

Impact of voltage dips on the operations of a high-power synchronous motor with a reactive power controller

The article presents the impact of voltage dips on the operations of a synchronous motor in the state of synchronism. The following characteristics were determined: static characteristics of the load angle depending on power voltage and excitation current for a GAe-1716t/01 high-power motor. The results of simulation tests of dynamic states were presented. Finally, it was investigated whether it is justifiable to force excitation current during voltage dips in order to keep the motor in the state of synchronous work.

Keywords: *synchronous motor, reactive power compensation, voltage dips*

1. INTRODUCTION

High-power synchronous motors are used in the mining industry chiefly in the drives of main fans installed to ventilate the mine underground. Usually, these motors are supplied straight from the buses of 6 kV substations, however, systems supplied by inverters are encountered more and more frequently. For direct power supply, motors with salient poles are used as drive motors, because asynchronous start-up is possible in this case. In the steady state the motor works with synchronous speed resulting from the frequency of the supply voltage, while the ventilation efficiency is regulated by proper arrangement of the steering system valves. A 20-minute break in the ventilator operation results in a work stoppage and the personnel evacuation towards downcast shafts or to the surface [8]. It is important for the ventilation system to work reliably and the key element is proper operation of the motor that drives the ventilator.

One of the phenomena that can contribute to incorrect operations of the ventilator is a dip of the voltage supplying the drive motor. Such a phenomenon may cause the motor to fall out of synchronous work and, as a consequence, may cause emergency stopping of the ventilator.

Under-loaded synchronous motors are often used as regulated reactive power compensators, both locally

and in the systems with superior setting of reactive power [3, 4]. Reactive power regulation is administered by changing the current in the excitation winding of the motor.

The objective of the tests is to analyze how a voltage dip affects the drive operations when reactive power compensation procedures are applied. Another objective is to assess the possibility to keep the motor in the state of synchronism by forcing the excitation current. Only symmetrical dips are taken into account.

2. SYNCHRONOUS OPERATION OF SALIENT-POLES MOTOR

In synchronous motors with salient poles, the excitation winding is wound onto the poles of the rotor (field system). The core of the rotor is symmetrical to the salient pole axis which is marked as axis d and to the longitudinal axis marked as axis q which is perpendicular to d . The core contains solid elements of a magnetic circuit (pole pieces). Synchronous reactance has different values in both axes. This allows to achieve a starting torque at the direct-on-line start-up from the supply network.

In the state of synchronous work, when the motor is loaded with a braking torque (active power), the rotor

axis does not coincide with the axis of the rotating field generated by the windings of the stator. The axis is shifted by the ϑ angle, called load angle. The forces which operate between the poles evoke a mechanical torque which opposes the braking torque. Changes in the load do not cause any changes in the rotating speed of the rotor, only a delay of the rotor with respect to the rotating field produced by the machine stator. When the maximal admissible value of the load angle is exceeded, the motor falls out of synchronous work [1, 2, 5, 6, 7].

Figure 1 features a phasor diagram of a synchronous motor with salient poles in the dq coordinate system, disregarding losses in the stator winding.

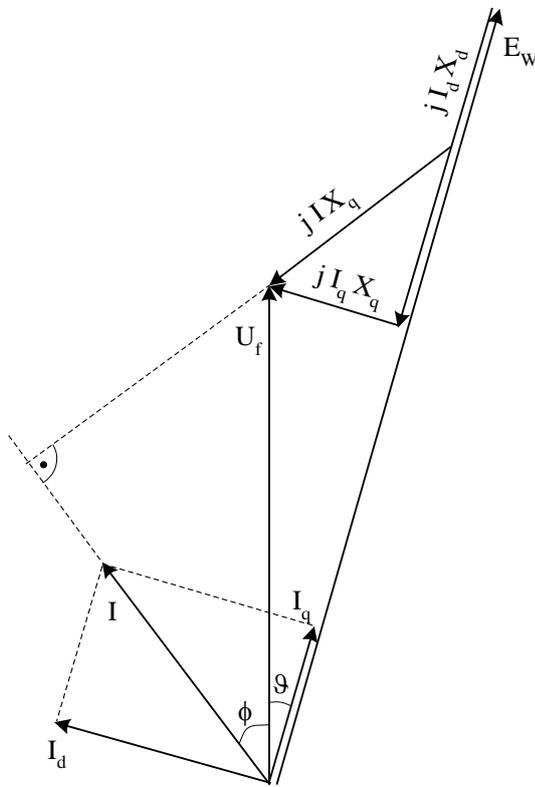


Fig. 1. Phasor diagram of a synchronous motor with salient poles

A rated load angle ϑ_N can be determined on the basis of the following dependency [2, 7]:

$$\vartheta_N = \arcsin \frac{I_N \cdot X_q \cdot \cos \varphi_N}{\sqrt{U_{fN}^2 + 2 \cdot U_{fN} \cdot I_N \cdot X_q \cdot \sin \varphi_N + I_N^2 \cdot X_q^2}}, \quad (1)$$

where:

- I_N – rated current of the stator,
- U_{fN} – rated phase-to-phase voltage,
- $\cos \varphi_N$ – rated power factor,
- X_d – diffusion reactance in axis d ,
- X_q – diffusion reactance in axis q .

Active power consumed by the motor in the state of synchronous work is described by the following dependency:

$$P = m \left(\frac{U_f E_w}{X_d} \sin \vartheta + \frac{1}{2} U_f^2 \left(\frac{1}{X_q} - \frac{1}{X_d} \right) \sin(2\vartheta) \right), \quad (2)$$

where:

- m – number of phases,
- U_f – phase-to-phase voltage,
- ϑ – load angle,
- E_w – electromotive force induced in the winding of the stator.

