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GENTLE SYNCHRONIZATION OF TWO-SPEED HIGH-POWER SYNCHRONOUS MOTOR OUT OF OVER SYNCHRONOUS SPEED

ŁAGODNA SYNCHRONIZACJA DWUBIEGOWEGO SILNIKA SYNCHRONICZNEGO DUŻEJ MOCY Z PRĘDKOŚCI NADSYNCHRONICZNEJ

Abstract

This paper presents an analysis of the synchronization process of the high-power, two-speed synchronous motor out of over synchronous speed. A method of increasing the effectiveness of synchronization by applying a change system of polarization of the field circuit supply DC voltage is proposed. The process of synchronization from the stator supply voltage is also analyzed. The influence of the periodic reduction value of the supply voltages on the synchronization processes was also investigated. The proposed synchronization method can be applied during the synchronization processes of line start permanent magnet synchronous motors with a two-stage start-up.

Keywords: *electrical machines*, *synchronous motor*, *synchronization*, *FEM calculation*

Streszczenie

W artykule przedstawiono analizę procesu synchronizacji silnika synchronicznego dużej mocy z prędkości nadsynchronicznej. Zaproponowano metodę zwiększającą skuteczność tego procesu dzięki zastosowaniu układu zmiany polaryzacji napięcia wzbudzenia. Analizowano przebieg procesu synchronizacji wzbudzonej maszyny od strony sieci zasilającej stojan. Zbadano również wpływ okresowego zmniejszenia wartości napięć zasilających podczas procesu synchronizacji na jego przebieg i skuteczność. Zaproponowana metoda synchronizacji może zostać zastosowana podczas procesów synchronizacji silników synchronicznych o wzbudzeniu od magnesów trwałych (LSPMSM) i rozruchu dwustopniowym.

Słowa kluczowe: *maszyny elektryczne, silnik synchroniczny, synchronizacja, obliczenia MES*

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1. Introduction

The use of switchable armature and field magnet windings in electromagnetically excited high-power synchronous motors allows for the design of two-speed motors with two synchronous speeds, and synchronous motors with a two-stage start-up and one rated speed. Salient-pole synchronous motors are mostly employed in the drive systems of the main-ventilation fans in deep mines. Two-speed drive motors are generally used, usually built as a result of the modernization of one-speed motors and significantly improving the starting properties by reducing starting currents and unfavorable mechanical stresses. The step change of speed achieved by changing the number of motor magnetic field poles [2, 9] ensures sufficient capacity control and results in a significant reduction of the power consumed by the fan. Major savings can be made and the total mining costs can be reduced through the rational use of the fans' capacity [2]. One of the machines is a two-speed synchronous motor of type GAe 1716/20t - its main specifications are presented in Table 1.

Table 1

The ratings of two-speed synchronous motor GAe 1716/20t

Rated power	kW	2600	1200
Stator voltage	V	6000 YY	6000 Y
Stator current	A	292	186
Field voltage	V	86	78
Field current	A	337	300
Rotational speed	rpm	375	300
Power factor	-	$0.9_{\text{poj.}}$	$0.77_{\text{ind.}}$
Efficiency	%	95.5	81.0

The synchronization process of the motor to a lower synchronous speed does not always proceed properly, therefore, studies have been conducted [7, 8] focusing on developing solutions that improve the course of this process, both out of over and under synchronous speed.

Developing methods of synchronization out of over the synchronous speed, in particular through switching supply voltages to the stator windings of the excited synchronous motor, can also be applied during gentle synchronization processes of line start permanent magnet synchronous motors with two-stage start-ups [1, 3]. The proposed two-stage method for starting-up the LSPMSM type motors significantly improves the starting properties of these machines and the synchronization process started above the rated synchronous speed may proceed gently.

This paper presents the results of numerical synchronization calculations for a selected model of the two-speed high-power salient-pole synchronous motor, realized from the field magnet side and the supply network side of the stator.

