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OPTIMIZATION OF DUTY OF SYNCHRONOUS MOTORS IN CENTRIFUGAL MACHINERY IN MINING

The article discusses the MATLAB Simulink-based model of a synchronous motor of centrifugal machinery which is common in the mining and processing industry. The computer modeling includes the characteristic static and dynamic modes of the motor. In the static conditions, the energy saving and stability control of a synchronous motor via the excitation channel is contradictory: the increase in the energy efficiency causes decreases the stability factor of the motor and vice versa. The possibility of increasing the operation stability of a synchronous motor at short-term losses of power supply–voltage falls on the stator winding–is studied. In the dynamic conditions of the motor, the combination of the cyclic excitation control and the frequency control via the frequency converter of the frequency-variable drive favors the self-synchronization of the synchronous motor during the long voltage falls, which allows reducing the events of the motor re-synch with the field killing and accelerates the normal operation recovery of the motor.

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Introduction

Synchronous motors actuate centrifugal fans [1–3], drain pumps, hoists and other machines in mines [4, 5]. This study focuses on a synchronous motor of centrifugal machinery widely employed in mining and in other industries [6–8]. Large synchronous motors in operation in the mining industry may have capacity up to 5 MW [2, 9]. Although more complex and more expensive as compared with asynchronous motor, the synchronous motors offer better power adjustability, are less metal-intensive and soundly compete with the asynchronous motors in higher capacity electric operations. Advancement of converting equipment open new ways to improve synchronous motors. Variable frequency drives simplify starting and self-starting of motors, and improves controllability and performance of synchronous motors [4, 9, 10].

Research objective and subject

A disadvantage of synchronous motors is their sensitivity to short-term interruptions of supply—main voltage falls which can destabilize a motor and kick it out of the in-sync operation [11, 12], which requires implementing complex control algorithms for power and technology processes. This research objective is to develop the automated controllability of a synchronous machine in transient modes to lessen the need of resynchronization of the motors. The task solving uses the mathematical modeling [8, 11–15].

The subject of the research is a synchronous motor of a mine drain pumping station with centrifugal pump TSNS 850-720 (Yasnogorsk Pump Plant) and synchronous drive SDP2-140-2500/6 (Ruselprom. Electric Machines). The ratings of the motor include: the capacity of 2500 kW, the voltage of 6 kV, the efficiency of 96%, the power factor cosφ of 0.9 and the speed of 1500 min^{-1}. The mechanical time constant of the motor is 2.2 s.

The mathematical model of a synchronous motor is a system of normalized operator equations for the projections of the generalized vectors of currents, voltages and flux linkages in the coordinates *d*–*q*, in the axis connected with the rotor; this system of equations describes the transient electromagnetic processes in a synchronous motor with damping winding [11, 15]:

$$
\begin{aligned}
&p\psi_{1d} = \omega_{0b}(u_{1d} - i_{1d}R_1 + \omega_0\psi_{1q});\\
&p\psi_{1q} = \omega_{0b}(u_{1q} - i_{1q}R_1 - \omega_0\psi_{1d});\\
&p\psi_f = (u_f - i_f)/T_f;\\
&p\psi_D = -\,i_D/T_D;\\
&p\psi_Q = -\,i_Q/T_Q;\\
&i_{1d} = (\psi_{1d} - i_f - i_D)/x_D;\\
&i_{1q} = (\psi_{1q} - i_Q)/x_q;\\
&i_f = \psi_f - (1-\sigma_f)x_d i_{1d} - \mu_f i_D;\\
&i_D = \psi_D - (1-\sigma_D)i_f - \mu_D x_D i_{1d};\\
&i_Q = \psi_Q - (1-\sigma_Q)x_q i_{1q};\\
&\mu_f = M_{Df}M_{df}/(L_f M_{dD});\\
&\mu_D = M_{Df}M_{dD}/(L_D M_{df}),
\end{aligned}
\qquad (1)
$$

