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doi:10.15199/48.2020.04.38

Analysis of synchronous motor with the periodically variable load using small signal oscillation method

***Abstract**. The article presents the methodology for testing dynamic states of a large-power salient-pole synchronous motor with a periodically variable load using the method of small oscillation stability. The analytical relationship taking into account the periodically variable load, which enables to obtain results without the need for numerical integration, is presented. The possibility of decreasing the motor field current in terms of using the motor in the automatic reactive power compensation system was considered. The effect of voltage dips on the motor's operation was investigated. Selected research results have been presented and discussed. The method errors have been discussed.*

Streszczenie.** W artykule przedstawiono metodykę badań stanów dynamicznych silnika synchronicznego jawnobiegunowego dużej mocy z okresowo zmiennym obciążeniem metodą małych wychyleń wirnika. Przedstawiono zależność analityczną uwzględniającą okresowo zmienny charakter obciążenia umożliwiającą uzyskanie wyników bez konieczności całkowania numerycznego. Rozpatrzono możliwość obniżenia prądu wzbudzenia silnika pod kątem wykorzystania w systemie automatycznej kompensacji mocy biernej. Zbadano wpływ zapadów napięcia na pracę silnika. Zamieszczono i omówiono przykładowe wyniki badań. Omówiono błędy metody. **(Badanie silnika synchronicznego z obciążeniem okresowo zmiennym metodą małych wychyleń wirnika)

Keywords: synchronous motor, reactive power compensation, compressor type load, small oscillation stability
Słowa kluczowe: silnik synchroniczny, kompensacja mocy biernej, obciążenie sprężarkowe, małe wychylenia wirnika

Introduction

Large-power low-speed synchronous motors are used, among others for driving compressors and piston pumps [1, 2]. A characteristic feature of this drives type is the periodic variability of load torque. It causes the motor is not working with a constant power angle but is subjected to constant dynamic actions due to the uneven, periodically variable torque on the machine shaft [3, 4] and rotational speed fluctuations. This feature affects also the stability conditions of the propulsion system.

The drive motors of compressors and piston pumps usually work with an average load torque less than the rated one, enabling their use in automatic reactive power compensation systems [5, 6, 7, 8, 9, 10] understood as reactive power compensation of the fundamental current and voltage harmonic. Due to the variability of operating conditions caused by the nature of the load, the mean value of reactive power is compensated [11].

The reactive power of the synchronous motor is controlled by the field current. A change in the field current causes a change in the power angle, which affects the stability of the propulsion system. Due to the inertia of the propulsion system and the effect of the damping windings, the variation of the power angle does not reflect the shape of the load torque changes.

The need to keep the motor in a synchronous mode of operation determines the maximum permissible value of the power angle in transient and steady-state, and thus the allowable control range of field current and reactive power.

The purpose of the article is to present the use of the small oscillation method to examine the impact of load torque variability on the stability of the motor in the synchronous state with changes in field current resulting from reactive power control and assumed voltage dips.

Compressor-type periodically variable load

Figure 1 presents the mechanical power waveform of periodically variable compressor-type load [12] being an approximation of the actual changes in the load torque of piston compressor drives.

The large-power compressors are usually driven by a low-speed synchronous motors directly coupled [13]. The frequency of load torque changes therefore results directly from the rotational speed of the motor.

A similar nature of load torque changes occurs in piston pump drive systems. Piston pumps are low-speed machines and for this reason they are coupled to drive motors via gearboxes of various types [13]. In this case, the frequency of load torque changes is less than the frequency resulting directly from the motor speed.

