Verification of Synchronous Generator Time Constants Given by Manufacturers Using the Short-Circuit Current Calculation

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Abstract — **Synchronous generators are an essential part of the power system, they perform a number of important tasks related to the production of electrical energy, voltage control and so on. The article deals with the verification of synchronous generator time constants given by manufacturers using by short-circuit currents calculation. The procedure of mathematical dynamic modeling of electromagnetic properties of the synchronous generator was used for this verification. Results obtained by short-circuit current calculation by this approach are compared to results obtained by short-circuit current calculation method using generator time constants.**

Keywords: synchronous generator modeling; short-circuit current calculation; synchrnous generator time constants

I. INTRODUCTION

Synchronous generators form the principal source of electric energy in power systems. The commercial birth of the synchronous generator can be dated to 1891, when the first alternate transmission of electricity from Lauffen to Frankfurt (Germany, length 175 km, 20 kV line) was realized. Many large loads are driven by synchronous motors. Synchronous compensators are used to compensate the reactive power and voltage control. These devices operate on the same principle and are collectively referred to as synchronous machines [1].

The basic operating state of each power system (and also of a synchronous generator) is its steady state (electrical and mechanical) of operating system quantities. Any change in system operating parameters leads to disturbing a steady state (equilibrium), resulting in a transient phenomenon. One of the most common causes of electromagnetic transient phenomena in the power system is short circuits. Short-circuit current generation is a steady state disturbance resulting in a corresponding voltage and current change. After the short circuit, the total network impedance decreases and the current increases, resulting in reduced voltage near the short circuit. The ideal short circuit is characterized by zero (or negligibly small) short-circuit impedance. The short-circuit current caused by the ideal short circuit is always greater than the short-circuit current caused by a non-ideal short circuit (created through an impedance that cannot be neglected) if the same conditions are considered. Therefore, the ideal short circuit is considered to determine maximum short-circuit currents. If all three phases are affected by the short circuit, it is referred to as a symmetrical short circuit. All other short circuits are listed as unsymmetrical [2], [3], [4], [5].

II. MATHEMATICAL MODEL OF A SYNCHRONOUS GENERATOR FOR THE SHORT-CIRCUIT CURRENT CALCULATION

The basic mathematical model of the synchronous generator (turbogenerator as well as hydrogenerator) is based on its design and consists of equations for stator voltages and rotor voltages. For turbogenerators (modeled with two amortisseurs in the q-axis), after applying dq0 transformation, a system of first order linear differential equations is obtained [1], [2], [6]-[9]:

$$\left[\frac{\mathrm{d}i}{\mathrm{d}t}\right] = -\left[N\right]^{-1}\left[M\right]\left[i\right] + \left[N\right]^{-1}\left[u\right] = \left[A\right]\left[i\right] + \left[B\right], \qquad (1)$$

$$\left[i\right] = \begin{bmatrix} i_{\mathrm{d}} \\ i_{\mathrm{q}} \\ i_{\mathrm{fd}} \\ i_{\mathrm{1d}} \\ i_{\mathrm{1q}} \\ i_{\mathrm{2q}} \end{bmatrix} \begin{array}{l} (\text{d-component of the stator current}) \\ (\text{q-component of the stator current}) \\ (\text{rotor field current}) \\ (\text{rotor amortisseur 1 current in the d-axis}) \\ (\text{rotor amortisseur 1 current in the q-axis}) \\ (\text{rotor amortisseur 2 current in the q-axis}) \end{array},$$

$$\left[u\right] = \begin{bmatrix} u_{\mathrm{d}} \\ u_{\mathrm{q}} \\ u_{\mathrm{fd}} \\ u_{\mathrm{1d}} = 0 \\ u_{\mathrm{1q}} = 0 \\ u_{\mathrm{2q}} = 0 \end{bmatrix} \begin{array}{l} (\text{d-component of the stator voltage}) \\ (\text{q-component of the stator voltage}) \\ (\text{rotor field voltage}) \\ (\text{rotor amortisseur 1 voltage in the d-axis}) \\ (\text{rotor amortisseur 1 voltage in the q-axis}) \\ (\text{rotor amortisseur 2 voltage in the q-axis}) \end{array},$$