Electromotive force induced in the winding of the stator is expressed by the following dependency:

$$E_w = \frac{I_w}{k_w}, \quad (3)$$

where:

- I_w – excitation current,
- k_w – force connected with the motor structure.

The T torque developed by the motor can be determined by the following dependency:

$$T = \frac{P}{\omega_l}, \quad (4)$$

where ω_l in the state of synchronous work is equal to angular velocity ω_N expressed by the following formula:

$$\omega_N = \frac{2\pi f_N}{p}, \quad (5)$$

where:

- f_N – rated frequency of supply voltage,
- p – number of pole pairs of the field system.

The dependencies (2), (3) and (4) show that the load angle is affected by the motor load with active power (proportional to the load torque), as well as by the supply voltage and excitation current values.

Safe operation of the motor in the state of synchronism is possible in a limited range for the load angle.

Motors manufacturers recommend that the motors should work with load angles not bigger than the rated value. Working with a bigger load angle may cause instable operations of the motor, particularly in transient states. In practice, synchronous motors have a certain reserve of the load angle which enables stable synchronous work.

Reactive power generated or consumed by the motor can be determined on the basis of the following dependency:

$$Q = \begin{cases} -3U_f \sqrt{I^2 - I_p^2} & \text{for } \vartheta < \vartheta_0, \\ 3U_f \sqrt{I^2 - I_p^2} & \text{for } \vartheta \geq \vartheta_0, \end{cases} \quad (6)$$

where:

I – stator current,

I_p – active current,

ϑ_0 – load angle while working with $\cos\varphi=1$.

Active current I_p is described by the below dependency:

$$I_p = \frac{P}{3U_f}, \quad (7)$$

while stator current I by:

$$I = \sqrt{I_d^2 + I_q^2}, \quad (8)$$

where:

I_d – current in d axis in the following form:

$$I_d = \frac{E_w - U_f \cos \vartheta}{X_d}, \quad (9)$$

I_q – current in q axis in the following form:

$$I_q = \frac{U_f \sin \vartheta}{X_q}. \quad (10)$$

Based on (6), (9) and (10) it can be observed that follow-up reactive power compensation with the use of a synchronous motor may lead to changes in the load angle at the unchanged load torque.

The use of the motor as a controlled reactive power compensator is possible only if the motor is loaded with a torque that is smaller than the rated value. In many industrial drives synchronous motors work with load torques significantly smaller than the rated one. For example, the load of a motor which drives a

ventilator in the mine underground typically does not exceed 60% of its rated power. Such load leaves an indispensable safety margin of the load angle during supply voltage dips.

Under-loaded synchronous motors used as reactive power compensators are equipped with current regulation systems in their excitation circuits [4]. Lower excitation current results in a higher value of the load angle. During a voltage dip such a situation may lead to the motor fall-out of synchronism.

A frequent practice during voltage dips is to follow the procedure of excitation current forcing in order to reduce the load angle. The forcing is conducted until the supply voltage comes back to the assumed value, a few seconds maximum. Longer forcing times are not used due to losses that occur in the excitation winding when the flowing current value is higher than the rated one. When the acceptable excitation forcing time is exceeded, there is an emergency switch-off of the motor.

3. TESTED OBJECT

The tested object is a GAe-1716t/01 salient-pole synchronous motor whose rated data are presented in Table 1.

Based on the dependency (1) the rated load angle $\vartheta_N = 22.9^\circ$ was determined.

Figures 2-7 feature static characteristics of the load angle depending on the active power load, supply voltage and excitation current determined analytically. The tested range of excitation current was increased to $1.2I_{wN}$, due to the assumed possibility to force the excitation current during a dip in the supply voltage of the stator. The dashed line stands for the rated excitation current and rated load angle.

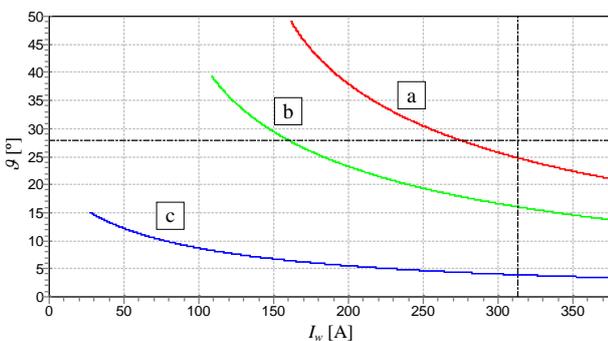


Fig. 2. Dependency of load angle ϑ on excitation current I_w for $U=U_N$: a) $P=0.9P_N$, b) $P=0.6P_N$, c) $P=0.15P_N$

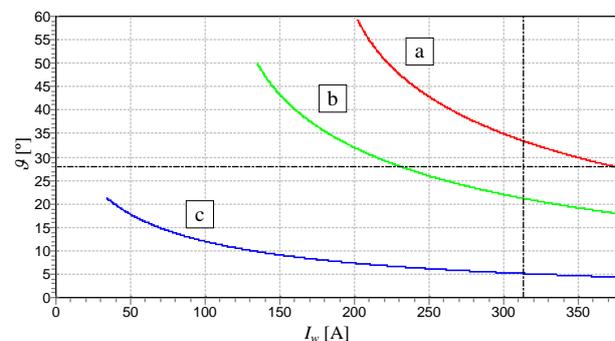


Fig. 3. Dependency of load angle ϑ on excitation current I_w for $U=0.8U_N$: a) $P=0.9P_N$, b) $P=0.6P_N$, c) $P=0.15P_N$