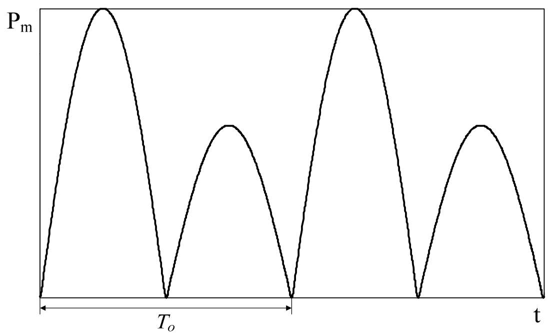

Fig.1. Waveform of compressor-type load: T_o - period

The waveform of the shape from Figure 1 can be described by the equation

$$P_m = P_{av}\left(\frac{\pi(1-B_o)}{2(1+B_o)}\sin\left(\frac{2\pi t}{T_o}\right)-1-2\sum_{n=0}^{\infty}\frac{\cos\left(\frac{4\pi nt}{T_o}\right)}{4n^2-1}\right), \quad (1)$$

where: P_{av} - average value, B_o - the ratio of the maximum value in the second half of the period to the maximum value in the first half of the period, T_o - period

A sufficiently accurate approximation is obtained when in the equation (1) only the first 10 elements of the series is taken.

Forced oscillations of the harmonic oscillator

The generalized harmonic oscillation equation with forcing can be represented in the form

$$\frac{d^2x}{dt^2}+2\beta\frac{dx}{dt}+\omega_0^2 x = F_o + F(t), \quad (2)$$

where: β - damping factor, ω_0 – natural frequency, F_o – permanent force, $F(t)$ – periodic variable force.

Assuming that the time-dependent force component is described by the equation

$$F(t) = P_o \left[\frac{\pi}{2} \frac{(1-B_o)}{(1+B_o)} \sin(\omega(t_0+t)) - 1 - 2\sum_{n=0}^{\infty} \frac{\cos(2\omega n(t_0+t))}{4n^2-1} \right] \quad (3)$$

where

$$\omega = \frac{2\pi}{T_o}, \quad (4)$$

and t_0 - time shift, the solution of the differential equation (2) was determined by analytical method, at initial conditions

$$x_{(t=0)} = x_0, \quad (5)$$

and

$$\left.\frac{dx}{dt}\right|_{t=0} = \Delta x_0. \quad (6)$$

This solution can take one of three forms, depending on the sign of the discriminant

$$\Delta = \beta^2 - \omega_0^2. \quad (7)$$

For the condition $\Delta<0$, i.e. the state in which the suppression of the damped component is oscillatory, the solution is the equation

$$\begin{aligned} x(t) = &-2P_o \sum_{n=0}^{\infty} \frac{1}{4n^2-1} \left[\frac{4n\beta\omega \cdot \sin(2\omega n(t_0+t))}{(4n\beta\omega)^2 + \left(\omega_0^2-(2n\omega)^2\right)^2} + \frac{\left(\omega_0^2-(2n\omega)^2\right)\cdot \cos(2\omega n(t_0+t))}{(4n\beta\omega)^2 + \left(\omega_0^2-(2n\omega)^2\right)^2} \right] \\ &-P_o \frac{\pi(1-B_o)}{2(1+B_o)} \left[\frac{2\beta\omega \cdot \cos(\omega(t_0+t))}{(2\beta\omega)^2 + \left(\omega_0^2-\omega^2\right)^2} - \frac{\left(\omega_0^2-\omega^2\right)\cdot \sin(\omega(t_0+t))}{(2\beta\omega)^2 + \left(\omega_0^2-\omega^2\right)^2} \right] \\ &+ e^{-\beta t} \left[\frac{x_0\beta + \Delta x_0}{\sqrt{\omega_0^2-\beta^2}} \sin\left(\sqrt{\omega_0^2-\beta^2}\, t\right) + x_0 \cos\left(\sqrt{\omega_0^2-\beta^2}\, t\right) \right] \\ &+ \frac{F_o - P_o}{\omega_0^2}. \end{aligned} \quad (8)$$

This equation allows to get the result for any time t without the need for stepwise calculations.

Rotor small oscillation method

The rotor small signal oscillation method is used to test the local stability of propulsion systems around the equilibrium point [14, 15, 16].

