Paper No. T3-1.10, pp. 1-9

15th INTERNATIONAL SYMPOSIUM on
POWER ELECTRONICS - Ee 2009
XV Međunarodni simpozijum Energetska elektronika – Ee 2009
NOVI SAD, REPUBLIC OF SERBIA, October 28th - 30th, 2009

# MODELLING OF SUDDEN SHORT CIRCUIT REGIMES ON SYNCHRONOUS GENERATORS WITH SALIENT POLES

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**Abstract:** *This work presents simulation and comparison of characteristics in dynamic regimes three-phase and two phases short circuits on synchronous generators with salient poles. For this purpose Runge Kutta numeric procedure is applied in step by step method.*

## 1. INTRODUCTION

Surge components of current, forces and torques, which appear in sudden short circuit regimes on large synchronous generator could cause different kind of damage to the generator and other units of the power plant. Therefore, beside the constructors of the generator the users of the generator must be familiar with the dynamic characteristics of different types of short circuit regimes with the aim of providing proper protection in power plant units.

Classical literature discusses the dynamic characteristics of short circuit regimes on synchronous generator using subtransient, transient, synchronous, inverse and zero reactance with the appropriate time constants. The producers of synchronous generators regularly give their values and other parameters to their buyers.

It must be noticed that in analytic method the differential equation systems of synchronous machines for describing short circuit regimes are very simplified with the aim to be transformed into the equation systems, which can be solved by analytic method. E.g. when discussing the short circuit regimes the influence of all ohmic resistances are neglected.

Applying numeric procedure of Runge Kutta method, we can eliminate all mistakes made by analytic method.

In general, there can be three types of short circuit regimes at synchronous generator: three-phase, two-phase and single-phase regime. Regarding current surges the most critical regimes are three-phase regimes and regarding torque surges, the most critical are two-phase regimes. Single-phase short circuit regimes on large synchronous generators are very rare because these generators do not have null-phase.

If numeric method is applied, it should be paid special attention to the choice of the coordinate system when defining differential equation system for simulation of various asymmetric regimes. In a case of „one-side" asymmetry, the mutual coordinate system should be chosen. At the same time, it is natural coordinate system on the side where the asymmetry exists. This means that when considering the three-phase short circuit regimes on synchronous generator with salient poles the mutual rotor coordinate system should be chosen, because asymmetry exists on rotor side. In that way the differential equation system with constant coefficients can be defined.

Worse case is discussing „two-side" asymmetry, like two-phase short circuit regimes. In that case, equation system should be defined in natural coordinate systems. It means that when defining differential equation system stator parameters should be written in stator coordinate system and rotor parameters in rotor coordinate system.

In case of two-side asymmetry, mutual coordinate system (on stator or rotor side) cannot eliminate time variable coefficients from the system. In this case, in differential equation systems time interrupted trigonometric functions *(tg$\theta$, ctg$\theta$)* and their undefined values would disrupt progress of numeric solving.

In equations written in natural coordinate systems in case of „two-side" asymmetry time changeable coefficients also exist, but because of continuous trigonometric functions *(sin$\theta$, cos$\theta$)* defined system for two-phase short circuit regime is easy to solve using numeric method.

## 2. WORK DESCRIPTION

The fact is that surge currents and surge torques have the biggest values when sudden short circuit appears in loaded generator regimes. Starting from this fact this work will discuss characteristics of three-phase and two-phase short circuits that appear in load operations.

We start from the assumption that synchronous generator with salient poles works normally and it is loaded with rated power before short circuit occurs. A schematic of load is shown on Fig.1.

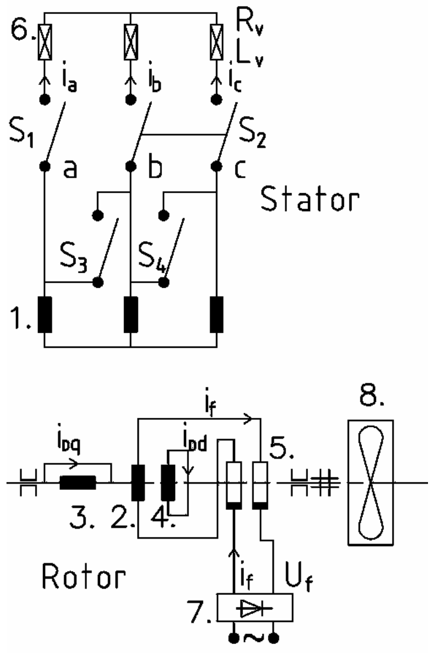


Fig. 1. *Schematic of load of generator*

Machine-consumer (6) is connected to three-phase stator windings (1). Excitation rotor winding (2) is excited by the sliding rings (5) and regulator (7) in a way that the consumer is supplied with rated voltage. In modelling process, an asymmetric dumper rotor cage is replaced with two equivalent short-circuited windings positioned orthogonally (3, 4). Beside drive elements, the schematic of load contains various switches, which enable different operating regimes, as follows:

- Three-phase load: $S_1$, $S_2$ switched-on, $S_3$, $S_4$ switched-off, $R_V>0$, $L_V>0$,
- Three-phase short circuit: $S_3$, $S_4$ switched-on, $R_V=0$, $L_V=0$,
- Two-phase load: $S_2$ switched-on, $S_1$, $S_3$, $S_4$ switched-off, $R_V>0$, $L_V>0$,
- Two-phase short circuit: $S_4$ switched-on, $S_1$, $S_3$ switched-off, $R_V=0$, $L_V=0$.

For modelling, we will assume that the drive turbine will provide for constant synchronous speed $\omega_1$ before and after appearance of sudden short circuits due to large total moment of inertia and fast turbine regulator.