$$\left[M\right] = \begin{bmatrix} -R_{\mathrm{a}} & \omega L_{\mathrm{q}} & 0 & 0 & -\omega L_{\mathrm{aq}} & -\omega L_{\mathrm{aq}} \\ -\omega L_{\mathrm{d}} & -R_{\mathrm{a}} & \omega L_{\mathrm{ad}} & \omega L_{\mathrm{ad}} & 0 & 0 \\ 0 & 0 & R_{\mathrm{fd}} & 0 & 0 & 0 \\ 0 & 0 & 0 & R_{\mathrm{1d}} & 0 & 0 \\ 0 & 0 & 0 & 0 & R_{\mathrm{1q}} & 0 \\ 0 & 0 & 0 & 0 & 0 & R_{\mathrm{2q}} \end{bmatrix},$$

$$\left[N\right] = \begin{bmatrix} -L_{\mathrm{d}} & 0 & L_{\mathrm{ad}} & L_{\mathrm{ad}} & 0 & 0 \\ 0 & -L_{\mathrm{q}} & 0 & 0 & L_{\mathrm{aq}} & L_{\mathrm{aq}} \\ -L_{\mathrm{ad}} & 0 & L_{\mathrm{ffd}} & L_{\mathrm{ad}} & 0 & 0 \\ -L_{\mathrm{ad}} & 0 & L_{\mathrm{ad}} & L_{\mathrm{11d}} & 0 & 0 \\ 0 & -L_{\mathrm{aq}} & 0 & 0 & L_{\mathrm{11q}} & L_{\mathrm{aq}} \\ 0 & -L_{\mathrm{aq}} & 0 & 0 & L_{\mathrm{aq}} & L_{\mathrm{22q}} \end{bmatrix},$$

where

$[i]$ is the matrix of output unknown quantities, it is formed by the matrix of stator currents and rotor currents in amperes or per units,

$\left[\frac{\mathrm{d}i}{\mathrm{d}t}\right]$ is the matrix of time derivations of unknown rotor and stator currents in amperes or per units,

$[u]$ is the matrix of input known quantities with constant coefficients, it contains the matrix of stator voltages and rotor voltages in volts or per units,

$[M]$ is the matrix with constant coefficients, it contains parameters of the synchronous generator (resistances and inductive reactances) in ohms or per units bound to unknown currents,

$[N]$ is the matrix with constant coefficients, it contains parameters of the synchronous generator (inductances) in henrys or per units bound to time derivations of unknown currents,

R_a is the (stator) armature resistance per phase in ohms or per units,

L_d is the (stator) synchronous inductance in the d-axis in henries or per units,

L_q is the (stator) synchronous inductance in the q-axis in henries or per units,

L_ad is the mutual inductance bound to rotor circuits in the d-axis in henries or per units,

L_aq is the mutual inductance bound to rotor circuits in the q-axis in henries or per units,

ω is the rotor angular velocity in radians per second or per units.

R_fd, R_1d, R_1q, R_2q are the (rotor) resistances of the field winding, amortisseur winding 1 in the d-axis, amortisseur winding 1 in the q-axis and amortisseur winding 2 in the q-axis in henries or per units. L_ffd, L_11d, L_11q, L_22q are the (rotor) inductances of the field winding, amortisseur winding 1 in the d-axis, amortisseur winding 1 in the q-axis and amortisseur winding 2 in the q-axis in ohms or per units.

The solution of the system (1) consists of determining the initial conditions (for example generator no-load operation): unknown currents (the matrix $[i]$) at time 0. The initial conditions are defined by the steady state solution of the synchronous generator: simplification of the system (1). During steady state, time derivations do not occur in the equations (1) for describing the synchronous machine. Also, all currents flowing in amortisseur windings are equal to 0. They are closed circuits in which currents are induced only in the case of a transient event. The zero component is skipped and the angular velocity is not changed (is equal to the nominal) [2].

The control and regulation of the synchronous generator voltage is realized by changing the excitation current, respectively the excitation voltage of the synchronous generator. As a result, the excitation voltage (which is determined from the steady state of the synchronous generator [6]) is required as the single input to the calculation (whether the steady state or transient phenomena). This can be achieved by expressing the stator voltages u_d and u_q in the system (1) via an external load ($R_\mathrm{ext} + \mathrm{j}\omega L_\mathrm{ext}$) connected to synchronous generator terminals. In other words, the stator voltages u_d and u_q can be moved from the input matrix $[u]$ to the matrices $[M]$ and $[N]$ of synchronous generator parameters. The ideal three-phase short circuit at synchronous generator terminals can be realized by setting the external load (R_ext and L_ext) to zero. Some elements of matrices $[u]$, $[M]$, $[N]$ change to:

$[u](1,1)=0$, $[u](2,1)=0$,

$[N](1,1)=-(L_\mathrm{d}+L_\mathrm{ext})$, $[N](2,2)=-(L_\mathrm{q}+L_\mathrm{ext})$,

$[M](1,1)=-(R_\mathrm{a}+R_\mathrm{ext})$, $[M](1,2)=\omega(L_\mathrm{q}+L_\mathrm{ext})$,

$[M](2,1)=-\omega(L_\mathrm{d}+L_\mathrm{ext})$, $[M](2,2)=-(R_\mathrm{a}+R_\mathrm{ext})$.

