0} \quad (pu) \qquad (7)$$

for phase-to-neutral short circuit where torque m_k, voltage u and reactance x_d'', x_2 and x_0 are expressed per unit.

Maximums occur 1/4 of period after the moment of short circuit at three-phase short circuit or 1/3 of period at two-phase and phase-to-neutral short circuits. At unbalanced short circuits the alternating component oscillates with basic and double frequency.

3. MATHEMATICAL MODEL OF SYNCHRONOUS GENERATOR

The base of the mathematical model is a set of differential equations of a synchronous generator represented with 2d-1q rotor coils and equations of motion of turbine-generator set masses together with relating turbine governor.

Voltage equations in *dq0* rotating axes are modified for different unbalanced short circuits according to [8,9]. Because of limited space, only modelling of short circuits from no-load conditions is presented in the paper (Appendix I). The modified differential equations of a synchronous generator in *dq0* coordinates originate from short circuits' zero conditions in *abc* coordinates. By substituting expressions for transformation of currents and voltages from the *abc* to *dq0* system and further modification equations similar to those for three-phase short circuits are obtained. However, these expressions include variable coefficients inevitable in analysis of the unbalanced short circuits.

4. MATHEMATICAL MODEL OF TURBINE-GENERATOR SET

In order to compute torsional strains in the shafts of a turbine-generator set, its rotational motion should be described by an equation of motion for each of its rotor part. In case of the largest turbogenerator sets, it is usually sufficient to take 5 concentrated masses into account: rotor of a high pressure turbine (HP), intermediate turbine (IP), two low pressure turbines (LP1, LP2) and a generator (G). The differential equation system can be presented (per unit) as:

$$\frac{d\varphi_i}{dt} = \omega_i \qquad (8)$$

$$T_{mi}\frac{d\omega_i}{dt} = m_{Ti} + C_{i+1}(\varphi_{i+1} - \varphi_1) - C_i(\varphi_i - \varphi_{i-1}) + \\ + D_{i+1}(\omega_{i+1} - \omega_i) - D_i(\omega_i - \omega_{i-1}) - D_{ai}\cdot\omega \qquad (9)$$

where index i is an integer from 1 to 5 indicating turbine stages HP (i=5), IP (i=4), LP1 (i=3) and LP2 (i=2).

The equation of motion of the generator rotor ($i=1$) involves electrical torque ($m_{T1}=m_{elm}$). In the equations φ_i (rad) is rotational masses twist angle, ω_i (pu) angle speed difference, T_{mi} (pu) mechanical time constant, C_i (pu) coefficient of torsional stiffness and D_i, $D_{\alpha i}$ (pu) coefficient of damping.

Torque at coupling zones between two concentrated rotational masses can be calculated (per unit) as:

$$m_{si} = C_i \cdot (\varphi_i - \varphi_{i-1}) \qquad (10)$$

For the purpose of mathematical modelling, the laboratory model is described with three masses: the DC-motor mass, mass of flexible joint together with the torque transducer and the generator mass.

5. LABORATORY MODEL

Measurements have been carried out on a laboratory model of the turbine-generator set. The laboratory model included a 4-pole synchronous generator 25 kVA, 400/231 V, 50 Hz, driven by a DC motor 17 kW. The synchronous generator data are given in the Appendix II. The DC motor was supplied from a SIMOREG compact convertor which included speed regulation circuits. The excitation of the generator was supplied from an independent source of constant voltage.