### 2.1 Generator technical data

- Generator type: G20-315-61S
- Rated apparent power: S=6300 kVA
- Power factor: cosφ=0.844 ind.
- Rated line voltage: $U_L$=6300 V
- Stator winding connection: Y
- Rated current: I=577.35 A
- Frequency f=50 Hz
- Rated speed: n=300 min-1
- Rated overspeed: $n_p$=750 min-1
- Number of poles: p=10
- Excitation voltage: $U_P$=122 V
- Excitation current: $I_P$=234 A
- Coefficient of reduction of excitation voltage: $k_{uf}$=0.1025
- Coefficient of reduction of excitation current: $k_{if}$=0.1535
- Coefficient of reduction of excitation winding resistance: $k_{Rf}$=0.01571

### 2.2 Generator parameters for modelling

Values of the parameters have been taken from electromagnetic calculation made during designing of a generator.

$R_S$=39.266 mΩ; $R_f$=8,18 mΩ; $R_{Dd}$=458 mΩ; $R_{Dq}$=211.13 mΩ

$L_{S\sigma}$=3.509 mH; $L_{f\sigma}$=3.71mH; $L_{D\sigma d}$=2.954 mH; $L_{D\sigma q}$=1.174 mH; $L_{md}$=19.596 mH; $L_{mq}$=8.099 mH;

$R_V$=5.3172 Ω; $L_V$=10.76 mH for 3~load;

$R_V$=3.243 Ω; $L_V$=6.453 mH for 2~load

Note: generator parameters for modelling of completed generator can also be determined by measurement procedure.

## 3. DIFFERENTIAL EQUATION SYSTEMS USED IN SIMULATION

In this work for simulation of short circuit regimes, used parameters have been taken from electromagnetic calculation of the generator during its designing.

Equation system will be written in a way that it can be used for a simulation of load operation as well as a simulation of short circuit regimes. This can be achieved by treating resistance and inductance of a consumer ($R_V$, $L_V$) as time variable parameters. At load operation, these parameters will have constant values, which correspond to rated power of the generator, and in short circuit regimes their values will become zero.

### 3.1 Differential equation system for operation modelling in three-phase regimes

In this case, synchronous generator with salient poles has „one-side" asymmetry because of single-phase excitation winding and unisothrophy of rotor magnetic circuit.

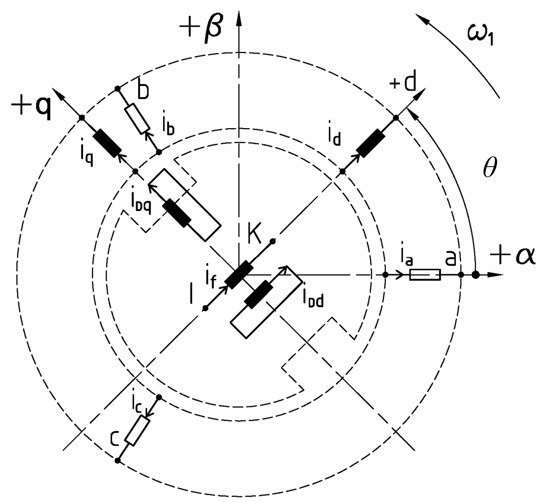


Fig.2.*Schematic of modelling of synchronous machine in mutual rotor coordinate system d-q*

Because of one-side asymmetry on rotor side, differential equation system should be written in „mutual rotor" coordinate system.

Basis for determination of differential equation system is shown on Fig. 2.

In this case scalar flux components of synchronous generator with salient poles in direction of transversal axis (d) and longitudinal axis (q) can be determined with the following matrix equations:

$$\begin{bmatrix}\psi_d\\ \psi_f\\ \psi_{Dd}\end{bmatrix}=\begin{bmatrix}L_d & L_{md} & L_{md}\\ L_{md} & L_f & L_{md}\\ L_{md} & L_{md} & L_{Dd}\end{bmatrix}\begin{bmatrix}i_d\\ i_f\\ i_{Dd}\end{bmatrix} \quad (1)$$

$$\begin{bmatrix}\psi_q\\ \psi_{Dq}\end{bmatrix}=\begin{bmatrix}L_q & L_{mq}\\ L_{mq} & L_{Dq}\end{bmatrix}\begin{bmatrix}i_q\\ i_{Dq}\end{bmatrix} \quad (2)$$

In these equations $\psi_d$ , $\psi_f$ , $\psi_{Dd}$ are scalar flux components of the stator, excitation and dumper cage in transversal direction and $\psi_q$ , $\psi_{Dq}$ are scalar flux components of stator flux and dumper cage flux in longitudinal direction.

Symbols of inductance in equations (1) and (2) have the following descriptions:

$L_d$ ,$L_q$ – total three-phase inductances of stator winding

$L_{md}$,$L_{mq}$ - three-phase inductances of magnetization

$L_{Dd}$ ,$L_{Dq}$- total inductances of dumper cage linked to three-phase stator

$L_f$ - total inductance of excitation winding (d-axis) linked to three-phase stator

Corresponding total inductances of stator winding *($L_d$ ;$L_q$)* are the sum of consumer inductance *($L_V$)*, inductance of magnetization *($L_{md}$ , $L_{mq}$)* and inductance of disperse *($L_{s\sigma}$)* as follows:

$$L_d = L_V + L_{md} + L_{s\sigma} \quad (3)$$

$$L_q = L_V + L_{mq} + L_{s\sigma} \quad (4)$$

On rotor side, total inductances are sum of inductance of magnetization and corresponding inductance of disperse according the following equations:

$$L_f = L_{md} + L_{f\sigma} \quad (5)$$

$$L_{Dd} = L_{md} + L_{D\sigma d} \quad (6)$$

$$L_{Dq} = L_{mq} + L_{D\sigma q} \quad (7)$$

According to above equations differential equation system for modelling can be written in the following form:

$$\begin{aligned}
d\psi_d / dt &= -(R_V + R_S)\cdot i_d + \omega_1 \cdot \psi_q\\
d\psi_q / dt &= -(R_V + R_S)\cdot i_q - \omega_1 \cdot \psi_d\\
d\psi_f / dt &= u_f - R_f \cdot i_f\\
d\psi_{Dd} / dt &= -R_{Dd}\cdot i_{Dd}\\
d\psi_{Dq} / dt &= -R_{Dq}\cdot i_{Dq}
\end{aligned} \quad (8)$$