2. Analysis of synchronization processes

A specially developed field-circuit model of the two-speed motor type GAe 1716/20t [6, 7] was used to analyze the synchronization process of the motor.
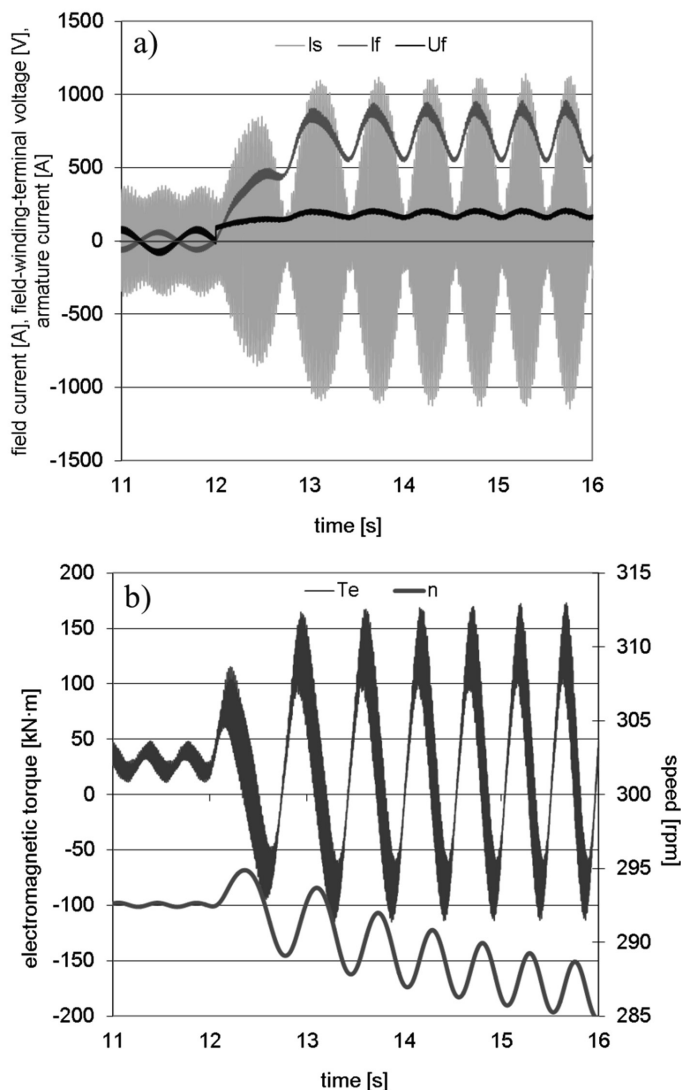

Fig. 1. Waveforms of the quantities during motor synchronization started at: $n \approx 293$ rpm and field current forcing, $p = 10$

To verify the calculation model, measurements of the actual motor installed in a mine fan station and the corresponding calculations were carried out [7]. A comparison of the calculation results with the measurements showed the field-circuit model of the GAe 1716/20t

two-speed synchronous motor to be correct and suitable for further investigation of the phenomena occurring during the operation of motors of this type.

Figures 1–5 show the calculated waveforms of armature phase A, current I_s, field current I_p, field-winding-terminal voltage U_f (a), electromagnetic torque and rotational speed (b) during synchronization processes at the lower rotational speed ($p = 10$) of the motor. The calculations were performed for load torque 0.8 T_N. This corresponds to the load which the WPK 5.3 fan constitutes with its control unit flaps fully opened. The resultant moment of inertia of the fan drive system: $J_r \approx 40\ 000$ kg·m² [7, 8] was used in the calculations.

Figure 1 shows the calculated waveforms of the quantities during motor synchronization started at an angle of $\delta = 0°$ and field current forcing of 2.5 I_{fn}, where δ is the angle between the stator field axis and the rotor field axis [5].
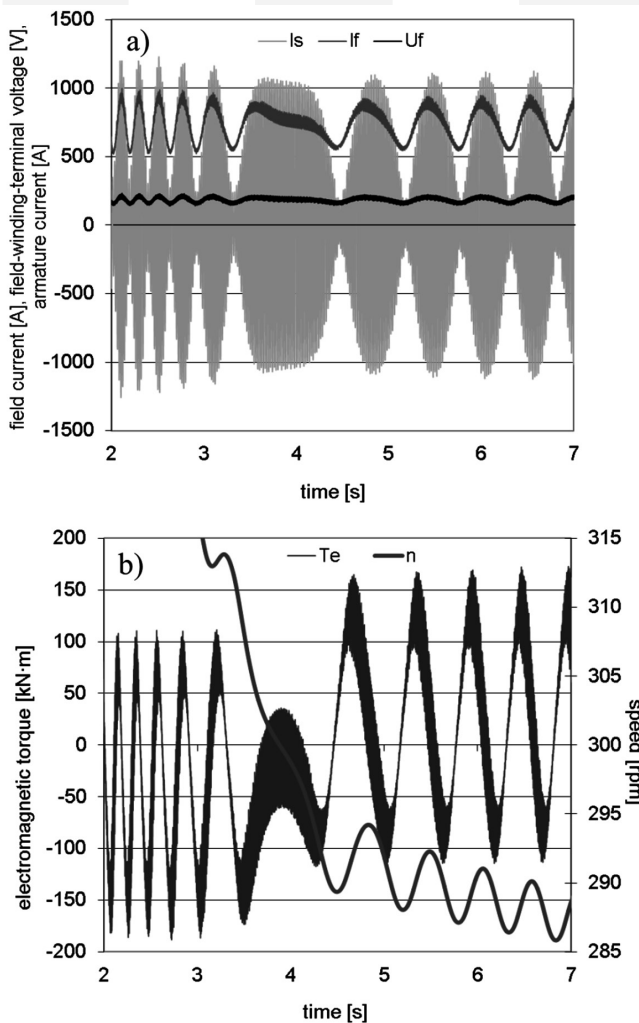