Applying the inverse dq0 transformation determines time courses of phase currents i_ka , i_kb , i_kc (index k in the case of the ideal three-phase short circuit) in amperes or per units [2]:

$$\begin{pmatrix} i_\mathrm{ka} \\ i_\mathrm{kb} \\ i_\mathrm{kc} \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta & 1 \\ \cos(\theta-120°) & -\sin(\theta-120°) & 1 \\ \cos(\theta+120°) & -\sin(\theta+120°) & 1 \end{pmatrix} \begin{pmatrix} i_\mathrm{d} \\ i_\mathrm{q} \\ i_0 \end{pmatrix}, \tag{2}$$

where i_0 is the zero component of the stator current. Zero component i_0 is neglected in the case of symmetric systems, it is $i_0 = 0$.

III. TIME CONSTANTS AND REACTANCES OF A SYNCHRONOUS GENERATOR

Following a disturbance, currents are induced in the synchronous machine stator and rotor circuits. Some of these currents decay more rapidly than others. Accordingly, parameters of the synchronous machine are divided into three types (reactances and time constants) [7]:

- subtransient (characterized by two commas above the quantity symbol),
- transient (characterized by one comma above the quantity symbol),
- synchronous (without comma above the quantity symbol).

The duration of dynamic events in the synchronous generator is described by time constants. Time constants are based on basic resistances and inductances of the synchronous generator. Basic time constants (in seconds or per units) in the d-axis and the q-axis are [10]:

T'_do is the transient open-circuit time constant in the d-axis, it expresses the rate of decay or buildup of the field current when the stator is open circuited and there is zero resistance of the field winding,

T''_do is the subtransient open-circuit time constant in the d-axis,

T'_d is the transient short-circuit time constant in the d-axis, it expresses the rate of decay of the transient component of the stator current in the d-axis under an ideal three-phase short circuit at synchronous generator terminals,

T''_d is the subtransient short-circuit time constant in the d-axis, it expresses the rate of decay of the subtransient component of the stator current in the d-axis under an ideal three-phase short circuit at synchronous generator terminals,

T_a is the armature (stator) time constant, it expresses the rate of decay of the DC component of the short-circuit current under an ideal three-phase short circuit at synchronous generator terminals.

Other important data belonging to the synchronous generator are its inductances, respectively inductive reactances (in henries, respectively ohms or per units) [10]:

X_l is the leakage reactance, it expresses the reactance due to flux setup by armature windings, but not crossing the air gap. It can be divided into end-winding leakage and slot leakage,

X''_d	is the subtransient reactance in the d-axis, it expresses the magnitude of the subtransient component of the stator current in the d-axis under an ideal three-phase short circuit at synchronous generator terminals,
X'_d	is the transient reactance in the d-axis, it expresses the magnitude of the transient component of the stator current in the d-axis under an ideal three-phase short circuit at synchronous generator terminals. It is the reactance after the currents in amortisseurs windings have decayed, but before the transient event ending in the field winding,
X_d	is the synchronous reactance in the d-axis, it is the reactance related to the steady-state stator current in the d-axis after or before the ideal three-phase short circuit at synchronous generator terminals,
X_2	is the negative sequence reactance, it is the reactance encountered by a voltage of reverse phase sequence applied to the stator, with the machine running. Negative sequence flux revolves opposite to the rotor and is at twice the system frequency,
X_0	is the zero sequence reactance, it is the reactance related to the zero sequence current,
X_p	it is the Potier reactance, it is the reactance used for calculation of field current when open circuit and zero power factor curves are available.