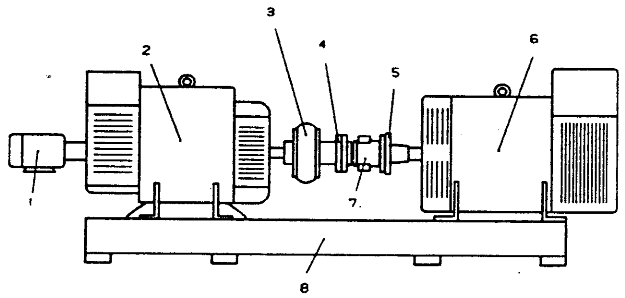

Fig.1 Illustration of laboratory model: 1-tachogenerator; 2-DC motor; 3-flexible joint; 4-flange 1; 5-flange 2; 6-synchronous generator; 7-torque transducer; 8-base

The generator and the DC motor were connected at opposite sides of a torque transducer T 30 FN with torque rated at 2000 Nm. Measurements were taken using a 16-channel high performance data acquisition card PCL-818 controlled by the "Asystant" software package on a personal computer. Current signals were taken by current sensors, and the speed at the drive side was measured by a tachogenerator. In addition, all electrical values were also measured using classical measurement instruments.

Figure 1 shows the laboratory model with a torque transducer. On the drive side a flexible joint is implemented. With the implementation of a flexible joint torsional natural frequencies similar to those of large turbogenerator sets were obtained.

6. RESULTS OF MEASUREMENTS AND COMPARISON WITH CALCULATED RESULTS

A number of measurements and calculations have been carried out for different ratios of excitation and loading conditions at which unbalanced short circuits were applied. All measurements have been carried out at the isolated generator. The results of measurements are compared to the calculated results. All presented results refer to the unbalanced short circuits of the nominally excited generator from no-load conditions so they can be compared to the analytical expressions regularly relating to the short circuits from no-load conditions.

6.1. Two-phase short circuit

Figures 2 to 4 show the calculated time response of electrical torque, and measured and calculated time responses of torsional torque for two-phase short circuit.

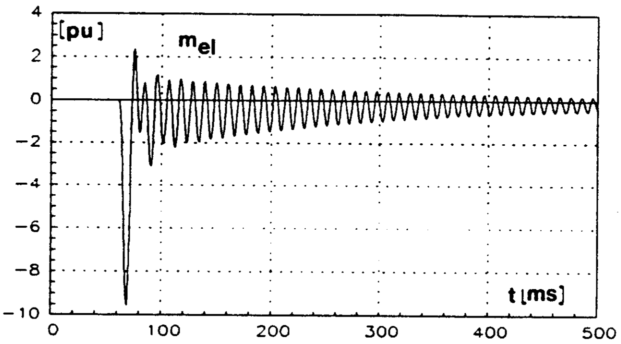

Fig.2 Electrical torque at two-phase short circuit - calculated

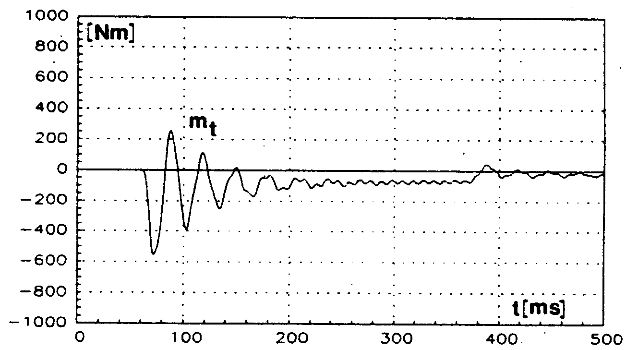

Fig.3 Torsional torque at two-phase short circuit - calculated

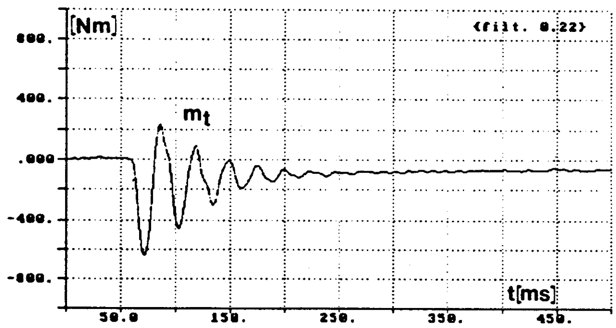

Fig.4 Torsional torque at two-phase short circuit - measured

6.2. Phase-to-neutral short circuit

Figures 5 to 7 show the calculated time response of electrical air-gap torque, and measured and calculated time responses of torsional torque for phase-to-neutral short circuit.