For the motor operation of a synchronous machine, the equation of motion can be represented in the form

$$T_e - T_m - \frac{D_r}{p}\omega_s + \frac{D}{p\omega_s}\frac{d\vartheta}{dt} = -\frac{J}{p}\frac{d^2\vartheta}{dt^2}, \quad (9)$$

where: T_m – mechanical torque, D_r – damping factor from friction, D – damping factor from the torque generated by the damping windings, T_e – electrical torque, J – moment of inertia, p – number of pole pairs, ω_s- synchronous pulsation.

By multiplying the equation (14) on both sides by ω_s and dividing by p, after the transformations, the following equation is obtained:

$$P_e - P_m - \frac{D_r}{p^2}\omega_s^2 + \frac{D}{p^2}\frac{d\vartheta}{dt} = -\frac{J}{p^2}\omega_s \frac{d^2\vartheta}{dt^2}. \quad (10)$$

Assuming small rotor deflections $\Delta\vartheta$ from equilibrium at a power angle ϑ_0, it can be assumed

$$\vartheta = \vartheta_0 + \Delta\vartheta \quad (11)$$

and

$$\sin(\vartheta_0 + \Delta\vartheta) \approx \sin\vartheta_0 + \Delta\vartheta\cos\vartheta_0, \quad (12)$$

what allows to linearize the differential equation (10) to a form

$$(P_{e0} + \Delta\vartheta\Delta P_e) - P_m - \frac{D_r}{p^2}\omega_s^2 + \frac{D}{p^2}\frac{d\Delta\vartheta}{dt} = -\frac{J}{p^2}\omega_s \frac{d^2\Delta\vartheta}{dt^2} \quad (13)$$

in which:

$$P_{e0} = m\left(\frac{E_f U_p}{X_d}\sin\vartheta_0 + \frac{U_p^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\vartheta_0 \right), \quad (14)$$

$$\Delta P_e = m\left(\frac{E_f U_p}{X_d}\cos\vartheta_0 + U_p^2\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\cos 2\vartheta_0 \right), \quad (15)$$

where: P_{e0} – active power at a fixed duty point, ΔP_e – change in active power associated with knocking the system out of equilibrium, m – number of phases, E_f – electromotive force of the excitation depends on the field current, U_p – phase voltage, X_d, X_q – synchronous reactance in *d* and *q* axis respectively.

In the case when the mechanical power is a function of the time of the compressor-type load represented by equation (1), the equation of the suppressed harmonic oscillator with the excitation of the form (2) is obtained, for which, assuming $\Delta<0$,

$$\beta = \frac{D}{2J\omega_s}, \quad (16)$$

$$\omega_0 = p\sqrt{\frac{\Delta P_e}{J\omega_s}}, \quad (17)$$

$$F_o = \frac{D_r}{J}\omega_s - \frac{p^2}{J\omega_s}P_{e0}, \quad (18)$$

and $F(t)$ is described by equation (3), where

$$P_o = \frac{p^2}{J\omega_s}P_{av}. \quad (19)$$

Substituting (16-19) to (8), an analytical relationship is obtained describing the deviation of the power angle $\Delta\vartheta$ from the equilibrium angle ϑ_0 as a function of time.

The synchronous motor researches

The object of the study was a GAP1512s/01 salient-pole synchronous motor with rated data presented in Table 1. The motor was used to drive the compressor. Excitation winding was supplied with a microprocessor-controlled power block with a reactive power regulator [8].

The reactive power regulation is carried out by controlling the current in the motor excitation circuit during synchronous operation.

The tests were carried out by the rotor small signal oscillation method.

Table 1. Rated data of GAe1512s/01 synchronous motor

Parameter	Symbol	Value
Mechanical power	P_{mN}	1600 kW
Electrical power	P_N	1665 kW
Stator voltage	U_N	6000 V
Stator current	I_N	178 A
Excitation voltage	U_{fN}	105 V
Field current	I_{fN}	185 A
Frequency	f_N	50 Hz
Rotor speed	n_N	500 rpm
Power factor	$\cos\varphi_N$	0.9 cap.
Power angle	ϑ_N	24.8 °

Assuming a constant electrical power load of $0.7P_N$, voltage supply U_N and limiting the power angle to ϑ_N, the range of filed current regulation was determined based on static characteristics as from I_{fmin}=107 A to $I_{fmax}=I_{fN}$.