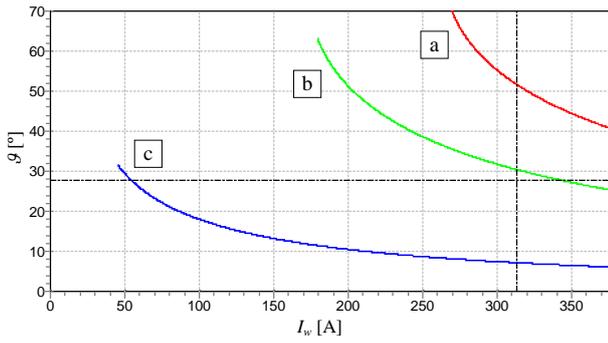


Fig. 4. Dependency of load angle ϑ on excitation current I_w for $U=0.6U_N$: a) $P=0.9P_N$, b) $P=0.6P_N$, c) $P=0.15P_N$

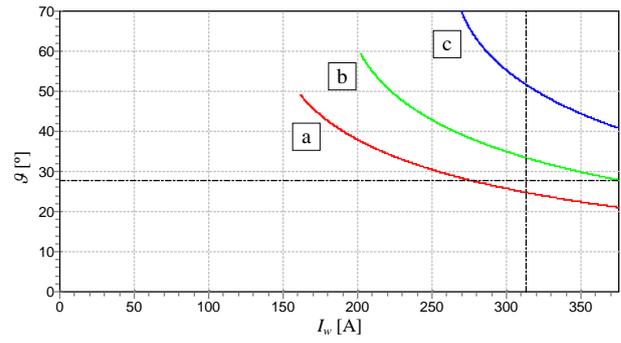


Fig. 5. Dependency of load angle ϑ on excitation current I_w for $P=0.9P_N$: a) $U=U_N$, b) $U=0.8U_N$, c) $U=0.6U_N$

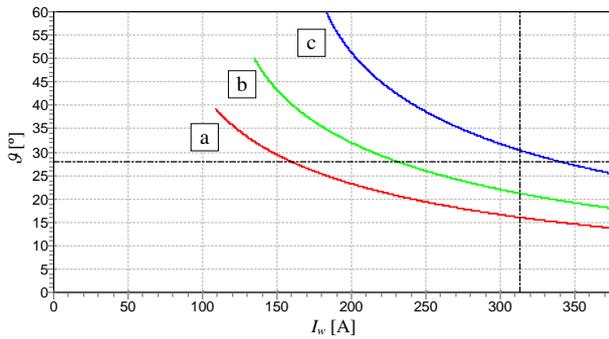


Fig. 6. Dependency of load angle ϑ on excitation current I_w for $P=0.6P_N$: a) $U=U_N$, b) $U=0.8U_N$, c) $U=0.6U_N$

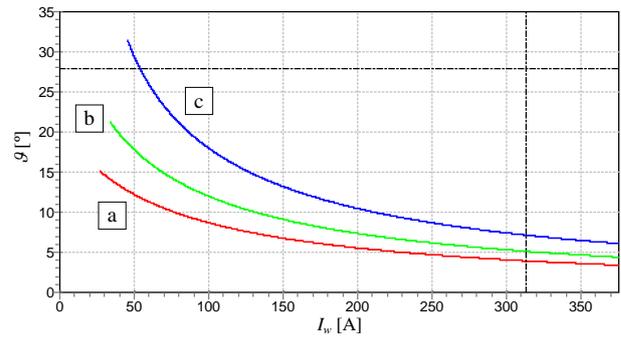


Fig. 7. Dependency of load angle ϑ on excitation current I_w for $P=0.15P_N$: a) $U=U_N$, b) $U=0.8U_N$, c) $U=0.6U_N$

Table 1.

Rated data of GAe-1716t/01 motor

Rated power (mechanical)	P_{mN}	3150 kW
Active power	P_N	3274 kW
Stator voltage	$U_{N(Y)}$	6000 V
Stator current	I_N	350 A
Excitation voltage	U_{wN}	90 V
Excitation current	I_{wN}	313 A
Power factor	$\cos\varphi_N$	0.9
Rotating speed	n_N	375 rpm
Frequency	f_N	50 Hz

If we assume that the drive operates at the load of $0.6P_N$ and the load angle is limited to the rated value, based on static characteristics we can determine the range of the excitation current regulation from $0.51I_{wN}$ (160 A) to I_{wN} (313 A).

4. DYNAMIC STATES DURING VOLTAGE DIP

In order to designate the motor behaviour in dynamic states, a simulation test was carried out with the use of the Matlab-Simulink program.

The simulation model is presented in Fig. 8. In the model an increased moment of inertia is taken into account. This moment corresponds to the drive system of the WPK-5.3 ventilator and amounts to 40,000 kgm².

Figure 9-10 present the results of dynamic states simulation tests at a step change of supply voltage to $0.8U_N$ during synchronous work and for terminal values of the determined range of excitation current regulation.