The time constants T'_qo, T''_qo, T'_q, T''_q and the reactances X''_q, X'_q, X_q in the q-axis have the same meaning as the time constants in the d-axis, but they are related to currents in the q-axis. Typically, manufacturers list the above time constants and reactants in data sheets. Other parameters (for example, rotor reactances and inductances in Chapter II) must be calculated according to the equations given in [11]. There are also interconnections between the manufacturers' time constants and reactances mentioned above. Time constants T'_d, T''_d, T_a can be determined from the equations:

$$T'_\mathrm{d} = T'_\mathrm{do}\frac{X'_\mathrm{d}}{X_\mathrm{d}}, \tag{3}$$

$$T''_\mathrm{d} = T''_\mathrm{do}\frac{X''_\mathrm{d}}{X'_\mathrm{d}}, \tag{4}$$

$$T_\mathrm{a} = \frac{1}{\omega R_\mathrm{a}}\left(\frac{2X''_\mathrm{d}X''_\mathrm{q}}{X''_\mathrm{d}+X''_\mathrm{q}}\right) = \frac{X_2}{\omega R_\mathrm{a}}. \tag{5}$$

IV. Simplified Model of a Synchronous Generator for the Short-Circuit Current Calculation

The simplified model of the synchronous generator for the calculation of short-circuit currents is based on the subtransient, transient and steady-state parameters of the synchronous generator (time constants and reactances mentioned in Chapter III). Only d-axis parameters are considered, the model is suitable for round-rotor generators where $X''_\mathrm{d} \cong X''_\mathrm{q}$. Using this theory, the ideal three-phase short circuit at synchronous generator terminals is modeled. It is considered that at the moment of the short circuit, the synchronous generator operates in the no-load state [4], [5].

For the RMS value of the subtransient I''_k, transient I'_k and the steady-state I_k component of the short-circuit current in amperes or per units it is possible to write (U_n is the nominal voltage of the synchronous generator in volts or per units) [4], [5]:

$$I''_\mathrm{k} = \frac{U_\mathrm{n}}{\sqrt{3}X''_\mathrm{d}}, \tag{6}$$

$$I'_\mathrm{k} = \frac{U_\mathrm{n}}{\sqrt{3}X'_\mathrm{d}}, \tag{7}$$

$$I_\mathrm{k} = \frac{U_\mathrm{n}}{\sqrt{3}X_\mathrm{d}}. \tag{8}$$

Time courses of the current flowing in each phase i_ka, i_kb and i_kc in the case of the ideal three-phase short circuit at generator terminals can be expressed as the sum of the AC short-circuit component $i_\mathrm{k\,AC}$ and the DC short-circuit component $i_\mathrm{k\,DC}$. The instantaneous values of stator phase currents $i_\mathrm{ka}(t)$, $i_\mathrm{kb}(t)$, $i_\mathrm{kc}(t)$ at time t can be determined from (φ_k is the short-circuit angle between voltage and current at generator terminals during a short circuit, α is the voltage angle in degrees or radians) [4], [5]:

$$i_\mathrm{ka}(t) = i_\mathrm{ka\,AC}(t) + i_\mathrm{ka\,DC}(t), \tag{9}$$

$$i_\mathrm{ka\,AC}(t) = \sqrt{2}\left[\left(I''_\mathrm{k}-I'_\mathrm{k}\right)\mathrm{e}^{-\frac{t}{T''_\mathrm{d}}} + \left(I'_\mathrm{k}-I_\mathrm{k}\right)\mathrm{e}^{-\frac{t}{T'_\mathrm{d}}} + I_\mathrm{k}\right]\sin\left(\omega t+\alpha+\varphi_\mathrm{k}\right),$$

$$i_\mathrm{ka\,DC}(t) = \sqrt{2}I''_\mathrm{k}\sin\left(\alpha+\varphi_\mathrm{k}\right)\mathrm{e}^{-\frac{t}{T_\mathrm{a}}},$$

$$i_\mathrm{kb}(t) = i_\mathrm{kb\,AC}(t) + i_\mathrm{kb\,DC}(t), \tag{10}$$

$$i_\mathrm{kb\,AC}(t) = \sqrt{2}\left[\left(I''_\mathrm{k}-I'_\mathrm{k}\right)\mathrm{e}^{-\frac{t}{T''_\mathrm{d}}} + \left(I'_\mathrm{k}-I_\mathrm{k}\right)\mathrm{e}^{-\frac{t}{T'_\mathrm{d}}} + I_\mathrm{k}\right]\sin\left(\omega t+\alpha+\varphi_\mathrm{k}-120^\circ\right),$$

$$i_\mathrm{kb\,DC}(t) = \sqrt{2}I''_\mathrm{k}\sin\left(\alpha+\varphi_\mathrm{k}-120^\circ\right)\mathrm{e}^{-\frac{t}{T_\mathrm{a}}},$$