where ψ_{1d}, ψ_{1q} are the flux linkages in the winding along the relevant axes; $\omega_{0b} = 2\pi f_n$ is the reference circular frequency at the stator at the nominal frequency f_n ; ω_0 is the relative line frequency at the stator at the non-nominal mains frequency f; ψ_{1d}, ψ_{1q} and i_{1d}, i_{1q} are the flux linkages and the stator currents along the relevant axes; R_1 is the active resistance in the stator winding; ψ_f is the flux linkage in the drive winding; i_f is the current in the drive winding; ψ_D, ψ_Q, i_D, i_Q are the flux linkages and the currents in the damping winding along the axes *d* and *q*, respectively; $M_{dD} = M_{Dd}$ is the mutual inductance between the stator winding and the damping winding along the axis *d*; $M_{qQ} = M_{Qq}$ is the mutual inductance between the stator winding and the damping winding along the axis *q*; $M_{fD} = M_{Df}$ is the mutual inductance between the drive winding and the damping winding along the axis *d*; T_f is the time constant of the drive winding; L_D, L_f are the inductance of the damping winding along *d* and the inductance of the drive winding; T_D, T_Q are the time constants of the damping winding along the axes *d* and *q*, respectively; $(1-\sigma_D)(1-\sigma_Q)$ are the coupling coefficients between the stator and the damping windings along the axes *d* and *q*, respectively; μ_f, μ_D are the coupling coefficients between the drive and the damping windings along the axis *d*.