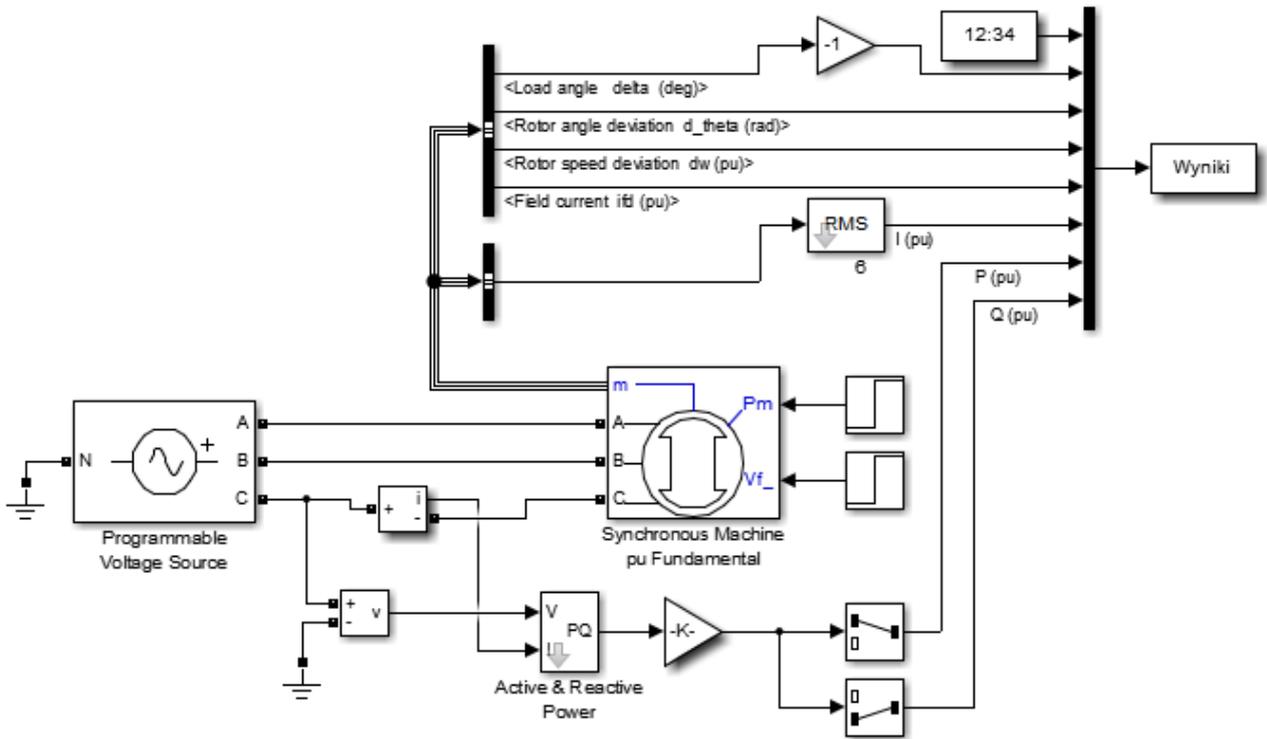


Fig. 8. Matlab-Simulink simulation model

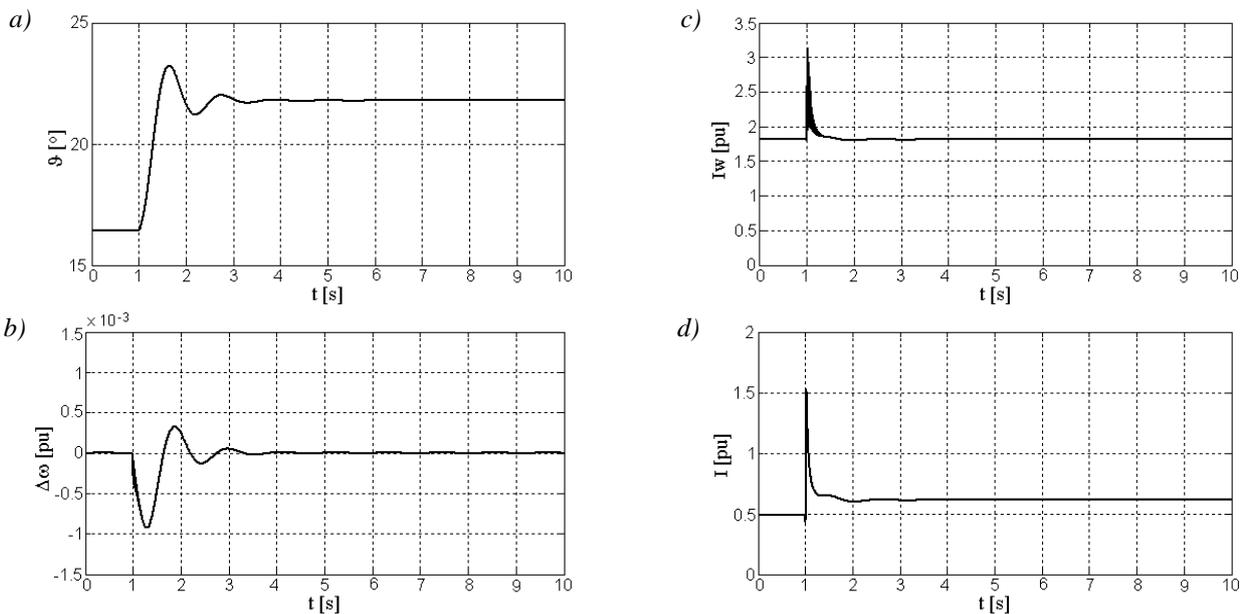


Fig. 9. Voltage change from U_N to $0.8U_N$ in time $t=1$ s for $P=0.6P_N$ $I_w=I_{wN}$: a) load angle ϑ , b) speed deviation $\Delta\omega$, c) excitation current I_w , d) stator current I

When operating conditions change, the power angle is the first to change. An electromagnetic transient state, in turn, occurs only as a consequence of a mechanical transient state [5]. The processes impact each other leading to a transient electromechanical state.

A big moment of inertia stabilizes the rotating speed but impacts negatively the dynamics of chang-

es in the angle between the location of the motor rotor and the axis of the rotating field generated by the stator windings as a consequence of the changing load angle. This phenomenon causes over-regulation of the load angle in dynamic states and may lead to falling out of synchronism [1, 6], though the admissible value determined for a static state of new operating conditions is not exceeded.