$$i_\mathrm{kc}(t) = i_\mathrm{kc\,AC}(t) + i_\mathrm{kc\,DC}(t), \tag{11}$$

$$i_\mathrm{kc\,AC}(t) = \sqrt{2}\left[\left(I''_\mathrm{k}-I'_\mathrm{k}\right)\mathrm{e}^{-\frac{t}{T''_\mathrm{d}}} + \left(I'_\mathrm{k}-I_\mathrm{k}\right)\mathrm{e}^{-\frac{t}{T'_\mathrm{d}}} + I_\mathrm{k}\right]\sin\left(\omega t+\alpha+\varphi_\mathrm{k}+120^\circ\right),$$

$$i_\mathrm{kc\,DC}(t) = \sqrt{2}I''_\mathrm{k}\sin\left(\alpha+\varphi_\mathrm{k}+120^\circ\right)\mathrm{e}^{-\frac{t}{T_\mathrm{a}}}.$$

V. Verification of Synchronous Generator Time Constants By the Short Circuit Current Calculation

In this chapter, a three-phase ideal short circuit at the terminals of different turbogenerators (G1, G2, G3) is simulated and compared by two methods (Chapter II and IV). At the moment of the short circuit, synchronous generators operate in the no-load state. A principal single-line diagram of an ideal three-phase short circuit at synchronous generator terminals is shown in Fig. 1. Manufacturers' generator parameters (nominal data, reactances and time constants [12]) are shown in Table 1, the calculated generator parameters (resistances and inductances of field and amortisseurs windings according to [11]) are shown in Table 2. A comparison of manufacturers' and calculated (according to equations (3), (4), (5)) generator (G1, G2, G3) time constants T''_d, T'_d, T_a is given in Table 3. All generators are modeled with two amortisseurs in the q-axis. The only input is the field voltage, which is constant during the calculation, so the voltage regulation is not considered. The model is analyzed in physical units.

Table 1. Manufacturers' parameters of modeled synchronous generators

Manufacturers' parameters		G1	G2	G3
Rated voltage	U_{nG} (kV)	13.8	18	24
Rated power	S_{nG} (MVA)	25	192	384
Rated frequency	f_{nG} (Hz)	60	60	60
Rated power factor	$\cos\varphi_{nG}$ (–)	0.8	0.85	0.85
Synchronous reactance in d-axis	X_d (Ω)	9.522	2.648	2.697
Transient reactance in d-axis	X'_d (Ω)	1.767	0.547	0.486
Subtransient reactance in d-axis	X''_d (Ω)	0.914	0.42	0.39
Synchronous reactance in q-axis	X_q (Ω)	9.293	2.612	2.667
Transient reactance in q-axis	X'_q (Ω)	5.447	1.549	1.577
Subtransient reactance in q-axis	X''_q (Ω)	0.914	0.419	0.383
Leakage reactance	X_l (Ω)	1.021	0.344	0.29
Armature resistance	R_a (Ω)	0.0107	0.0027	0.0021
Transient open-circuit time constant in d-axis	T'_{do} (s)	4.75	5.9	5.21
Subtransient open-circuit time constant in d-axis	T''_{do} (s)	0.059	0.033	0.042
Transient short-circuit time constant in d-axis	T'_d (s)	0.882	0.829	0.159
Subtransient short-circuit time constant in d-axis	T''_d (s)	0.035	0.023	0.035
Transient open-circuit time constant in q-axis	T'_{qo} (s)	1.5	0.535	1.5
Subtransient open-circuit time constant in q-axis	T''_{qo} (s)	0.21	0.078	0.042
Transient short-circuit time constant in q-axis	T'_q (s)	–	0.415	0.581
Subtransient short-circuit time constant in q-axis	T''_q (s)	0.035	0.023	0.035
Armature time constant	T_a (s)	0.177	0.254	0.45

Table 2. Calculated parameters of modeled synchronous generators

Calculated parameters		G1	G2	G3
Field winding resistance	R_{fd} (Ω)	0.0052	0.0011	0.0013
Amortisseur winding 1 resistance in d-axis	R_{1d} (Ω)	0.0294	0.026	0.0254
Amortisseur winding 1 resistance in q-axis	R_{1q} (Ω)	0.0315	0.024	0.0092
Amortisseur winding 2 resistance in q-axis	R_{2q} (Ω)	0.0546	0.0437	0.0876
Mutual d-axis inductance	L_{ad} (H)	0.0225	0.0061	0.0064
Mutual q-axis inductance	L_{aq} (H)	0.0219	0.006	0.0063
Field winding inductance	L_{ffd} (H)	0.0247	0.0067	0.007
Amortisseur winding 1 resistance in d-axis	L_{11d} (H)	0.0223	0.0064	0.0069
Amortisseur winding 1 resistance in q-axis	L_{11q} (H)	0.0472	0.0128	0.0137
Amortisseur winding 2 resistance in q-axis	L_{22q} (H)	0.0217	0.0062	0.0066