Alongside with the reference circular frequency ω_{0b}, the reference

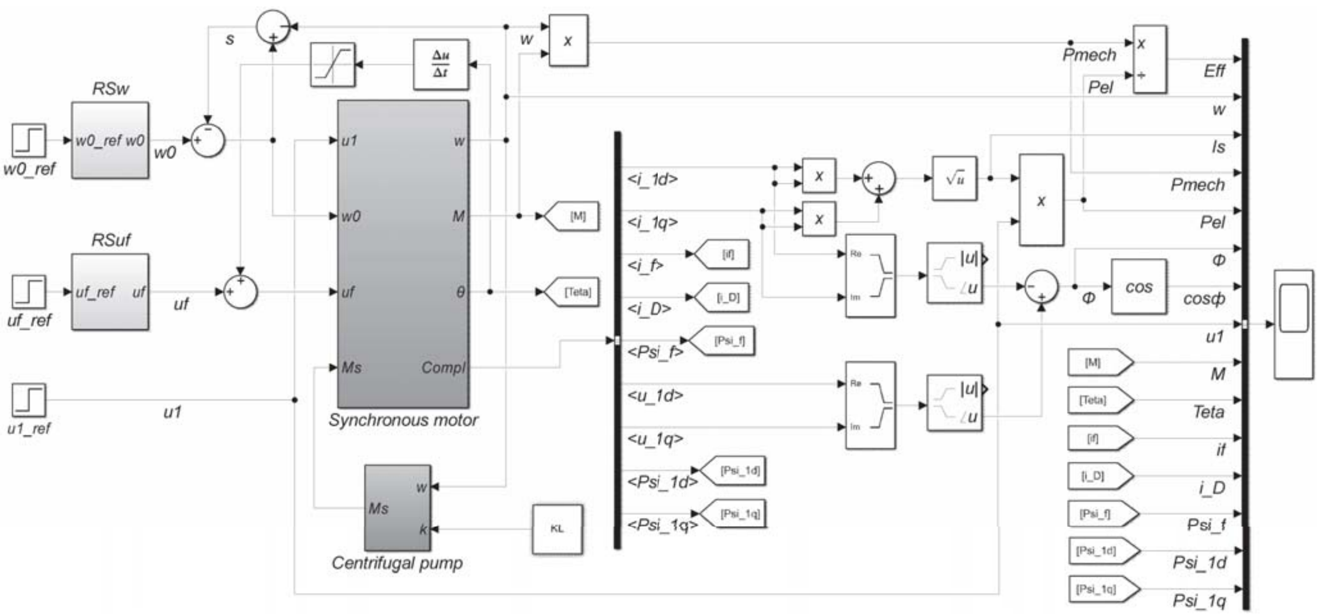

Fig. 1. Simulation model of motor

values include: the reference voltage of the stator, expressed in terms of the nominal voltage $U_{1b} = U_{1n} - \sqrt{2}$; the reference current of the stator, expressed in terms of the nominal current $I_{1b} = I_{1n}\sqrt{2}$; the reference resistance $Z_b = U_{1b}/I_{1b}$; the reference flux linkage of the stator windings $\psi_{1b} = U_{1b}/\omega_{0b}$; the reference inductance $L_b = \psi_{1b}/I_{1b}$; the reference momentum $M_b = (3/2)p_n\psi_{1b}I_{1b}$, where p_n is the number of poles pairs.

The mechanical part of the motor is described with the normalized equation of dynamics:

$$p\omega = (m_d - m_s)/T_M, \quad (2)$$

where p is the operator; m_d is the drive momentum; m_s is the resistance momentum; T_M is the mechanical constant of time.

The electromagnetic moment of the synchronous motor is defined by the scalar product of the flux linkage vector and the stator current vector

$$m_d = \psi_{1d}i_{1q} - \psi_{1q}i_{1d}, \quad (3)$$

where ψ_{1d}, ψ_{1q}, i_{1d}, i_{1q} are the components of the flux linkage and the stator winding current in the relevant axes.

The resistance moment of a centrifuge gear is proportional to the squared velocity. In terms of the relative units, it is given by

$$m_s = m_0 + (k_L - m_0)\omega^2, \quad (4)$$

where m_0 is the breakaway torque of the centrifuge gear; k_L is the coefficient of load; ω is the rotor speed.

The torque angle in radians is expressed in terms of speeds in relative units

$$\theta = \omega_{0b}(\omega_0 - \omega)/p, \quad (5)$$

where $\omega_{0b} = 2\pi f_n$ is the reference circular frequency at the stator at the nominal frequency f_n; ω_0 is the relative frequency at the stator at the non-nominal frequency f.

On this basis and using MATLAB Simulink, the simulation model of a synchronous motor of a centrifugal pump with a static actuator was developed in [11]. This mode is modified in this study, and is added with an extended list of epy output parameters (**Fig. 1**).

The input data of the motor are found using the procedure from [16]. The input data of the model include the stator voltage, stator frequency, exciting winding voltage and the resistance of the working gear.

The output parameters of the model are the motor moment, rotor speed, torque angle, the stator and rotor currents and flux linkages, as well the power characteristics of the drive: the total power intake, effective horse power, efficiency and the power factor. The initial duty is assumed to be the mode of a perfect idle travel when $\omega_{init} = \omega_0$, $\theta_{init} = 0$. The modeling used also the parameters of the standard static exciting devices. The demand factor in the examples below was assumed as $k_L = 0.75$ unless otherwise stipulated.

Results

Let as discuss adjustment of static operating modes of a nonadjustable synchronous motor. A synchronous motor has two control channels: the static circuit and the actuation circuit. Adjustment via the stator circuit is possible in the variable frequency drives. Adjustment via the actuation circuit is carried out in the speed-variable and speed-invariable drives. The automatic excitation control (AEC) is commonly used in synchronous motors to improve performance of the motor and the mains. The excitation control of a synchronous motor has different tasks in the static and dynamic modes [16–18].

The static duty control aims to minimize power loss in the motor and in the mains, and to maintain voltage in the load center connected with the motor.