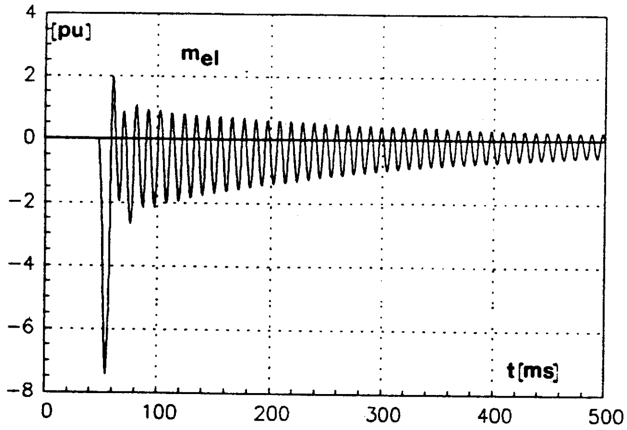

Fig.5 Electrical torque at phase-to-neutral short circuit - calculated

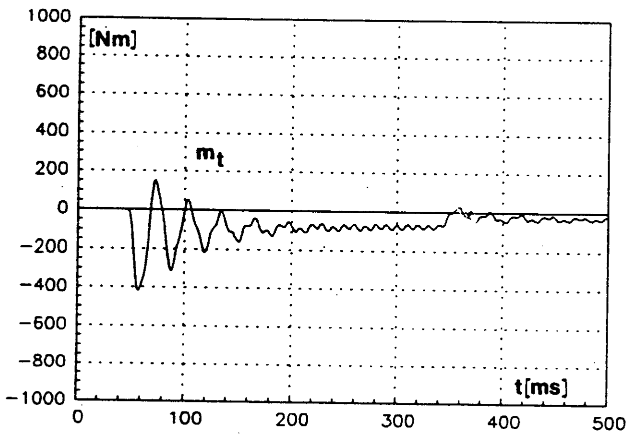

Fig.6 Torsional torque at phase-to-neutral short circuit - calculated

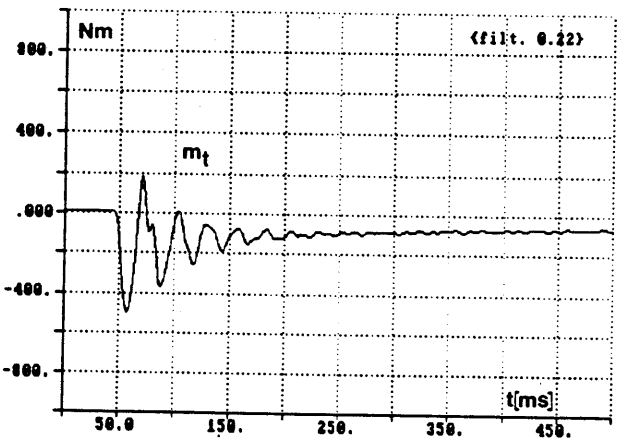

Fig.7 Torsional torque at phase-to-neutral short circuit - measured

6.3. Two-phase-to-neutral short circuit

Figures 8 to 10 show the calculated time response of electrical air-gap torque, and measured and calculated time responses of torsional torque for two-phase-to-neutral short circuit.