Where: $R_S$-resistance of stator winding per phase, $R_f$– value of excitation winding resistance linked to stator, $R_{Dd}$, $R_{Dq}$ – values of dumper cage resistances linked to stator in direction of d and q axis, $u_f$–value of excitation winding voltage linked to stator at rated load, and $\omega_1$ is rotor synchronous electrical angular speed

Electrical angular turning of rotor *($\theta$)* in relation to the positive part of pulsation axis of first stator phase in function of time, with the stated assumption, has the following value:

$$\theta = \theta_0 + \omega_1 \cdot t \quad (9)$$

Where is: $\theta_0$-starting angular turning of rotor.

Solving the equation system (8) instantaneous values of scalar flux components can be determined, and after that, using equations (1) and (2) instantaneous values of scalar current can be determined.

Regarding that, the regime does not have zero components, for determining the instantaneous values of stator currents per phase the following equations can be used:

$$i_a = i_d \cdot \cos\theta - i_q \cdot \sin\theta \quad (10)$$

$$i_b = i_d \cdot \cos(\theta - 120^o) - i_q \cdot \sin(\theta - 120^o) \quad (11)$$

$$i_c = i_d \cdot \cos(\theta - 240^o) - i_q \cdot \sin(\theta - 240^o) \quad (12)$$

Instantaneous value of actual current in rotor excitation winding is:

$$i_p = i_f \cdot k_{if} \quad (13)$$

Instantaneous value of line voltage (e.g. between phase b-c) on the consumer's connections is:

$$u_{bc} = R_V \cdot (i_b - i_c) + L_V \cdot \frac{d}{dt}(i_b - i_c) \quad (14)$$

Resistance $R_V$ and inductance $L_V$ will be chosen in a way that in steady stable load regime at rated power and power factor, the phase voltage is equal to rated line voltage. Instantaneous value of the power of the generator is:

$$p_e = \frac{3}{2}\cdot R_V \cdot (i_d^2 + i_q^2) \quad (15)$$

Instantaneous values of power losses in stator windings and rotor windings are:

$$p_{cus} = \frac{3}{2}\cdot R_S \cdot (i_d^2 + i_q^2) \quad (16)$$

$$p_{cuD} = \frac{3}{2}\cdot (R_{Dd}\cdot i_{Dd}^2 + R_{Dq}\cdot i_{Dq}^2) \quad (17)$$

$$p_{cuf} = \frac{3}{2}\cdot R_f \cdot i_f^2 \quad (18)$$

Regarding that, this work deals with sudden short circuit regimes, which have small values of induced voltages, the influence of losses in iron is neglected in modelling process.

Instantaneous value of produced electrical torque is determined by the following equation:

$$m_e = -\frac{3}{2}\cdot p \cdot (\psi_d \cdot i_q - \psi_q \cdot i_d) \quad (19)$$

Sign (-) in front of the expression (19) is used to describe the generator-operating regime.

Designers of the generator and designers of the protection are the most interested in so-called surge components of current and torque. They are the first and the highest amplitudes of the current and the torque, which appear immediately after sudden short circuits. Since one-direction components have significant influence on their values, the moment of appearance of the sudden short circuit from the load operation should be chosen so that we get theoretically possible highest values for the surge components.

### 3.2 Differential equation system for operation modelling in two-phase regimes

In this case, synchronous generator with salient poles has „two-side” asymmetry. Because of that, the differential equation system should be written in natural coordinate systems.

Basis for determination of differential equation system is shown on Fig.3.

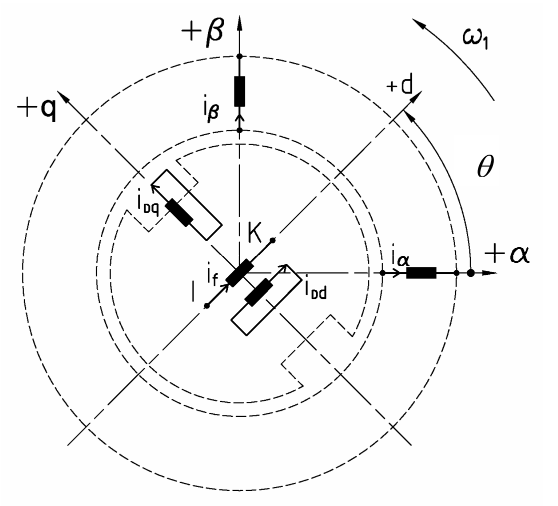


Fig.3. *Schematic of modelling of synchronous machine in natural coordinate systems α-β and d-q*

In this type of modelling three-phase stator windings are replaced with steady orthogonal two-phase system of windings in a way that real axis $\alpha$ matches with pulsation axis of the first phase of the stator winding. In relation to this axis, orthogonal rotor coordinate system rotates by synchronous electrical angular speed. In general, the real axes of these orthogonal coordinate systems make the time variable angle $\theta$ between themselves.

Because of constant rotation, the fictive orthogonal systems of stator and rotor windings will be related with angular and time variable inductances.