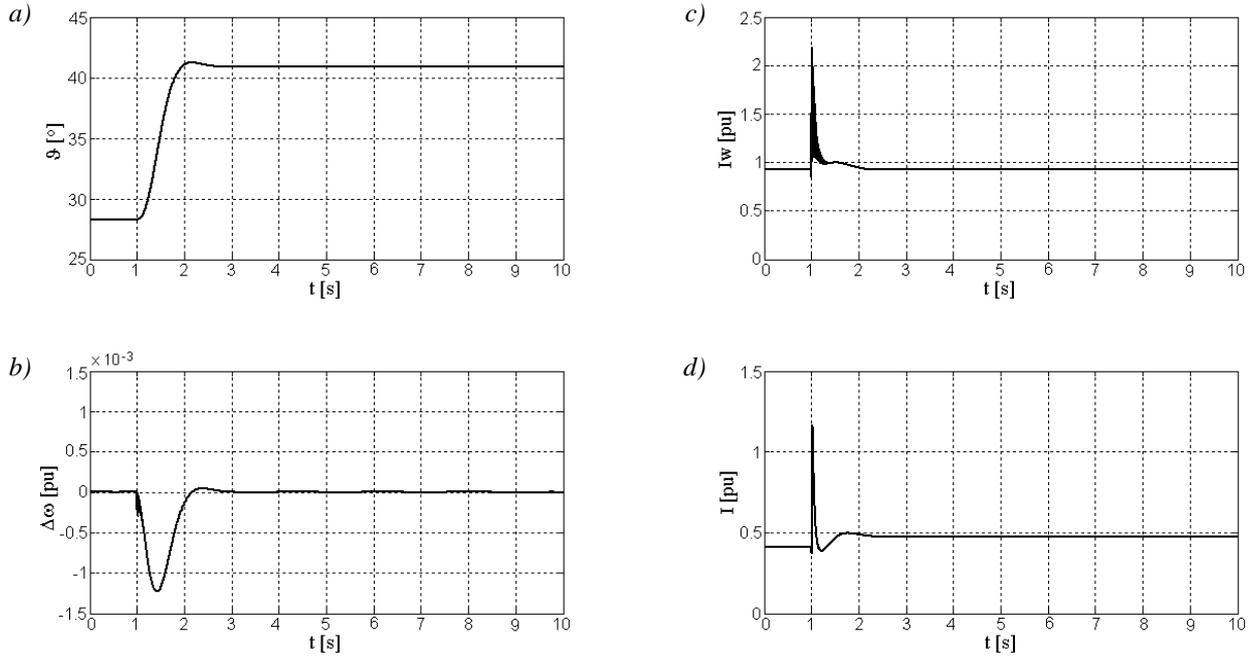


Fig. 10. Voltage change from U_N to $0.8U_N$ in time $t=1$ s for $P=0,6P_N$ $I_w=0,5I_{wN}$: a) load angle ϱ , b) speed deviation $\Delta\omega$, c) excitation current I_w , d) stator current I

Figures 11-12 feature the results of simulation tests of dynamic states at the step change of supply voltage up to $0.6U_N$ during synchronous work, for terminal values of the determined excitation current range. If there is a $0.6U_N$ voltage dip at lowered excitation current, the motor falls out of synchronous work. In

such a case there should be an emergency switch-off of the motor by the security system.

A frequently undertaken operation in this case is automatic forcing of excitation current during the supply voltage dip.

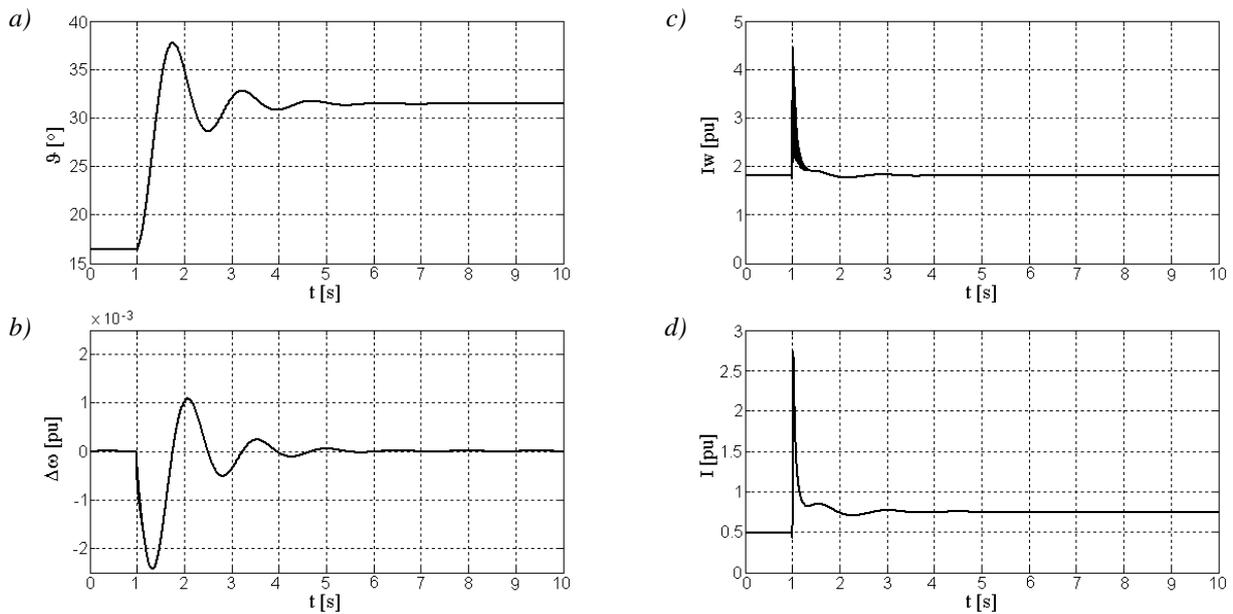


Fig. 11. Voltage change from U_N to $0.6U_N$ in time $t=1$ s for $P=0,6P_N$ $I_w=I_{wN}$: a) load angle ϱ , b) speed deviation $\Delta\omega$, c) excitation current I_w , d) stator current I