For the powerful synchronous motors of pumps, with smoothly variable speed, operating under conditions of minor voltage fluctuations in the mains, it is expedient to maintain the power factor close to one to minimize the power loss in the motor and in the mains [16, 18, 19]. A power supplier forbids as a rule to run the powerful synchronous motors in the nominal excitation mode at $\cos\varphi = 0.9$ with the capacitive power generation in the mains because of the excessive capacitive power in the long-distance transmission circuits in external supply lines. The indicators of the energy efficiency of a synchronous motor may be the efficiency η and the power factor cosφ. For the pumping stations using synchronous motors and having low asynchronous load, when the listed parameters have values closer to one, the duty of the electrics of the station is more economically efficient.

In the dynamic modes, AEC is to ensure stability of a synchronous motor in the events of voltage falls or shaft load changes [3, 11, 16, 20]. An indicator of the motor stability may be the operating angle θ: as the operating angle gets closer to the critical value of $\pi/2$, the stability factor of a synchronous motor reduces.

In the speed-invariable motors, the control only uses the excitation channel. In certain ranges, there is a possibility of the uncontrollable variation in the motor supply voltage and in its load—shaft power. By way of illustration, **Fig. 2** shows the curves of the efficiency, working angle θ and voltage u_1 at different demand factors k_L, which govern the shaft drag torque, and at different excitation currents i_f. All parameters listed, except for the angle θ, hereinafter are given in relative units, and the working angle is measured in degrees. The curves result from the simulation modeling accomplished. It should be mentioned that the efficiency curves almost follow the power factor curves plotted for the same conditions but omitted in this paper. The curves of the efficiency reveal that the increase in the excitation current within the ranges of the real-life loads and voltages of the stator increases the energy efficiency of the motor, reduces the working angle and enhances the stability factor of the motor.

Thus, in the static modes, the energy saving and stability control via the excitation channel is contradictory as the energy characteristics rise but the safety factor drops, and vice versa.

Regarding the static mode control of a synchronous frequency-variable motor, the controllable input parameters are the stator winding voltage U_1, the stator frequency f_1 and the excitation winding current i_f. The electromagnetic torque of the synchronous non-salient pole moto can be given by:

$$M = A\frac{U_1 i_f}{f_1}\sin\theta, \quad (6)$$

where A is a constant.

The speed control is carried out via adjustment of the supply voltage frequency. When the frequency is varied at the constant stator voltage and excitation current, it follows from formula (6) that the torque of the motor grows and the load angle decreases as the frequency is lowered. The modeling shows that the decrease in the frequency by 10% at the nominal voltage of the stator winding results in the same decrease in the working angle; the frequency decrease at the lower voltage increases the working angle.

For the stable operation of a synchronous motor during frequency adjustment, it is desirable to ensure the constant working angle θ and to limit its fluctuations in the dynamic modes. On the assumption that θ = const and (6), the law of the synchronous motor control in transition from the initial duty to a j-th speed mode can be given by [1]:

$$U_{1(j)} i_{f(j)}/(U_1 i_f) = M_{(j)} f_{1(j)}/(M f_1). \quad (7)$$

It follows from (7) that at the variable excitation i_f = var, the frequency adjustability law subject to the constant load angle for a motor of a centrifugal pump at the drag torque M_S proportional to the squared speed ω^2 takes on the form of:

$$U_1/f_1^2 = \text{const},\ i_f \sim f_1 \text{ at } M_s \sim \omega^2. \quad (8)$$

It is more difficult to maintain an invariable load angle in the dynamic mode as the rate of variation in the frequency should agree with the