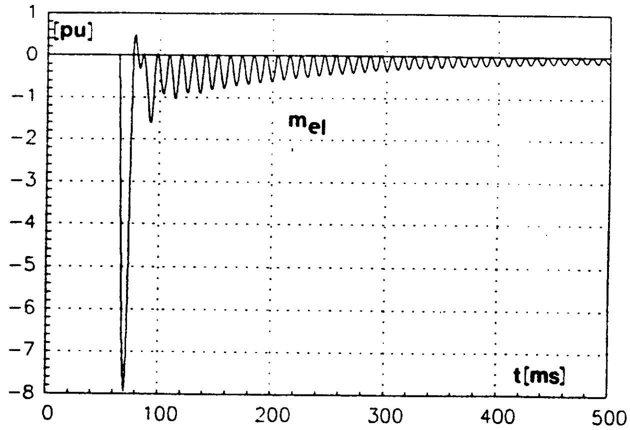

Fig.8 Electrical torque at two-phase-to-neutral short circuit - calculated

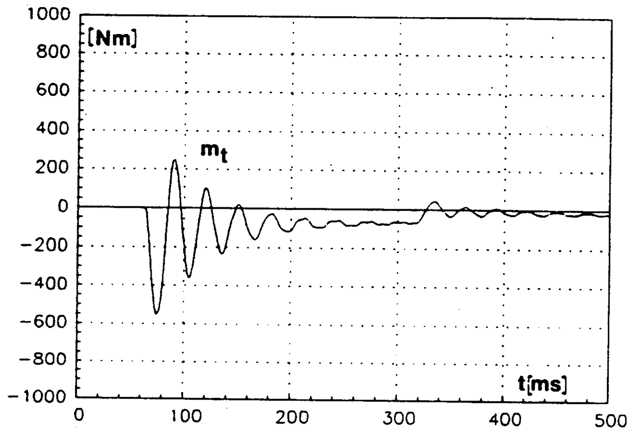

Fig.9 Torsional torque at two-phase-to-neutral short circuit - calculated

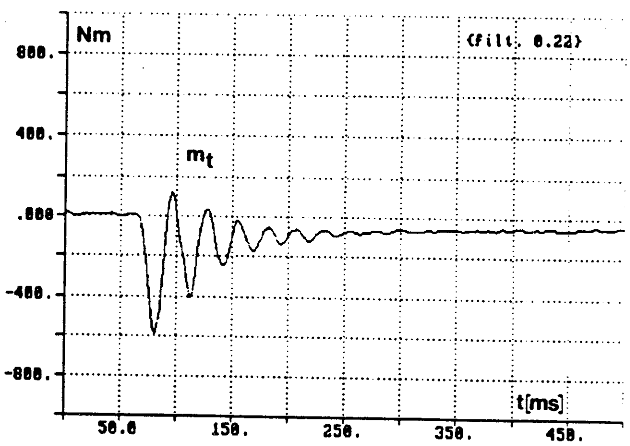

Fig.10 Torsional torque at two-phase-to-neutral short circuit - measured

6.4. Comparison of the results

From the presented time responses it can be seen that the natural frequency of the mechanical system of the laboratory turbine-generator set is approximately 33 Hz. This is the frequency of oscillations that occurs at step change of the external excitation torque.

Table 1 Comparison of calculated and measured maximum current

Maximum armature current					
Short circuit type	Compl. math. model (pu)	Analytical expression		Measurement	
		(A)	(pu)	(A)	(pu)
Three-phase	10.05	849	16.6	529	10.4
Two-phase	9.6	716	14.0	482	9.43
Phase-to-neutral	13.2	827	16.2	632	12.4
Two-phase-to-neutral	11.9	-	-	617	12.1

Table 2 Comparison of electrical torques calculated by complete mathematical model and by analytical expressions

Maximum electrical torque (pu)		
Short circuit type	Compl. math. model	Analytical expression
Three-phase	7.01	9.24
Two-phase	9.59	11.7
Phase-to-neutral	7.44	9.55
Two-phase-two-neutral	7.96	-

Table 3 Comparison of calculated and measured torsional torques

Maximum torsional torque			
Short circuit type	Compl. math. model (pu)	Measurement	
		(Nm)	(pu)
Three-phase	3.73	712	4.47
Two-phase	3.50	641	4.03
Phase-to-neutral	2.63	497	3.12
Two-phase-to neutral	3.49	599	3.76

Table 1 shows that measured peak values of the armature currents and the ones calculated by complete mathematical model are in good agreement. Values calculated by simplified analytical expressions (1), (2), (3) and (4) are 30 to 50% larger than measured values. The main reason for the discrepancy is that a relatively small synchronous generator whose electrical time constants are small has been examined, so in expression (4) a factor significantly smaller than 1.8 should be used.