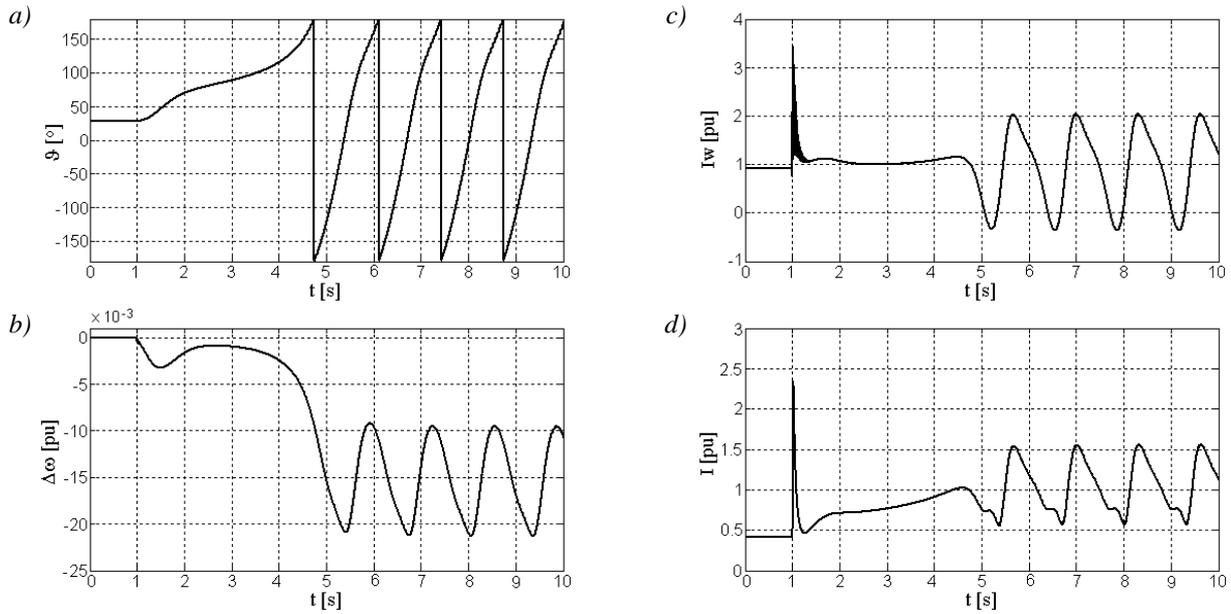


Fig. 12. Voltage change from U_N to $0.6U_N$ in time $t=1$ s for $P=0.6P_N$ $I_w=0.5I_{wN}$: a) load angle ϑ , b) speed deviation $\Delta\omega$, c) excitation current I_w , d) stator current I

Figures 13-14 present the results of simulation tests when the excitation forcing procedure is used for two extreme cases: supply voltage dip down to $0.8U_N$ at excitation current I_{wN} and voltage dip to $0.6U_N$ at excitation current of $0.5I_{wN}$.

For the case from Fig. 13, with the comparison of results from Fig. 9, the excitation current forcing is not necessary and it leads to unwanted increase of the excitation and stator currents. For the case from Fig. 14, with the comparison of results from Fig. 12, the excitation current forcing allowed to keep the motor in the state of synchronous work.

Based on static characteristics it is possible to determine the value of supply voltage for which the excitation current forcing should be done. In the microprocessor supply block for the excitation of synchronous motors [4] this value is set parametrically.

The excitation forcing time usually does not exceed a few seconds. If, at that time, the supply voltage does not return to the acceptable value, the drive system should have an emergency switch-off from the moment the excitation current forcing time is exceeded.