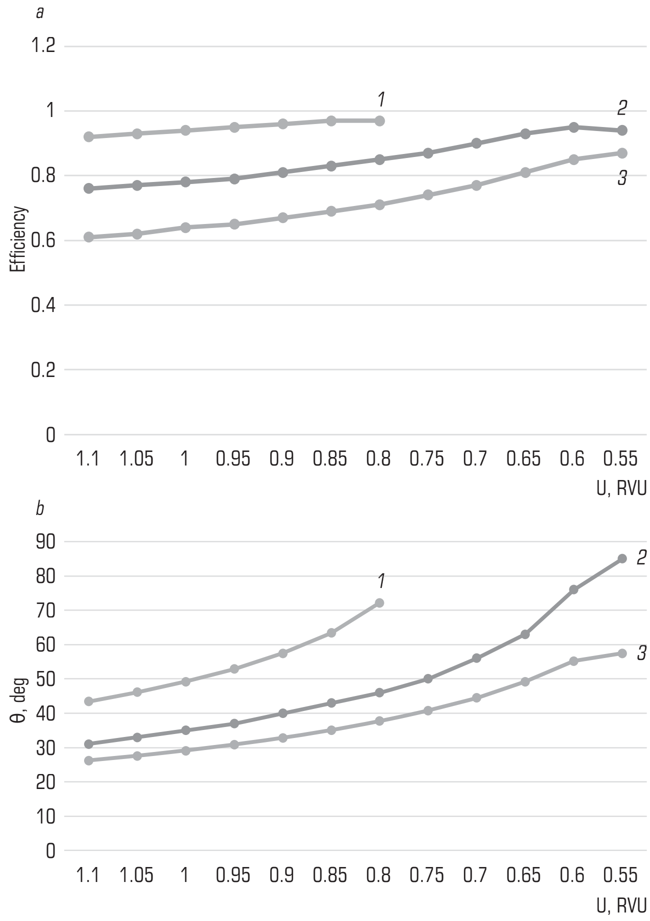

Fig. 2. Motor efficiency versus voltage at different loads and excitation currents: 1. $k_L = 0.9$; $i_f = 0.9$; 2. $k_l = 0.75$; $i_f = 1$; 3. $k_L = 0.75$; $i_f = 1.2$ (*a*) and working angle θ versus voltage U at different loads and excitation currents: 1. $k_L = 0.9$; $i_f = 0.9$; 2. $k_l = 0.75$; $i_f = 1$; 3. $k_L = 0.75$; $i_f = 1.2$ (*b*)

momentum of inertia of the motor in order to avoid the asynchronous operation, which limits the application of the scalar control laws of the frequency-variable synchronous motors, and the better dynamics results from the vector control and an ac converter-fed motor system.

Let us consider the dynamic mode operation of a synchronous motor. The initial mode in the modeling is the synchronous duty at the nominal values of the stator voltage, stator frequency, excitation voltage and the demand factor $k_L = 0.75$. The initial values of the orthogonal components in the flux linkages of the stator windings, rotor and damping winding are found from solving a system of equations of an electromagnetic model constructed for a synchronous motor in transition to a stable operation mode [11, 15]. The transient processes in the motor operation can result from the uncontrollable impacts due to the change in the load of the working gear, or because of the perturbations in the supply mains with voltage falls. The dynamic modes resultant from the change of the load can violate stability—the motor falls out of synchronism when the load demand jumps above the nominal values in the absence of AEC. For instance, in the developed model, the loss of synchronism takes place if the demand factor k_L changes from 0.5 to 1.2 within 30 s at the unaltered excitation current. The controllable variation in loading upon repositioning of valves in the flow schemes of pumping stations are rather slugged, unmeant for the excessive nominal load and initiate no instability in the motor operation. It is more probable that the motor instability ensues from some process reasons, due to wave processes in pipelines together with fast variations in pressure.

Given an AEC present in such situation, it is sufficient to increase the excitation current in the period of the load rise by 3% to keep the motor stable. The same effect of keeping stability of the motor in the load rise is achievable without AEC by maintaining the initial excitation current at the level 3% higher than the nominal current, but this reduces the motor efficiency in the initial mode more than by 5%. Finally, the AEC with the field forcing is an effective tool of preserving stability in the load rise and allows energy saving in the initial nominal modes. In the example under discussion, with the automated speed control in the frequency-variable motors, it is possible to keep up synchronism by decreasing the setting of the speed (frequency) by 1%. The automated frequency control in the load rise can be a better way of preserving stability of the motor than the control via the excitation channel.