For easier analysis of this regime, first we will introduce the average inductance of magnetization $(L_m)$ and average difference of inductance of magnetization $(\Delta L_m)$ according to the following equations:

$$L_m = \frac{L_{md} + L_{mq}}{2} \quad (20)$$

$$\Delta L_m = \frac{L_{md} - L_{mq}}{2} \quad (21)$$

The own inductances at steady fictive orthogonal two-phase stator windings have the following values:

$$L_\alpha(\theta) = L_d \cdot \cos^2\theta + L_q \cdot \sin^2\theta = \\ = L_V + L_{S\sigma} + L_m + \Delta L_m \cdot \cos(2\theta) \quad (22)$$

$$L_\beta(\theta) = L_q \cdot \cos^2\theta + L_d \cdot \sin^2\theta = \\ = L_V + L_{S\sigma} + L_m - \Delta L_m \cdot \cos(2\theta) \quad (23)$$

Equations (22) and (23) are noticeable naturally and can easily be made out of Fig.3.

However, it should be mentioned that orthogonal fictive stator windings are also linked with mutual inductances due to unizotrophy of rotor magnetic circuit. This mutual inductance also depends on rotor angular turning and has the value:

$$L_{\alpha\beta}(\theta) = (L_d - L_q) \cdot \sin\theta \cdot \cos\theta = \\ = \Delta L_m \cdot \sin(2\theta) \quad (24)$$

It means that mutual inductance between steady orthogonal fictive stator windings has the biggest value when angle $\theta$ is $\pi/4$ or it is equal to $\pi/4$ multiplied with odd number. Further, it can be noticed that mutual inductance on synchronous machine with cylindrical rotor always has zero value.

According to Fig.3, it can also be noticed that mutual inductances between steady stator and movable rotor orthogonal windings depend on cosine of instantaneous angles $\theta$ defined by their axes.

In general, taking into consideration all stated facts, instantaneous values of scalar flux components between stated orthogonal systems can be determined applying the following matrix equation:

$$\begin{bmatrix} \psi_\alpha \\ \psi_\beta \\ \psi_f \\ \psi_{Dd} \\ \psi_{Dq} \end{bmatrix} = \begin{bmatrix} L_\alpha(\theta) & \Delta L_m \sin(2\theta) & L_{md}\cos\theta & L_{md}\cos\theta & -L_{mq}\sin\theta \\ \Delta L_m \sin(2\theta) & L_\beta(\theta) & L_{md}\sin\theta & L_{md}\sin\theta & L_{mq}\cos\theta \\ L_{md}\cos\theta & L_{md}\sin\theta & L_f & L_{md} & 0 \\ L_{md}\cos\theta & L_{md}\sin\theta & L_{md} & L_{Dd} & 0 \\ -L_{mq}\sin\theta & L_{mq}\cos\theta & 0 & 0 & L_{Dq} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \\ i_f \\ i_{Dd} \\ i_{Dq} \end{bmatrix} \quad (25)$$

In general, differential equation system of synchronous machine in natural coordinate systems has the following form:

$$\begin{aligned} d\psi_\alpha / dt &= -(R_V + R_S) \cdot i_\alpha \\ d\psi_\beta / dt &= -(R_V + R_S) \cdot i_\beta \\ d\psi_f / dt &= u_f - R_f \cdot i_f \\ d\psi_{Dd} / dt &= -R_{Dd} \cdot i_{Dd} \\ d\psi_{Dq} / dt &= -R_{Dq} \cdot i_{Dq} \end{aligned} \quad (26)$$

Assuming that the first stator phase is switched off ($S_1$-switched-off), the generator will work with two phases because of $i_a = i_\alpha = 0$. Two-phase short circuit regime between phase b-c can be gained with the assumption that in this regime in these phases parameters $R_V$ and $L_V$ have zero value (S3-switched-off, S4-switched-on).

The condition of two-phase operation between phase b-c can be defined with the following equations:

$$i_a = 0\ ;\ i_b + i_c = 0 \quad (27)$$

From the previous the result is:

$$i_\alpha = 0\ ;\ i_b = \frac{\sqrt{3}}{2} i_\beta\ ;\ i_c = -\frac{\sqrt{3}}{2} i_\beta \quad (28)$$

From the condition (28) we can say that two-phase operation can be defined by the system, which consists of only four differential equations.

If we make proper derivation according to equation (25) and considering „derivative of multiplication” of time variable inductance and time variable current, and we put flux derivative into equation system (26), than we get current form of differential equation system for two-phase operation analysis. This system has the following matrix form:

$$L(t)\frac{d}{dt}i(t) = u(t,i) \tag{29}$$

Where $L(t)$- matrix of inductance

$i(t)$ – current vector

$u(t,i)$- voltage vector

Angular and time variable matrix of inductance in two-phase regime has the following value:

$$L(t) = \begin{bmatrix} L_V + L_{S\sigma} + L_m - \Delta L_m \cos(2\theta) & L_{md}\sin\theta & L_{md}\sin(\theta) & L_{mq}\cos(\theta) \\ L_{md}\sin\theta & L_f & L_{md} & 0 \\ L_{md}\sin\theta & L_{mq} & L_{Dd} & 0 \\ L_{mq}\cos\theta & 0 & 0 & L_{Dq} \end{bmatrix} \tag{30}$$

Current vector in equation (29) contains the following elements:

$$i(t)^T = [i_\beta, i_f, i_{Dd}, i_{Dq}] \tag{31}$$

Elements of voltage vector are:

$$u(t,i) = \tag{32}$$

$$= \begin{bmatrix} -(R_V + R_S)i_\beta - \omega_1(2\Delta L_m i_\beta \sin(2\theta) + L_{md}(i_f + i_{Dd})\cos\theta - L_{mq}i_{Dq}\sin\theta) \\ u_f - R_f i_f - \omega_1 L_{md} i_\beta \cos\theta \\ -R_{Dd}i_{Dd} - \omega_1 L_{md} i_\beta \cos\theta \\ -R_{Dq}i_{Dq} + \omega_1 L_{mq} i_\beta \sin\theta \end{bmatrix}$$