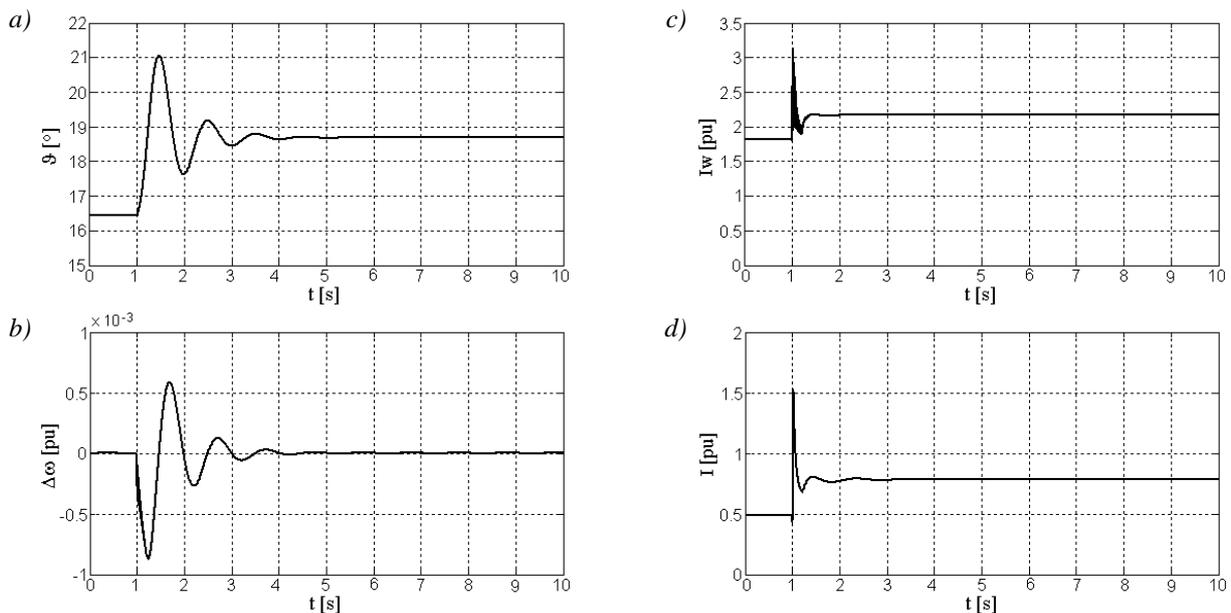


Fig. 13. Voltage change from U_N to $0.8U_N$ in time $t=1$ s for $P=0.6P_N$ and change of excitation current forcing from $I_w=I_{wN}$ to $1.2I_{wN}$ in time 1.2 s: a) load angle ϑ , b) speed deviation $\Delta\omega$, c) excitation current I_w , d) stator current I [elaborated by the author]

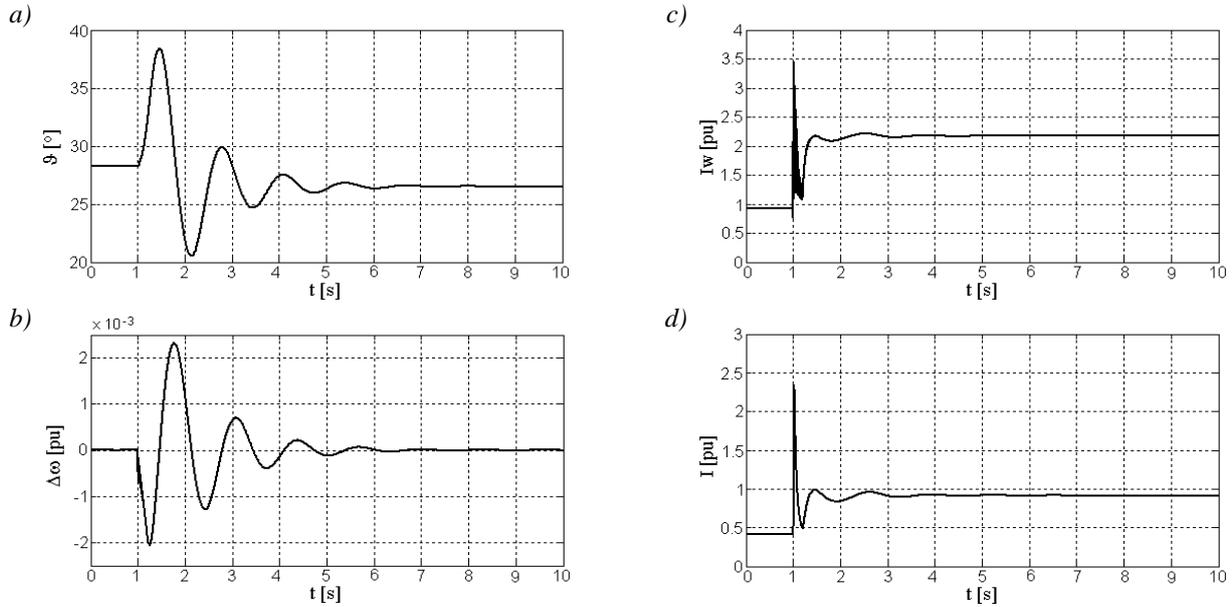


Fig. 14. Voltage change from U_N to $0.6U_N$ in time $t=1$ s for $P=0.6P_N$ and change of excitation current forcing from $I_w=0.51I_{wN}$ to $1.21I_{wN}$ in time 1.2 s: a) load angle ϑ , b) speed deviation $\Delta\omega$, c) excitation current I_w , d) stator current I

Separate tests should be conducted to determine the duration of a voltage dip after which the excitation current forcing should begin. At short voltage dips a considerable moment of inertia can help to keep the motor in the synchronous state and, if the motor falls out of synchronism, can even make it return to synchronous work.

Figures 15-16 present the results of dynamic states simulation tests at a voltage dip to $0.6U_N$ lasting 1 s and 5 s and excitation current of $0.51I_{wN}$ with no forcing procedures.

For the conditions from Fig. 16, there was a short fall-out from synchronous work. In this case the excitation current forcing procedure should be initiated no later

than 2 s (load angle about 90°) from the beginning of a voltage dip.

In practical solutions, excitation current forcing begins immediately after the set level of supply voltage is exceeded. This is due to long time constants of excitation which may last up to 2-3 seconds. They may cause a situation when the change of the excitation current to the value allowing to keep the motor in synchronous work is too late. Often, to increase the dynamics of current changes in the excitation circuit, in the initial stage of the forcing procedure the enforced voltage is higher than the forcing voltage, and when the excitation current value is suitable, the voltage decreases to the value corresponding to the current forcing value.