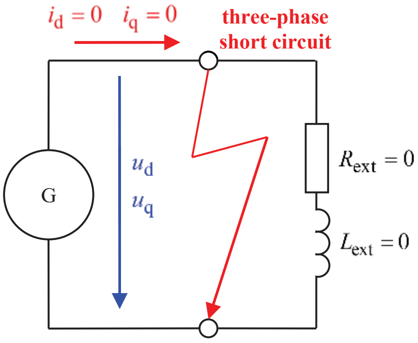

Figure 1. Principal single-line diagram of an ideal three-phase short circuit at synchronous generator terminals

Table 3. Comparison of manufacturers' and calculated time constants of modeled synchronous generators

Time constant (s)		G1	G2	G3
Subtransient short-circuit time constant in d-axis	Manufacturers'	0.035	0.023	0.035
	Calculated	0.031	0.025	0.034
Transient short-circuit time constant in d-axis	Manufacturers'	0.882	0.829	0.159
	Calculated	0.881	1.219	0.939
Armature time constant	Manufacturers'	0.177	0.254	0.45
	Calculated	0.227	0.412	0.488

If the short circuit occurs when the phase voltage passes the maximum positive value, then the short-circuit current in the corresponding phase is symmetrical and the DC component is zero. The peak short-circuit current has a positive value. Otherwise, if the short circuit occurs when the phase voltage passes the maximum negative value, then the short-circuit current in the corresponding phase is symmetrical and the DC component is zero. The peak short-circuit current has a negative value. If the voltage reaches zero from a negative half-period and the short-circuit occurs, the unsymmetrical short-circuit current with the maximum positive DC component is generated. If the voltage reaches zero from a positive half-period and the short-circuit occurs, the unsymmetrical short-circuit current with the maximum negative DC component is generated [1].

In Fig. 2 are shown time courses of the generator G1 (18 kV and 192 MVA) current and voltage after the ideal three-phase short circuit at its terminals (determined by analytical model consisting of differential equations, Chapter II). At the moment of the short circuit, the phase a voltage was zero (from the negative half-period) and the generator G1 was operating without load. In the phase a, the maximum positive DC and peak short-circuit current of 22.8 kA were generated.

The representation of generator G2 phase currents, field and amortisseur currents in the d-axis and the q-axis is shown in Fig. 3 (determined by analytical model consisting of differential equations, Chapter II). After the short circuit, there was a strong armature (stator) reaction. It means that the stator winding (magnetic flux caused by a stator short-circuit current flowing) was acting against the main magnetic flux (caused by the field current and rotation of the rotor). In order to reduce the armature reaction, the excitation current value rapidly increased as well as the amortisseur current values. At the end of the transient phenomena (ideal three-phase short circuit at generator G2 terminals), the field current was the same as before the short circuit, and the amortisseur currents were equal to zero.

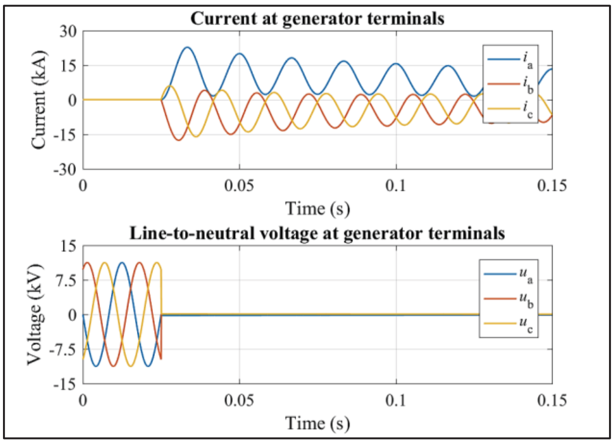

Figure 2. Time courses of the generator G1 current and voltage after the ideal three-phase short circuit at its terminals