If matrix equation (29) is multiplied from left by inverse matrix of inductance $L(t)^{-1}$, than we have matrix system of differential equations with time variable coefficients, where each equation contains only one derivative. Applying numeric method of Math Cad this system is suitable for solving and has the following form:

$$\frac{d}{dt}i(t) = L(t)^{-1}u(t,i) \tag{33}$$

This two-phase regime does not contain null components. However, starting from the differential equation system (33) and because of choosing the natural coordinate system, the method of determining instantaneous values of stator currents is different then in previous case. Instantaneous values of currents per phase are:

$$i_a = i_\alpha = 0 \;;\; i_b = \frac{\sqrt{3}}{2}i_\beta \;;\; i_c = -\frac{\sqrt{3}}{2}i_\beta \tag{34}$$

Instantaneous value of actual current ($i_p$) in excitation winding is determined according to equation (10) as before.

Instantaneous value of line voltage between phase b-c on consumer's connections is:

$$u_{bc} = 2(R_V i_b + L_V\frac{di_b}{dt}) = \sqrt{3}(R_V i_\beta + L_V\frac{di_\beta}{dt}) \tag{35}$$

Resistance $R_V$ and inductance $L_V$ at two-phase load are chosen in a way that in case of the same value of excitation voltage line voltage $u_{bc}$ is as the same as in three-phase regime at rated three-phase load.

In two-phase regime, it is interesting to discuss the change of instantaneous value of induced voltage in a free phase „*a*", where no flow of the current exists. Instantaneous value of induced voltage in the free phase „*a*" is:

$$e_a = \frac{d\psi_\alpha}{dt} \tag{36}$$

Instantaneous value of electrical power output in two-phase regime is:

$$p_e = \frac{3}{2}R_V i_\beta^2 \tag{37}$$

Instantaneous value of the power losses in the stator windings is:

$$p_{cus} = \frac{3}{2}R_S i_\beta^2 \tag{38}$$

Power losses in rotor excitation windings and dumper cage at two-phase regime are calculated in the same way as in three-phase regime using equations (17) and (18). Instantaneous value of produced electrical torque in two-phase regime is:

$$m_e = -\frac{3}{2}p\psi_\alpha i_\beta \tag{39}$$

Sign (-) in front of the expression (39) is used to describe the generator-operating regime.

## 4. MODELLING RESULTS

In both cases, the modelling process will be started with connecting the consumer to the generator. In three-phase regime resistance $R_V$ and inductance $L_V$ per phase are chosen that if the rated excitation voltage is applied the generator has rated output with rated power factor and rated line voltage on consumer's connections.

Two-phase load is discussed with the same excitation voltage as in three-phase load, but with lower values of $(R_V, L_V)$ to keep the line voltage between phase *b-c* equal to line voltage in three-phase load.

During the simulation parameters $R_V$ and $L_V$ are time variable components. Their values are constant during the load operation, and in moments of appearance of short circuits their values are zero.

From the moment of connecting the customer to the chosen synchronous generator to the moment of steady load operation, it has to pass at least 5 seconds. Because of it, the moments of appearance of short circuits are chosen in a way that short circuits appear in stationary part of load characteristic and the surge current $\hat{i}_U$ and surge torque component $\hat{m}_U$ have the biggest possible values.

In this work, we discuss the short circuits. Because of it, the duration of the simulation is chosen to include stationary regime 0,05 s before the appearance of short circuits and transient period of short circuits in duration of 0,3 s starting from the moment of the appearance of short circuit. Total duration of modelling of load regime and short circuit regime is 14 s. In this way, numeric procedure can also include stationary parts in short circuit characteristics.

Stationary values of voltages, currents, powers and torques, which will result from the simulation of short circuits, will be given certain numeric values.

### 4.1 Modelling results of three-phase short circuit regime

The changes of instantaneous values of line voltage, electric power and produced torque in three-phase regime in function of time are shown on Fig. 4.

On basis of instantaneous value of line voltage (Fig. 4a) and value of electric power output (Fig. 4b) we can say that during three-phase short circuit *(* $t_k$*=5.1803 s)* the generator in stationary regime was loaded by rated power *(*$P_3$*)*, actual current *(*$I_3$*)* and rated torque *(*$M_3$*)* with rated line voltage. Their values are the following: $P_3=5317\ kW$ , $I_3=577.35\ A$ , $M_3=173.3\ kNm$.