Steady-state power angle values ϑ_0 and critical angle ϑ_{cr} at lowered supply voltage $0.8U_N$ were also determined. The results are shown in Table 2.

Table 2. Values determined on the basis of static characteristics at an electric power load of $0.7P_N$

U	I_f	ϑ_0 [°]	ϑ_{cr} [°]
U_N	I_{fN}	16.8	70.0
$0.8U_N$	I_{fN}	22.8	72.9
U_N	I_{fmin}	24.8	63.0
$0.8U_N$	I_{fmin}	36.5	65.9

The motor was loaded with a mechanical torque with a compressor characteristic of the frequency of 8.33 Hz, the coefficient of B_o=0.7 and an average value, with mechanical losses taking into account, consuming the average electrical power of $0.7P_N$.

Figures 2-4 show the waveforms of the power angle after quenching the damped component and trajectories associated with the speed deviation and rotor acceleration determined by differentiation and double differentiation the equation (8). The results obtained for the operation of the motor with rated and reduced field current are presented.

As can be seen, for the assumed load parameters, in both cases the power angle oscillations are small, within 1 degree. It is caused by the assumed value of the moment of inertia of the propulsion system and the effect of the damping windings.

Based on Table 2 and the power angle oscillation value, it can be stated that the operation of the motor with the field current reduced to the I_{fmin} value does not cause a danger of falling out of synchronism.

Changes in rotor acceleration adversely affect the mechanical components of the drive system, resulting in accelerated wear of the bearings. Based on Figures 2-4, it can be stated that lowering the field current to the I_{fmin} value does not cause deterioration of the mechanical conditions in relation to operation with the rated field current, and the differences in speed and acceleration changes are practically the same.

One of the most troublesome phenomena in the exploitation of synchronous motors is the supply voltage dip causing a decrease in the value of the torque developed by the motor. This type of phenomena may lead to an increase in the power angle above the permissible value and the motor falling out of synchronism [9].

In practice, when the supply voltage decreases to a certain value, the field current forcing procedure [9] is used

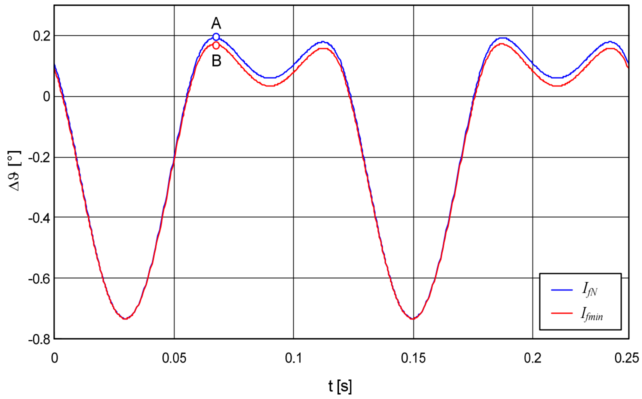

Fig.2. Power angle deviation from the stable value for the load P_{av} for the field current I_{fN} and I_{fmin}

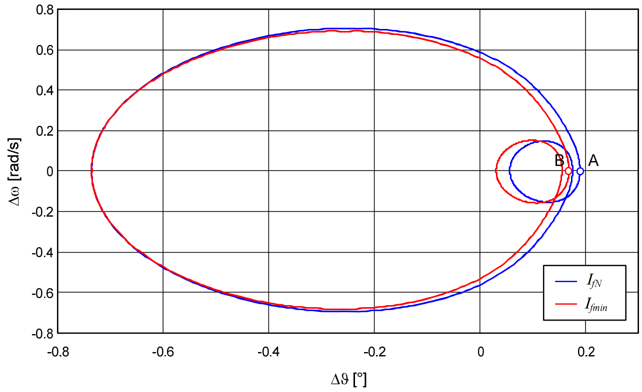

Fig.3. Rotational speed deviation trajectory depending on the power angle deviation for the field current I_{fN} and I_{fmin}