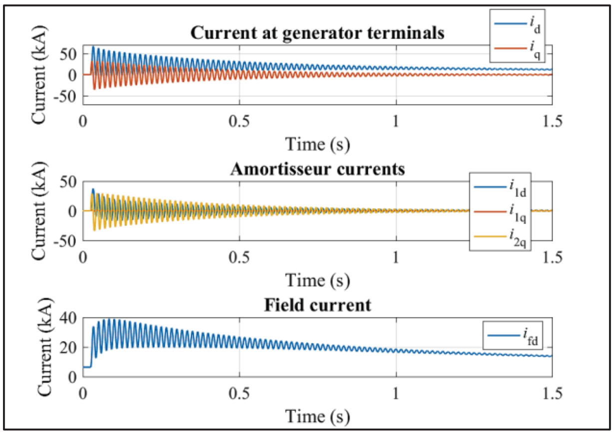

Figure 3. Time courses of the generator G2 stator, field and amortisseur currents after the ideal three-phase short circuit at its terminals

In Fig. 4 to Fig. 6 are shown time courses of the generator G1, G2 and G3 stator current in phase a after the ideal three-phase short circuit determined by the analytical method (system of differential equation) and the simplified model (with data sheet or calculated time constants). In the case of generators G1 and G2, the maximum positive DC component was generated (voltage passed through zero), in the case of the generator G3, the DC component was zero (voltage passed through maximum). The upper graph compares the analytical method (differential equations) with a simplified model with calculated time constants (Table 3). The lower graph compares the analytical method (differential equations) with a simplified model with manufacturers' time constants (Table 2).

Comparison of manufacturers' and calculated generator G1 time constants implies that the calculated armature time constant $T_a = 0.227$ s differs significantly from the data sheet value $T_a = 0.177$ s. This difference is also seen in Fig. 4 where the DC component of the time course determined by the simplified method using the data sheet armature time constant $T_a = 0.177$ s differs from the DC component of the time course determined by the method of differential equations. According to the manufacturers' value of the armature time constant $T_a = 0.177$ s, the DC component disappears sooner than with considering the calculated armature time constant $T_a = 0.227$ s.

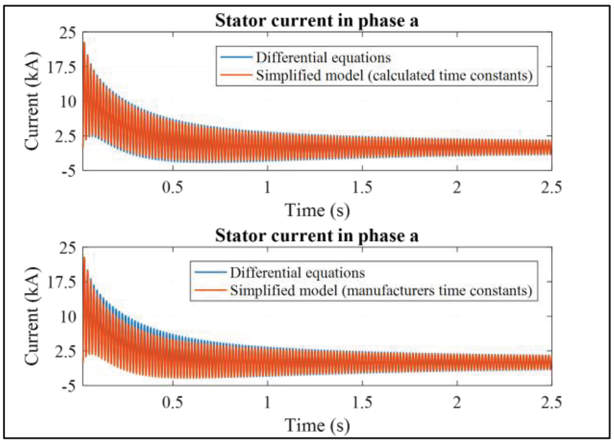

Figure 4. Time courses of the generator G1 stator current in phase a after the ideal three-phase short circuit at its terminals

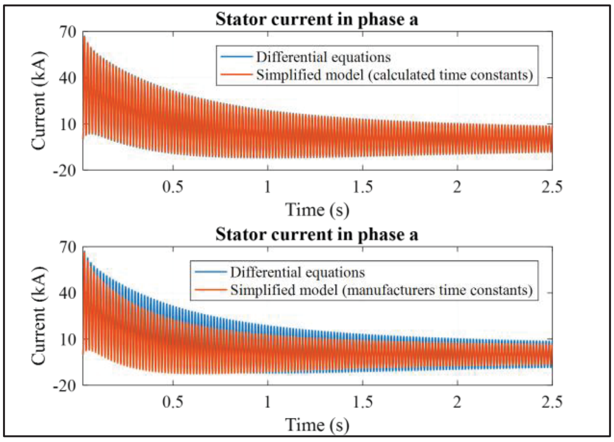

Figure 5. Time courses of the generator G2 stator current in phase a after the ideal three-phase short circuit at its terminals

In the case of the generator G2, in addition to the armature time constant ($T_a = 0.254$ s and calculated $T_a = 0.412$ s), the data sheet $T'_d = 0.829$ s and computed $T'_d = 1.219$ s transient short-circuit time constants in the d-axis differed. Fig. 5 shows that when using the data sheet value of the transient short-circuit time constant in the d-axis, the transient short-circuit current component disappeared faster than when applying the calculated transient short-circuit time constant in the d-axis. In the case of the generator G3, the difference between the data sheet $T'_d = 0.159$ s and calculated $T'_d = 0.939$ s transient short-circuit time constant was even more pronounced compared to the generator G2 (Fig. 6).