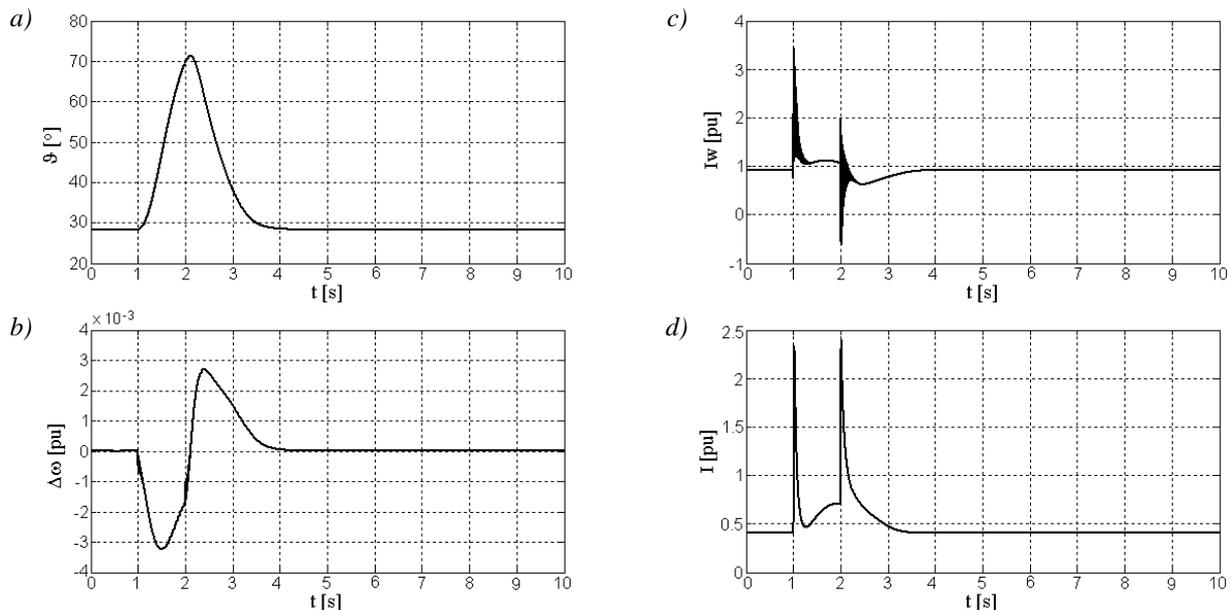


Fig. 15. Voltage change from U_N to $0.6U_N$ in time $t=1$ s and to U_N in time $t=2$ s for $P=0.6P_N$ $I_w=0.51I_{wN}$: a) load angle ϑ , b) speed deviation $\Delta\omega$, c) excitation current I_w , d) stator current I

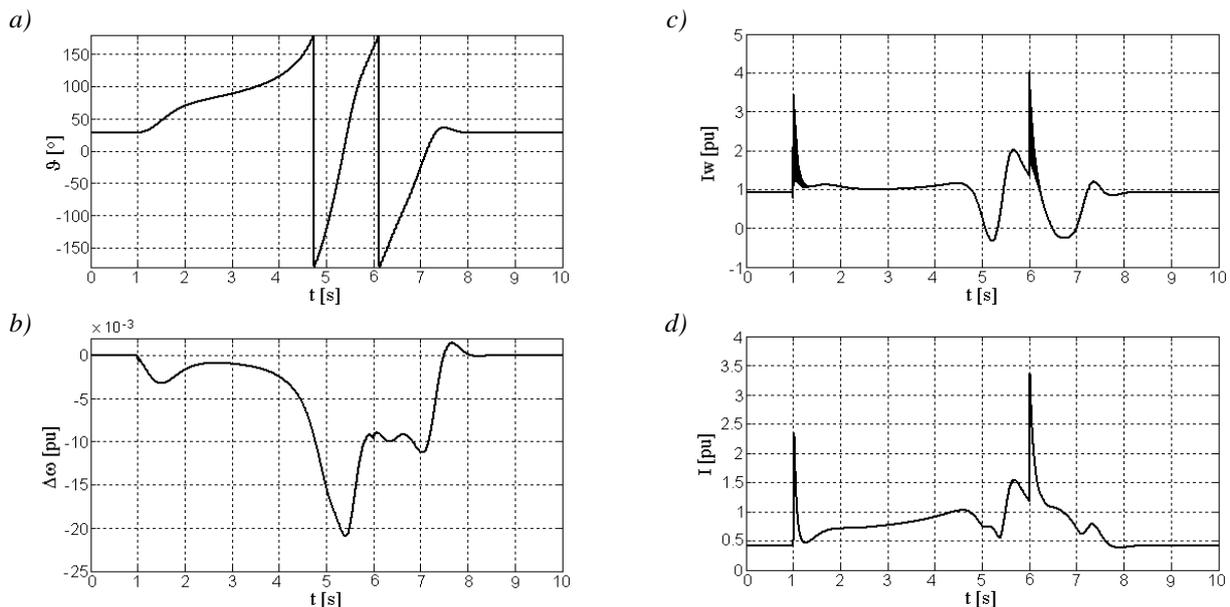


Fig. 16. Voltage change from U_N to $0.6U_N$ in time $t=1$ s and to U_N in time $t=6$ s for $P=0.6P_N$, $I_w=0.51I_{wN}$:
 a) load angle ϑ , b) speed deviation $\Delta\omega$, c) excitation current I_w , d) stator current I

If voltage dips are short, the current in the excitation circuit usually does not have enough time to increase to the current forcing value, while the return to the acceptable value breaks the forcing procedure.

5. CONCLUSIONS

The article features the impact of voltage dips on the operation of a synchronous motor in the state of synchronism.

Based on static characteristics and simulation tests it is possible to determine an acceptable range of the excitation current regulation for the purposes of reactive power compensation. As it is possible to have operations with reduced excitation current, it is necessary to determine the voltage level at which the excitation current forcing procedure should be followed in order to keep the motor in the state of synchronous work.

Proper selection of settings for the regulation system allows safe operations of the motor in the state of synchronism, within suitable excitation current and supply voltage values. This way it is possible to use an underloaded synchronous motor as a follow-up reactive power compensator with no worry about possible improper work of the drive.

Numerous industrial experiences of using a microprocessor supply block of a synchronous motor [4] show that the possibility to enforce the excitation current of a properly selected value during a voltage dip will often allow to keep the motor in the state of synchronous work. This would not be possible without automatic and fast current increase in the excitation circuit.

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