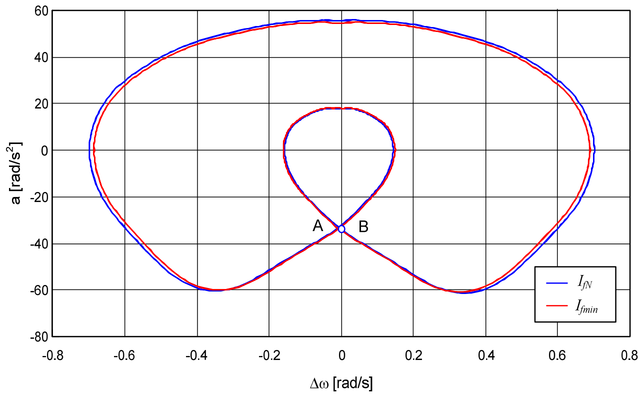

Fig.4. Acceleration trajectory depending on the speed deviation for the field current I_{fN} and I_{fmin}

to increase the torque developed by the motor and keep it in synchronous operation.

An important aspect is to know the behaviour of the motor during a supply voltage dip when the procedure of field current forcing has not been yet initiating.

It the research was assumed a voltage dip of $0.8U_N$ occurring at the moment when the power angle reaches the highest value. These points are marked in Figures 2-5 with the symbols A (for field current I_{fN}) and B (for field current I_{fmin}). A symmetrical voltage dip was assumed in each phase.

The relation (8) allows testing of transient states after changing the motor operating conditions by determining the power angle and motor shaft speed at any moment t before the change of state and taking into account the values obtained in the initial conditions for the changed operating state. The load phase at the time of the change of the operating state is taken into account by the parameter t_0.

Figures 5-7 show the waveforms of the power angle and trajectories associated with the speed deviation and rotor acceleration for motor operation with rated and reduced field current. Points A_0 and B_0 mean the initial conditions for a new motor operating condition determined on the basis of points A and B at the time of supply voltage dip.

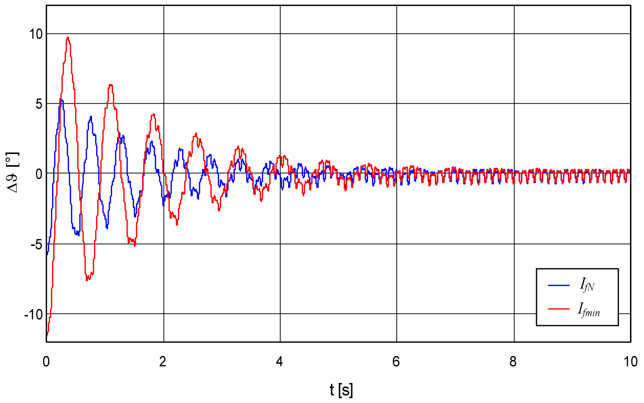

Fig.5. Power angle deviation from the stable value for the load P_{av} at a voltage dip to $0.8U_N$ for the filed current I_{fN} and I_{fmin}

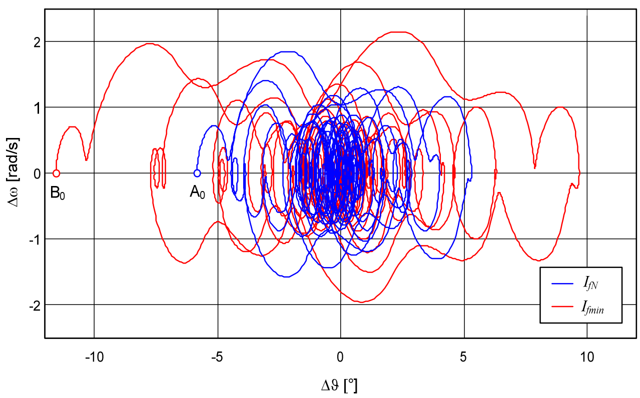

Fig 6. Rotational speed deviation trajectory as a function of the power angle deviation at a voltage dip to $0.8U_N$ for the field current I_{fN} and I_{fmin}

