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Analysis of power system operation at asymmetrical load

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Abstract. The paper presents a mathematical model of a power system (PS) consisting of a generating unit (with a synchronous generator) connected by a high voltage (transmission) power line to a bus. The state and output equations of the generator are expressed in the coordinate system d, q, 0 and with the use of phase quantities of the generator stator, the bus and the power line, which is especially useful in the analysis of asymmetrical states. A disturbance of the steady state in the form of a two-phase short-circuit in the transmission line was taken into account in the made calculations. The influence of the excitation system and angular speed control system of the generator as well as the impact of selected generator model parameters on the waveforms were investigated.

1 Introduction

During the PS operation, primarily asymmetrical disturbances occur. The asymmetrical state of PS operation causes a number of unfavorable phenomena, including additional heating of the rotor surface and mechanical vibrations of machine elements [1].

Equations describing asymmetrical short-circuit processes of a synchronous machine are differential equations with periodically variable coefficients, which makes their solution difficult [2, 3]. In the case of stand-alone operation of a synchronous machine (without PS), it is possible to find a solution by approximate methods [2, 3, 4]. The analysis of the PS work with all its elements (including synchronous generators) is complicated and only practically possible using numerical methods.

In the investigations presented in the paper, it was assumed that the PS consisted of a generating unit (with a synchronous generator) connected by a transmission line to a bus. The state and output equations of the generator were presented in the coordinate system d, q, 0 and using the phase quantities of the generator stator and power line. A compact mathematical description of the whole PS was obtained and the waveforms of appropriate quantities for selected asymmetrical loads in transient and steady states were calculated.

2 The PS mathematical model

A mathematical model of the PS was developed in the Matlab-Simulink environment. First, a general model of the generating unit was created. In this model, using *Configurable Subsystem* blocks, it is possible to conveniently configure a model of the generating unit by selecting the model of: a generator, an excitation system, a turbine.

In the investigations, the GENROU synchronous generator model when taking into account possible subtransient asymmetry was used [5]. When analysing asymmetrical PS states, it is convenient to express the equations of stator currents and voltages, transmission line and bus with the use of phase quantities. The equations of Park transformation relating the quantities in the d, q, 0 coordinate system to those in the phase A, B, C coordinate system are then used [1, 5].

Due to the assumption of neglecting transformation voltages [1, 5], algebraic relations between the currents and voltages in the equations of the generator stator and transmission line were determined:

$$i_k\left(t+\Delta t_{k1}\right)=\frac{v_k(t)+v_{\mathrm{d}}(t)-v_{\mathrm{sc}}(t)}{\left|\underline{Z}_{k1}\right|},\quad \Delta t_{k1}=\frac{\varphi_{k1}}{2\pi}\frac{1}{f},\tag{1a}$$

$$i_{\mathrm{C}}\left(t+\mathit{\Delta} t_{\mathrm{C}}\right)=\frac{v_{\mathrm{C}}(t)+v_{\mathrm{d}}(t)-v_{\mathrm{sc}}(t)}{\left|\underline{Z}_{\mathrm{C}}\right|},\quad \mathit{\Delta} t_{\mathrm{C}}=\frac{\varphi_{\mathrm{C}}}{2\pi}\frac{1}{f},\tag{1b}$$

$$i_{k\mathrm{b}}\left(t+\Delta t_{k2}\right)=\frac{v_{\mathrm{sc}}(t)-v_{k\mathrm{b}}(t)}{\left|\underline{Z}_{k2}\right|},\quad \Delta t_{k2}=\frac{\varphi_{k2}}{2\pi}\frac{1}{f},\tag{1c}$$

$$i_{\mathrm{A}}(t)+i_{\mathrm{B}}(t)+i_{\mathrm{C}}(t)=0,\quad i_{\mathrm{A}}(t)+i_{\mathrm{B}}(t)=i_{\mathrm{Ab}}(t)+i_{\mathrm{Bb}}(t),\tag{1d}$$

where: i_l, $i_{l\mathrm{b}}$, v_l, $v_{l\mathrm{b}}$ – phase currents and voltages of the generator and the bus, v_{sc} and v_{d} – voltages in the short-circuit location and difference voltages of the star points of the bus and the generator, $\underline{Z}_j$, φ_j, – complex impedances and their phase angles in the transmission line, $f = 50$ Hz, k = A, B, l = A, B, C, j = A1, B1, C, A2, B2.

3 Exemplary calculations

In the paper, the results of calculations carried out for two cases are presented.