A more frequent case of instability in synchronous motors are the perturbations in the mains in the form of short-term (fractions of a second to a second long) falls of voltage at the motor inlets. The most frequent voltage falls within 0.5–0.7 relative units in depth and 0.15–0.25 s long as a rule result in no desynchronism of large synchronous motors of centrifugal machinery even in the absence of AEC. The longer voltage falls may cause a longer loss of synchronism in a motor with the subsequent pull-in in the synchronism without additional stimulus. **Figure 3** depicts the motor parameters at the voltage fall 0.7 relative units in depth and 0.5 s long. In this case, the loss of synchronism goes with the cranking of the rotor and the fivefold current rush in the stator. The stator current remains within the allowable limits of $I_{s\ alw} = (1.1 - 1.2)I_{s\ start}$ for the excess of the stator inrush current $I_{s\ start}$, used in protection from the asynchronous stroke of the synchronous motor [16, 17, 21].

In the one and a half times current forcing during the voltage fall, it is possible to avoid the cranking of the rotor. A motor can self-synchronize without the field killing during longer voltage falls with numerous events of the rotor cranking relative to the stator field but such asynchronous modes are hazardous for the high current surges far higher than the allowable values. In such cases, a motor is deactivated by the asynchronous stroke protection with the subsequent stoppage or re-synch of the motor with the field killing. During long voltage falls (longer than 0.5 s in the case discussed), when self-synchronization is possible upon the excess of a theoretical critical slip [17], the field forcing both improves the conditions of pull-in in the synchronism and can yield an inverse effect—transition to the stable asynchronous mode. For this reason, the action of a regular forcing device when the slips are higher than the critical value is eliminated.

A critical point is to keep a motor in the synchronism without the field killing during long voltage falls (form 0.5 to a few seconds in the case discussed) in a wider range of slips beyond the critical values [11, 16, 17].

One of the ways of such synchronization is the cyclic control of the excitation mode in the asynchronous duty of a synchronous motor, which adds the alternating component of the synchronous torque with an intermittent component which induces additional boost of the rotor [16, 17, 21]. The synchronous torque in the asynchronous mode at the constant excitation and variable θ is an alternating parameter which causes additional swing of the rotor.

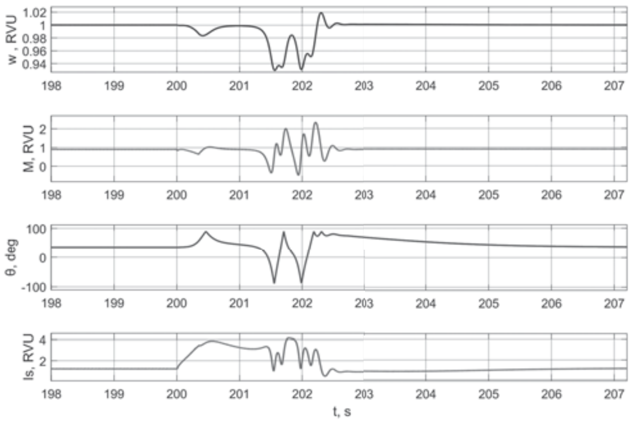

Fig. 3. Curves of synchronous motor parameters in voltage fall 0.7 RVU deep for t = 0.5 s

For the non-salient pole motor, the synchronous torque component conditioned by the voltage of the excitation winding is given by [16, 17]

$$M_{syn} = \frac{EU_1}{x_d}\sin\theta, \tag{9}$$

where E is the intermittent e.m.f. govern by the current in the excitation winding.