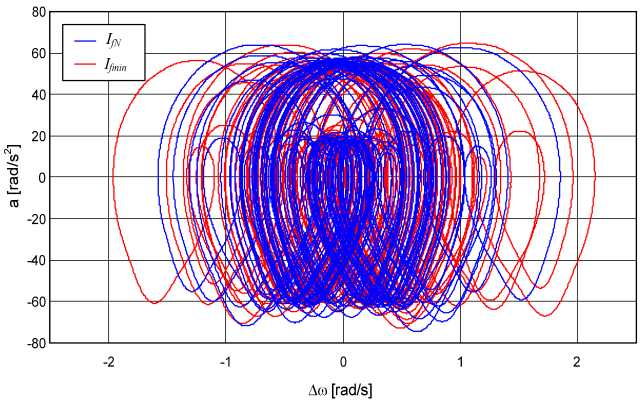

Fig 7. Acceleration trajectory as a function of the speed deviation at a voltage dip to $0.8U_N$ for the field current I_{fN} and I_{fmin}

As can be seen in Figures 5-7, the supply voltage dip causes the motor to move with oscillations to new steady-state conditions, which is accompanied by increased speed oscillations in relation to oscillations resulting from the variability of the motor load. There are also temporary, over a dozen percent increases in rotor shaft acceleration.

Based on Table 2 and the oscillation value of the power angle, it can be stated that even when the motor is operating with the field current reduced to the I_{fmin} value, the dip in supply voltage to $0.8U_N$ does not cause a danger of falling out of synchronism, and the suppressed component expires after about 10 seconds.

The method errors analyses

The rotor small signal oscillation method, by assuming E_f=*const*, does not take into account all electromagnetic phenomena occurring in the motor.

At the same time, the linearization of equation (10) at a point corresponding to the power angle for the average load value ϑ_0 means that in the entire considered oscillation range the torque increase in relation to the increase in the power angle has a constant value, this is the same as at the assumed equilibrium point, i.e.

$$\frac{dT_e}{d\vartheta} = \left.\frac{\Delta T_e}{\Delta\vartheta}\right|_{\vartheta=\vartheta_0} > 0\,. \tag{20}$$

Therefore, the greater the deviation from the equilibrium point, the greater the calculation errors of the method.

The method also does not take into account the condition

$$\left.\frac{dT_e}{d\vartheta}\right|_{\vartheta>\vartheta_{cr}} < 0\,, \tag{21}$$

i.e. changes in the sign of the torque increase in relation to the increase of the power angle after exceeding the critical angle.

In the considered cases, this situation did not take place. However, obtaining results with angles close to the critical angle in a real motor can lead to falling out of synchronism.

Summary and conclusions

The rotor small oscillation method, despite the fact that it is based on the linearization of the relationship of the torque increase in relation to the increase of the power angle at a fixed operating point, allows to obtain a good approximation of the motor behaviour under periodically variable operating conditions related to the load type. It also allows examination of transient states when working conditions change.

Obtaining description of discussed process as an analytical function (8) allows researching without the need to use simulation tools based on numerical integration and to obtain the result for any time range without the need for stepwise calculations.

Periodically varying loads can lead to mechanical resonance. For a load with the form described by the relation (3), the possibility of resonance phenomena depends on the values of the coefficients β, ω_0, ω and B_o.

The non-linear dependence of the natural frequency of the motor on the load and the excitation level [12] cause that the problem of mechanical resonance is complex and should be the subject of special attention and additional research.

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