Table 3 shows that the calculated torsional torques are somewhat smaller than the measured ones: 16% at three-phase short circuit, 18.6% at two-phase short circuit, 15.7% at phase to neutral short circuit and 7.2% at two-phase-to-neutral short circuit.

7. CONCLUSION

The developed mathematical model makes it possible to calculate the electrical and torsional torques of large turbogenerator sets during transient phenomena after different electrical faults. The presented examples of time responses after short circuits and maximum results displayed in the tables show that the largest torsional strains occur at three-phase short circuit, somewhat smaller at two-phase short circuit and the smallest at phase-to-neutral short circuit. Electrical torque is however largest at two-phase short circuit and smallest at three-phase short circuit while at phase-to-neutral it is only slightly larger. The cause of these disproportions is the dominance of the 50 Hz-alternating electrical torque at three-phase short circuit which has more influence on shaft oscillations with a natural frequency of 33 Hz it being closer to 50 Hz than it is the case with the 100 Hz-alternating torque occurring at unbalanced short circuits. Regardless of the distinctions in the calculated and measured results, it can be claimed that the results of the calculations by the complete mathematical model are in good agreement with the measured results and that the mathematical model can be used for calculating torsional torques in large turbogenerator-sets.

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Appendix I

Mathematical modelling of unbalanced short circuits

a) Two-phase short circuit

Zero conditions for two-phase to neutral short circuit from no-load conditions in *abc* coordinates are:

$$u_a = u_b \qquad i_a = -i_b \qquad i_c = 0 \tag{11}$$

The substitution of expressions for transformation of currents and voltages from *abc* to *dq0* system in (13) results in zero conditions in *dq0* coordinates:

$$\begin{aligned} u_q\cdot\cos(\gamma-\pi/3) - u_d\cdot\sin(\gamma-\pi/3) &= 0 \\ i_d\cdot\cos(\gamma-\pi/3) - i_q\cdot\sin(\gamma-\pi/3) &= 0 \end{aligned} \tag{12}$$

By the substitution of synchronous generator circuits equations and further modification of the (14), equations similar to those for three-phase short circuits are obtained:

$$\begin{aligned} \frac{d\psi_{d2}}{dt} + \omega\cdot\psi_{q2} + r\cdot i_d &= 0 \\ \frac{d\psi_{q2}}{dt} + \omega\cdot\psi_{d2} + r\cdot i_q &= 0 \end{aligned} \tag{13}$$

where:

$$\begin{aligned} \psi_{d2} &= a_{x2}\cdot i_d + b_{x2}\cdot(i_f + i_{kd}) + d_{x2}\cdot i_{kq} \\ \psi_{q2} &= a_{x2}\cdot i_q + e_{x2}\cdot(i_f + i_{kd}) + c_{x2}\cdot i_{kq} \end{aligned} \tag{14}$$

$$\begin{aligned} &a_{x2}=[x-y\cdot cos2(\gamma-\frac{\pi}{3})], \quad b_{x2}=\frac{x_{ad}}{2}\cdot[1-cos2(\gamma-\frac{\pi}{3})] \\ &c_{x2}=\frac{x_{aq}}{2}\cdot[1+cos2(\gamma-\frac{\pi}{3})], \quad d_{x2}=-\frac{x_{aq}}{2}\cdot sin2(\gamma-\frac{\pi}{3}) \\ &e_{x2}=-\frac{x_{ad}}{2}\cdot sin2(\gamma-\frac{\pi}{3}), \quad x=\frac{x_d+x_q}{2}, \quad y=\frac{x_d-x_q}{2} \end{aligned} \tag{15}$$

b) Phase-to-neutral short circuit

A similar procedure as for two-phase short circuit is applied where starting from:

$$u_a = 0 \qquad i_b = i_c = 0 \tag{16}$$

the following expression is obtained:

$$\begin{aligned} u_d\cdot\cos\gamma + u_q\cdot\sin\gamma &= -u_0 \\ i_d\cdot\cos\gamma + i_q\cdot\sin\gamma &= 2i_0 \end{aligned} \tag{17}$$

and further modifications brings to:

$$\begin{aligned} 3r\cdot i_{d10} + \frac{d\psi_{d10}}{dt} + \omega\cdot\psi_{q10} &= 0 \\ 3r\cdot i_{q10} + \frac{d\psi_{q10}}{dt} + \omega\cdot\psi_{d10} &= 0 \end{aligned} \tag{18}$$

where

$$\begin{aligned} \psi_{d10} &= a_{x10}\cdot i_{d10} + b_{x10}\cdot(i_{f10} + i_{kd10}) + c_{x10}\cdot i_{kq10} \\ \psi_{q10} &= a_{x10}\cdot i_{q10} + d_{x10}\cdot(i_{f10} + i_{kd10}) + e_{x10}\cdot i_{kq10} \end{aligned} \tag{19}$$

$$\begin{aligned} &a_{x10}=x_0+2x+2y\cdot\cos 2\gamma \\ &b_{x10}=x_{ad}\cdot(1+\cos 2\gamma), \quad c_{x10}=x_{aq}\cdot\sin 2\gamma \\ &d_{x10}=x_{ad}\sin 2\gamma, \quad e_{x10}=x_{aq}\cdot(1-\cos 2\gamma) \end{aligned} \tag{20}$$

c) Two-phase-to neutral short circuit

A similar procedure for two-phase to neutral starting from:

$$u_a = 0 \qquad u_b = 0 \qquad i_c = 0 \tag{21}$$

and consequently:

$$\begin{aligned} u_d\cdot\cos(\gamma+2\pi/3) + u_q\cdot\sin(\gamma+2\pi/3) &= 2u_0 \\ i_d\cdot\cos(\gamma+2\pi/3) + i_q\cdot\sin(\gamma+2\pi/3) &= -i_0 \end{aligned} \tag{22}$$

brings to:

$$\begin{aligned} 3ri_{d10} + p\psi_{d10} + \omega\psi_{q10} &= 0 \\ 3ri_{q10} + p\psi_{q10} + \omega\psi_{d10} &= 0 \end{aligned} \tag{23}$$

where

$$\begin{aligned} \psi_{d10} &= a_{x10}i_{d10} + b_{x10}(i_{f10} + i_{kd10}) + c_{x10}i_{kq10} \\ \psi_{q10} &= a_{x10}i_{q10} + d_{x10}(i_{f10} + i_{kd10}) + e_{x10}i_{kq10} \end{aligned} \tag{24}$$

$$\begin{aligned} &a_{x10}=2x+x_0+2y\cos 2\gamma \\ &b_{x10}=(1+\cos 2\gamma)x_{ad}, \quad c_{x10}=x_{aq}\sin 2\gamma \\ &d_{x10}=x_{ad}\sin 2\gamma, \quad e_{x10}=(1-\cos 2\gamma)x_{aq} \end{aligned} \tag{25}$$

Appendix II

Generator data

S_n = 25 kVA	x_d = 2.05 pu	x_l = 0.080 pu
U_n = 400 V	x_d' = 0.246 pu	x_2 = 0.172 pu
I_n = 36.1 A	x_d'' = 0.1082 pu	T_{d0}' = 2.17 s
cos φ_n =0.8	x_q = 0.541 pu	T_d'' = 0.0072 s
n = 1500r/min	x_q'' = 0.1197 pu	T_q'' = 0.0072 s
f = 50 Hz	x_o = 0.05 pu	r_a = 0.0265 pu
T_{mSG} = 0.341 s	T_{mDC} = 0.283 s	T_{mTT} = 0.054 s
$C_{SG\text{-}TT}$ = 1193.8 pu		$C_{TT\text{-}DC}$ = 23.3 pu
$D_{\alpha SG}$ = $D_{\alpha DC}$ = 0.025 pu		$D_{TT\text{-}DC}$ = 7 pu