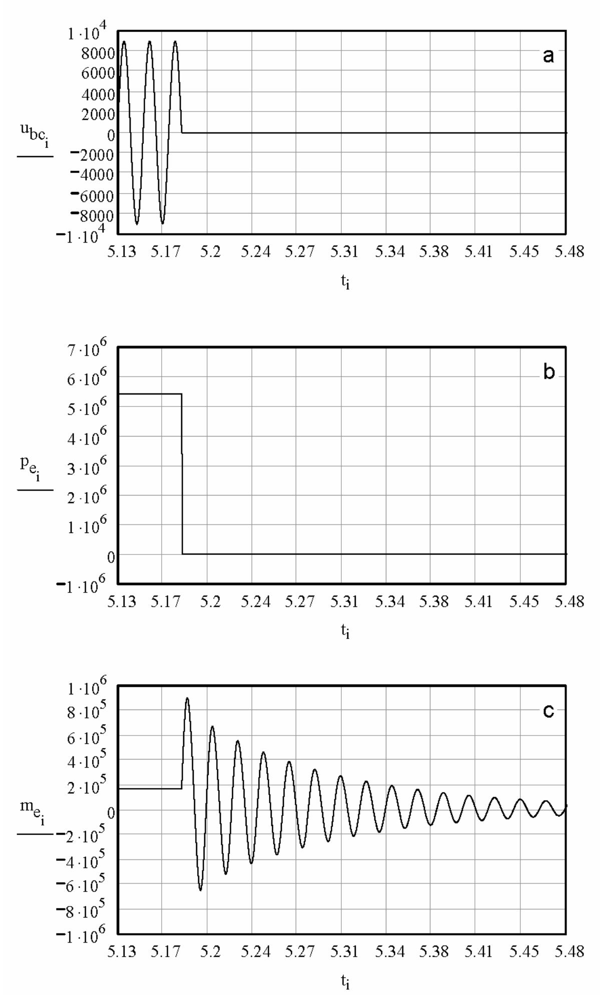


Fig.4 *Changes of instantaneous values of line voltage, electric power and produced torque in three-phase regimes*

The surge torque is considered to be the first biggest torque amplitude (Fig. 4c) after appearance of short circuit and in this case its value is: $\hat{m}_{U3}$ = *903.2 kNm.*

The changes of instantaneous values of current in stator windings in three-phase regimes in function of time are shown on Fig. 5.

According to this diagram, we can say that in this case in transient regime of three-phase short circuit the first phase (Fig. 5a) does not have one-direction current component while other phases (Fig. 5b, Fig. 5c) do. Because of it their first amplitudes have bigger values after short circuit. Their first amplitude can be treated as surge current component, which has a value: $\hat{i}_{U3}$ *=6017 A*

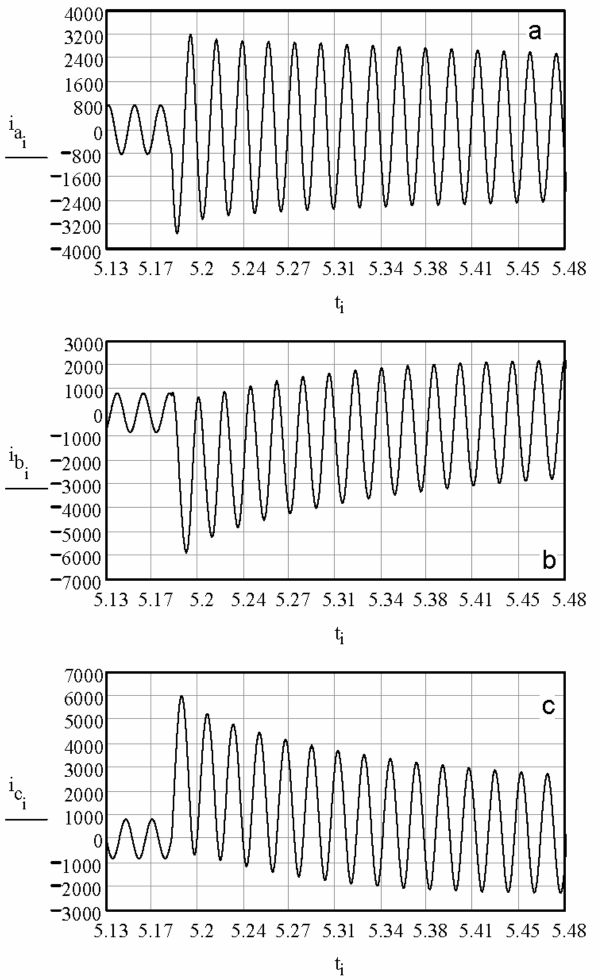


Fig.5 *Changes of instantaneous values of current in stator windings in three-phase short circuit regime*

The changes of instantaneous values of current in rotor windings in three-phase regimes in function of time are shown on Fig. 6.

It can be noticed that in transient regime of three-phase short circuit (Fig. 6a) excitation current beside its one direction component has an alternating component which disappears gradually in time (approximately in 3 s). Surge component of excitation current in this case is:

$\hat{i}_{p3}$ = *711.2 A.*

In dumper cage in transient regime of three-phase short circuit alternating currents appear. These currents lower in time and become zero. Surge components of linked current value in dumper cage in this case have the following values: $\hat{i}_{Dd3}$ = *2139 A* ; $\hat{i}_{Dq3}$ *=3562 A.*

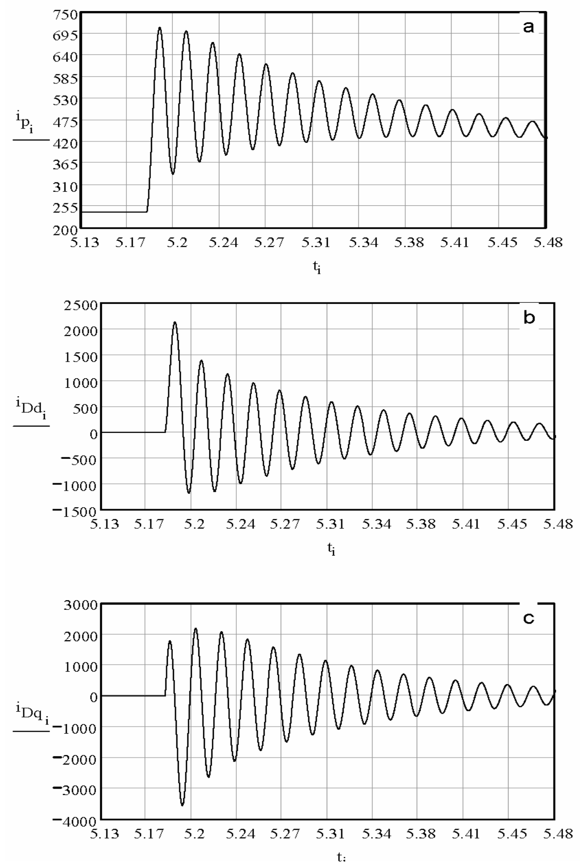


Fig.6 *Change of instantaneous values of current in rotor windings in three-phase short circuit*