It follows from formula (9) that if E owing to the excitation duty control changes as $E = A\sin\theta$, the synchronous torque even in the asynchronous regime ($\theta = st$) at the slip s acquires the intermittent component

$$M_{syn} = \frac{AU_1}{x_d}\sin^2\theta = \frac{AU_1}{2x_d}(1-\cos2\theta) = M_{syn.perm} + M_{syn.intermit}. \tag{10}$$

It is difficult to implement the alternate harmonic control over excitation with a varied period even in high-speed thyristor excitation gears, for this reason, it is simpler to approximate the sine wave by a rectangular function with an alternating voltage [16–19].

The easiest way to obtain this function is using a derivative with respect to the angle θ. The cyclic excitation control subsystem (Fig. 1) includes two branches: (1) setting of an initial excitation value and (2) cyclic excitation control including a derivative determination link and signal limitation block on the side of the input of the angle θ.

The voltage fall 0.7 RVU in depth and 4.5 s long at the inlet of the synchronous motor was modeled with the cyclic excitation control in asynchronous stroke of the motor. The synchronous mode recovers without the field killing within 8 s after the voltage fall ends. The stator current is never higher than the value of the inrush current of the motor. Thus, the cyclic excitation control favors stability of the synchronous motor of centrifugal machinery and ensures re-synch after long (seconds) voltage falls without the field killing and with the stator current limited to the inrush values in a slip range to 0.7. The problem of the synchronous motor stability in the post-forcing modes is solved by itself in this case [7]. The use of a frequency-variable motor allows new ways of control in the modes connected with the short-term losses of supply owing to an additional channel of control via the stator chain. As seen from formula (5), the decrease in the stator frequency promotes the increase in the moment of the synchronous motor. By means of including a slip-based feedback with setting of frequency, it is possible

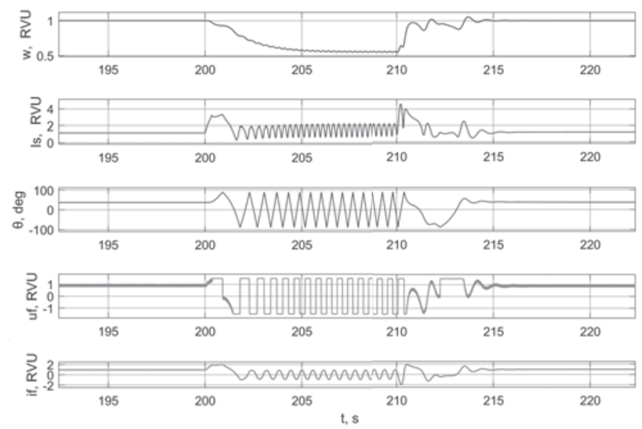

Fig. 4. Curves of synchronous motor parameter in voltage fall 0.7 RVU deep and 10 s long during control via frequency setting channel with cyclic excitation control

to increase the synchronous motor stability [11, 16, 17, 19]. Such feedback operation is particularly effective in combination with the cyclic control of excitation during long voltage falls. **Figure 4** illustrates the aforesaid by the modeling results on the simultaneous control via the two channels considered at the voltage fall 10 s long.

This way of adjustment enables recovery of synchronism at long falls of voltage with limited values of stator currents much lower than the starting values (to 4 Is.nom). Compared only with the cyclic control, the integrated frequency-and-excitation adjustment can reduce the rotor cranking by many times.

Conclusions

Using the modified model of a synchronous motor of centrifugal machinery, the authors have examined the characteristic static and dynamic behavior of the motor. In the static conditions, the energy saving and stability control of a synchronous motor via the excitation channel is contradictory: the increase in the energy efficiency decreases the stability factor of the motor and vice versa. It is possible to resolve the contradictions by improving the automated control of synchronous motors in their transient duties.

The dynamic operation with the cyclic excitation control in combination with the control via the frequency channel of the frequency-variable motor enhances the ability of the motor to self-synchronize during long voltage falls, which can reduce the events when the motor re-synch is required together with the field killing, and can accelerate recovery of the normal duty of the motor.

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