In Table 4 and Fig. 7 is shown the (maximal) deviation of the simplified synchronous generator model (manufacturers' or calculated time constants) from the analytical synchronous generator model (differential equations). The results show that when considering the calculated time constants (simplified synchronous generator model), the deviation is considerably smaller for all analyzed generators (G1, G2, G3). This is also visible in Fig. 4 to Fig. 6, where the upper time courses of currents are almost identical. The times at which the greatest deviation was reached also point to the difference in data sheet and calculated DC and transient short-circuit time constants. These times also point to the difference between the DC and transient short-circuit current component calculated by the simplified method versus the current time courses determined by the analytical method.

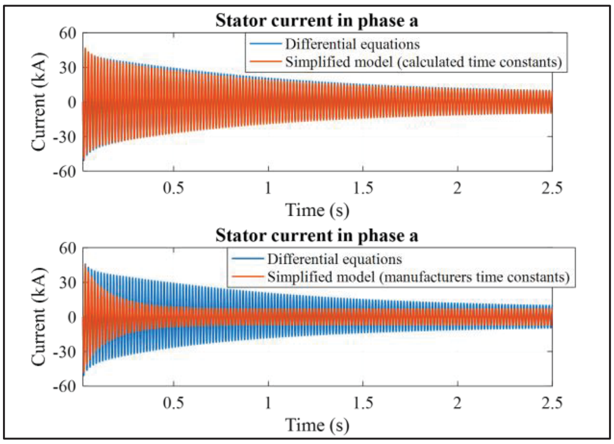

Figure 6. Time courses of the generator G3 stator current in phase a after the ideal three-phase short circuit at its terminals

Table 4. Maximum deviation of the simplified synchronous generator model (manufacturers' or calculated time constants) from the analytical synchronous generator model (differential equations)

Maximum deviation		**G1**	**G2**	**G3**
Manufacturers' time constants	Value (%)	17.26	25.8	68.53
	Time (s)	0.28	0.53	0.56
Calculated time constants	Value (%)	7.98	2.05	3.57
	Time (s)	1	1.36	0.02

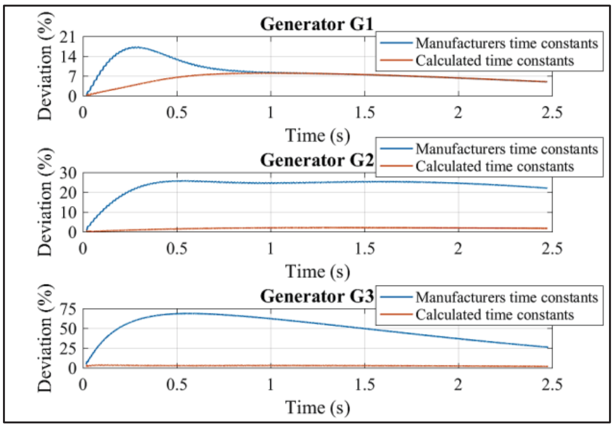

Figure 7. Deviation of the simplified synchronous generator model (manufacturers' or calculated time constants) from the analytical synchronous generator model (differential equations)

VI. CONCLUSION

This paper deals with the verification of manufacturers' time constants of three different synchronous generators using the short-circuit current calculation by two different methods.

The first of these methods, the complex analytical model of the synchronous generator, consists of a system of differential equations. The parameters entering the calculation, in addition to the nominal data (voltage, power, etc.), are resistances, self and mutual reactances, respectively inductances of each generator circuit (stator and rotor). The resistances and reactances of stator circuits are determined by manufacturers, the resistances and reactances of rotor circuits are calculated from the steady-state, transient and subtransient reactances and also from open-circuit time constants of the synchronous generator.

In the case of the second simplified method, only the synchronous generator nominal voltage, the steady-state, transient and subtransient reactance, the transient and subtransient short-circuit time constant and armature time constant enter the calculation. However, only the d-axis parameters are considered in this model.

It is presented in this paper that some manufacturers' values of synchronous generator time constants (given in [12]) do not correspond to calculated time constants. This difference caused a significant deviation of the analytical model from the simplified synchronous generator model (with manufacturers' time constants). When comparing the analytical model with the simplified model with calculated time constants, there was a relatively large match of current time courses. If it is considered that the synchronous generator model assembled in the form of differential equations is more accurate, even the simplified theory (with calculated time constants) yields satisfactory results. However, this only applies to turbogenerators, because there are no large differences between the parameters in d-axis and q-axis. It follows that it is necessary to consider the choice of parameters of synchronous generators as well as the methods of calculation according to the specified objectives.

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