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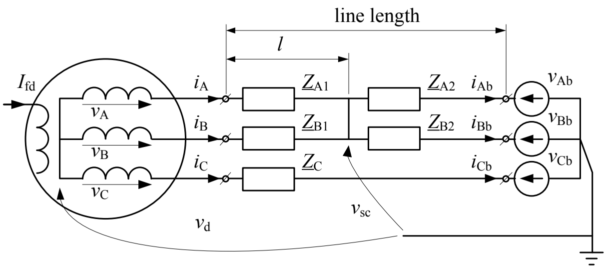

Fig. 1. Simplified diagram of the analysed PS for a two-phase short-circuit clear of earth.

In the first case, the stability of excitation voltage and angular velocity of the generator as well as the mechanical power of the turbine were assumed. It was assumed that the generator was loaded with low active and reactive power and its magnetization characteristic was linear. A long-term two-phase short-circuit in the transmission line located close to the generator terminals was modeled. In Tab. 1, there is compared the percentage content of higher harmonics in the steady state of the generator current in the short-circuited phase A (I_a), the generator voltage in the healthy phase C (V_c), and the generator excitation current (I_{fd}), with respect to the first harmonic for the stator quantities and with respect to the constant component for the field current.

Table 1. Harmonics amplitudes in the analysed waveforms in the steady state.

h	$X''_d \neq X''_q$			$X''_d = X''_q$		
	I_a, %	V_c, %	I_{fd}, %	I_a, %	V_c, %	I_{fd}, %
	0.0019	0.0065	100 (1.21 p.u.)	0.0023	0.0068	100 (1.21 p.u.)
1	100 (1.32 p.u.)	100 (0.56 p.u.)	0.0078	100 (1.40 p.u.)	100 (0.53 p.u.)	0.0078
2	0.0063	0.0045	87.029	0.0062	0.0046	86.275
3	9.1031	3.4390	0.0066	0.6228	0.2461	0.0066
4	0.0019	0.0009	2.9390	0.0024	0.0009	0.2119
5	0.3085	0.1160	0.0024	0.0025	0.0009	0.0026

In the second case, transient short-circuits (with a duration t_{sc} = 0.15 s) for the system at generator rated load, when taking into account the equation of motion and the impact of the excitation system and turbine were modeled. Fig. 2 shows the waveforms of the stator voltage and instantaneous power of the generator.

4 Conclusion

Based on the performed investigations one can state that:

– In the case of the synchronous generator subtransient asymmetry, in the steady state, during a long-term two-phase short-circuit in the transmission line, besides the fundamental harmonic, odd harmonics with significant amplitudes occur in the waveforms of the short-circuit current and voltage on the non-short circuited phase of the stator, in spite of the linear model of the system. In the steady state, the constant component, the second harmonic and higher even harmonics occur in the generator field current.

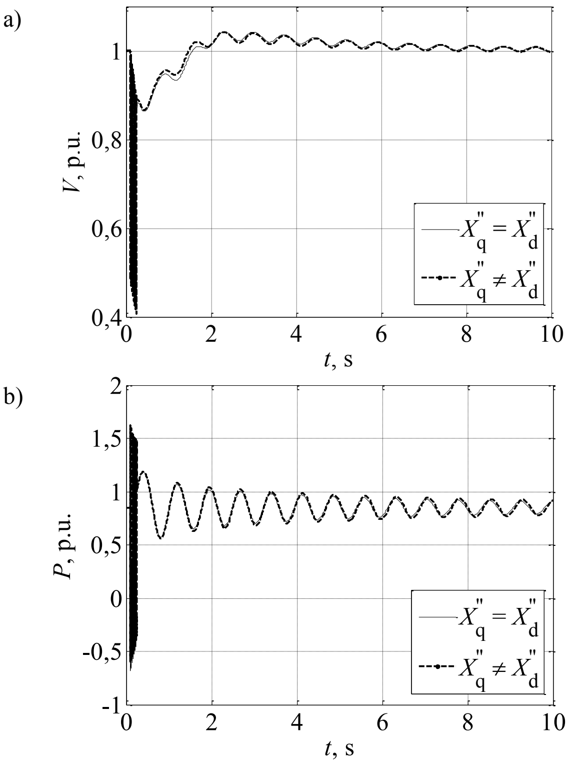

Fig. 2. Waveforms of the generator stator voltage (a) and instantaneous power (b) for a transient short-circuit.

– In the case of the generator subtransient symmetry, in the steady state, during a two-phase short-circuit, only the first harmonic in the short-circuit current and voltage on the non-short circuited phase of the stator as well as the constant component and second harmonic of the field current practically occur.

– In the case of short-term short-circuits, the generator subtransient asymmetry is of little importance. Its influence on the analysed waveforms can be observed when taking into account the impact of the excitation system and the turbine.

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