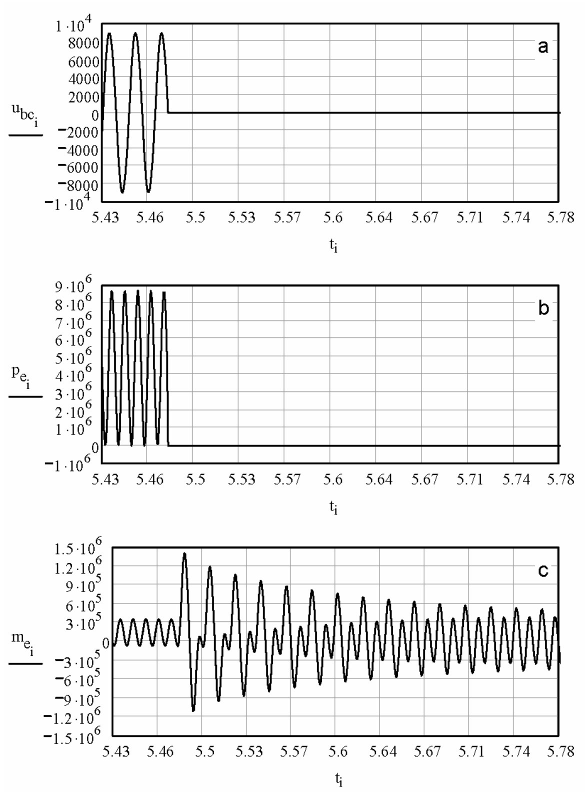


Fig. 7 *Change of instantaneous values of line voltage, power and torque in two-phase regimes*

### 4.2 Modelling results of two-phase short circuit regime

The change of instantaneous values of line voltage, electric power and produced torque in two-phase regimes in function of time are shown on Fig.7.

On basis of instantaneous value of line voltage (Fig. 7a) we can say that consumer is supplied with rated line voltage with two-phase load at the same excitation voltage. But in this case, electric power output (Sl.7b) beside one direction component has also an alternating component. Here at stationary two-phase load effective output power ($P_2$), effective current in loaded phases ($I_2$) and torque ($M_2$) just before appearance of short circuit ($t_k$=5.4755 s) have the following values: $P_2$= 4250 kW, $I_2$=768.6 A, $M_2$=135 kNm

The surge current component i.e. the first biggest current amplitude in stator windings after appearance of short circuit according to the shown diagram has the following value: $\hat{i}_{U2} = 5912$ A

On Fig. 7c we can see that instantaneous value of torque in two-phase regimes beside one-direction component also has alternating components, which don't, disappears even in stationary regimes. The value of surge torque in this two-phase short circuit regime: $\hat{m}_{U2} =$ *1404 kNm*

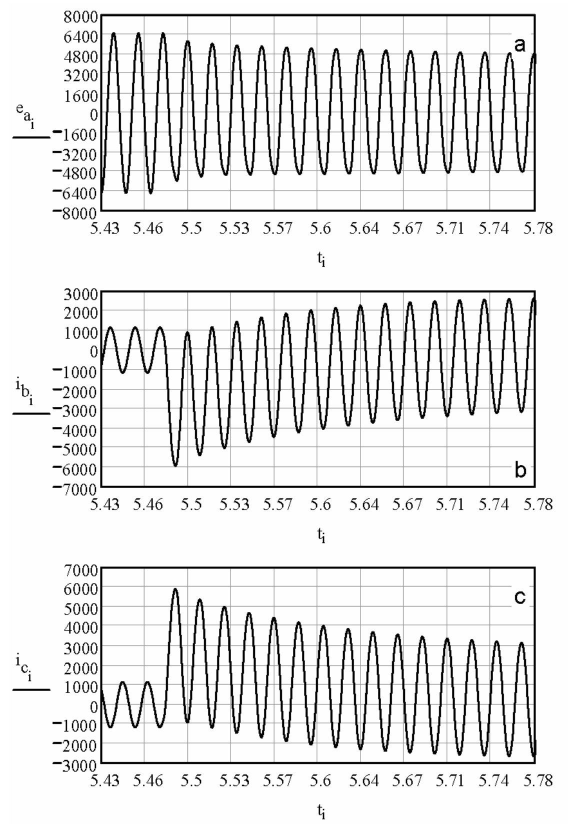

Fig. 8. *Change of instantaneous values of induced voltage in free phase and current in stator windings*

Change of instantaneous values of induced voltage in free phase and current in loaded stator phases in a function of time in two-phase regimes are shown on Fig. 8.

From the change of induced voltage value in free phase (Fig. 8a) we can notice that these voltage amplitudes have bigger values in two-phase loaded regime than in two-phase short circuit regime. Amplitude of the induced voltage in loaded stationary regime is: $\hat{e}_a = 6544\ V.$ If rotor had no dumper cage, the situation would be opposite. In that case, the surge component of voltage in free phase could be of double value of voltage amplitude per phase.

Change of instantaneous values of current in rotor windings in function of time in two-phase regimes are shown on Fig. 9.

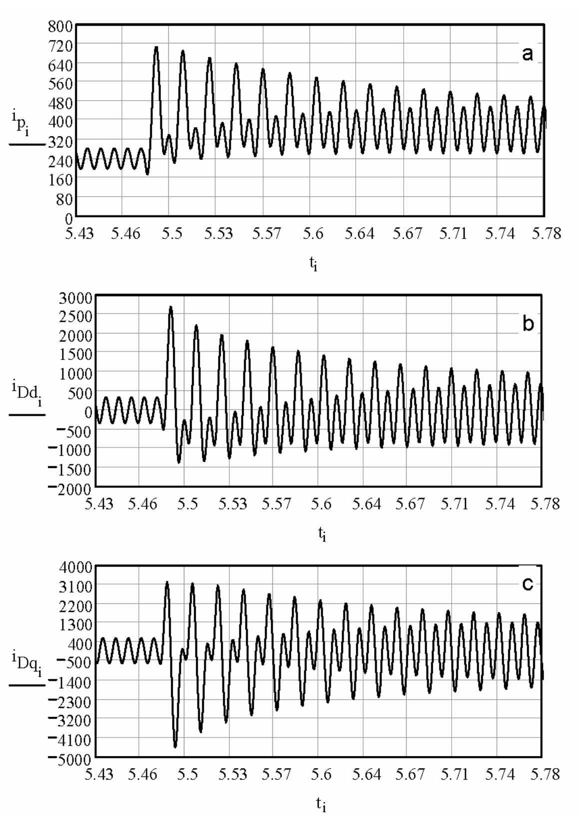


Fig. 9. *Change of instantaneous values of current in rotor windings in two-phase short circuit regime*

From the Fig. 9a we can notice that in two-phase operating regimes current in excitation winding beside one-direction component also has an alternating component, which with lower amplitude remains in the stationary operation of two-phase short circuit. The surge component of excitation current in this case has the value $\hat{i}_{p2} = 707.1\ A.$

Surge components of linked current values in dumper cage (Fig. 9b, Fig. 9C) in two-phase short circuit have the following values:

$$\hat{i}_{Dd2} = 2700\ A\ ;\ \hat{i}_{Dq2} = 4542\ A.$$

### 4.3 Comparison of modelling results of three- and two-phase short circuit regime

Values of surge components in three- and two-phase short circuit regime are shown in Table 1. The column *I* contains values calculated by modelling method and the column *II* contains results that can be calculated with classical method using simplified equation according to the literature [4] and [5].

Table 1. *Compared values of surge components in short circuit regimes*

| Currents and torques | | I | II |
|---|---|---|---|
| 3~ | $\hat{i}_{u3}$ [A] | 6017 | 6910 |
| | $\hat{i}_{p3}$ [A] | 711,2 | - |
| | $\hat{i}_{Dd3}$ [A] | 2139 | - |
| | $\hat{i}_{Dq3}$ [A] | 3562 | - |
| | $\hat{m}_{u3}$ [kNm] | 903,2 | 848,5 |
| 2~ | $\hat{i}_{u2}$ [A] | 5912 | 6054 |
| | $\hat{i}_{p2}$ [A] | 707,1 | - |
| | $\hat{i}_{Dd2}$ [A] | 2700 | - |
| | $\hat{i}_{Dq2}$ [A] | 4542 | - |
| | $\hat{m}_{u2}$ [kNm] | 1404 | 1171,5 |

Values of components in stationary regimes in three- and two-phase short circuits are given in Table 2.

Table 2 *Compared values of stationary components in short circuit regimes*

| Currents and torques | | I | II |
|---|---|---|---|
| 3~ | $\hat{I}_3$ [A] | 1286 | 1339 |
| | $\hat{I}_{p3}$ [A] | 233,94 | 233,9 |
| | $\hat{I}_{Dd3}$ [A] | 0 | 0 |
| | $\hat{I}_{Dq3}$ [A] | 0 | 0 |
| | $\hat{M}_3$ [kNm] | 0 | 0 |
| 2~ | $\hat{I}_2$ [A] | 1800 | 2300 |
| | $\hat{I}_{p2}$ [A] | 296,1/164,2 | - |
| | $\hat{I}_{Dd2}$ [A] | 502,2 | - |
| | $\hat{I}_{Dq2}$ [A] | 945,1 | - |
| | $\hat{M}_2$ [kNm] | -150/172,3 | - |

## 5. CONCLUSION

Based on modelling results and comparison of characteristic of sudden short circuits regimes on synchronous generator with salient poles we can conclude that surge components of current in three-phase regime have bigger values compared to surge components of current in two-phase short circuit.

In stationary short circuit regimes, the situation is opposite. Currents in two-phase short circuits are bigger than currents in three-phase short circuit regimes. According to our modelling results, the ratio of these currents is *1.41*, and if we use the classical method this ratio will be *1.48.*

Surge currents in excitation winding have approximately the same value in both cases of short circuits. In both cases excitation currents in short circuit transition period have alternating components, with the difference that in three-phase short circuit regime alternating components disappear in stationary regime but in two-phase short circuit regime, these components remain in stationary operation regime.

Surge current components in dumper cage have bigger value in two-phase than in three-phase short circuit regime. In stationary three-phase short circuit regime, these currents totally disappear, but in two-phase short circuit regime, they permanently remain with lower amplitude.

According to the shown pictures, it can be noticed that currents and voltages in presented two-phase regimes have approximately sinusoidal form. It was achieved by influence of the dumper cage, which reduces the inverse component of stator flux. If there were no dumper cage, the forms of current and voltage in two-phase regimes would be in a step form.

Surge torque in two-phase short circuit regime has bigger value than in three-phase short circuit regime Because of that designers of the generators have to determine the shaft dimension in a way that the shaft can withstand torque in two-phase short circuit regime without any damage. In three-phase short circuit, regime torque has only alternating character. From the moment of appearance torque amplitudes are gradually reducing and in stationary regime, they lower to zero.

In two-phase short circuit regime, the torque is modulated. It means that in this case the torque of the generator has one-direction component beside the alternating one. Their values, starting from the moment of appearance of two-phase short circuit regime, gradually lower to the certain values, which remain in stationary regime of two-phase short circuit. That is the reason why the generator works as a brake in two-phase short circuit regime.

## 6. LITERATURE


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