Fig. 2. Waveforms of the quantities during motor synchronization started at: $n \approx 370$ rpm and field current forcing, $p = 10$

According to Fig. 1, despite the selection of a proper synchronization initiating instant and the field current forcing, no effective synchronization is achieved. The calculation results show that for the adopted motor operating conditions, regardless of the choice of an instant of connecting the field voltage, synchronization processes started below the synchronous speed proceed ineffectively.

Figure 2 shows the calculated waveforms of the quantities during motor synchronization started at a rotational speed of $n \approx 370$ rpm (above the rated synchronous speed for $p = 10$) and field current forcing of 2.5 I_{fn}.

An accidental instant of connecting DC voltage to the field winding, despite the initiation of the process in proper operating conditions and the field current forcing, resulted in no effective synchronization. Switching the field voltage for such a high value of the rotational speed (above the synchronous speed) also causes adverse surges of stator currents (Fig. 2a)) and considerable electromagnetic torque fluctuations (Fig. 2b)).
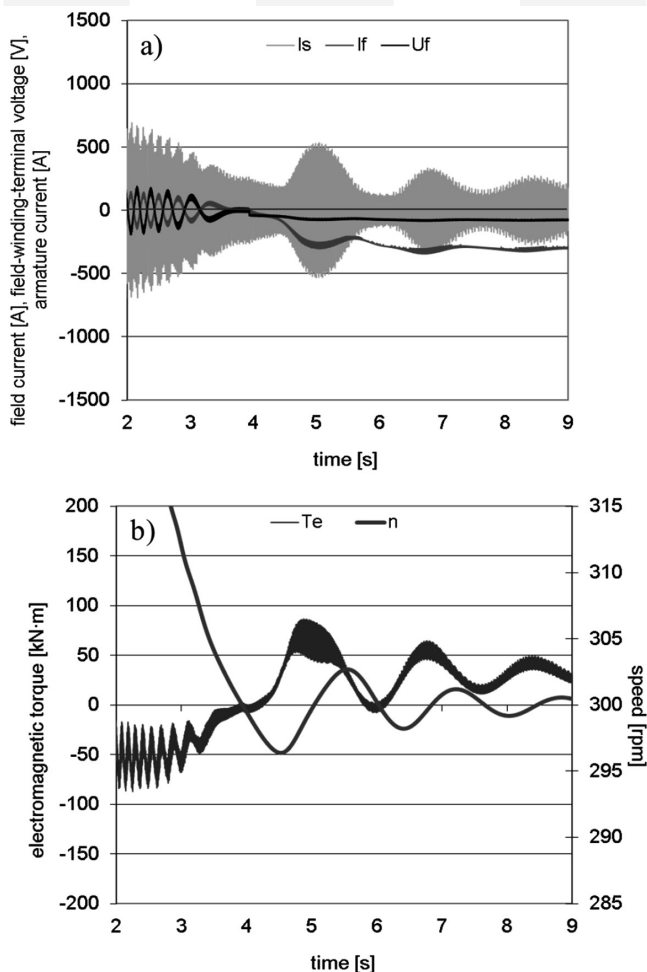
Fig. 3. Waveforms of the quantities during motor synchronization started at $n \approx 300$ rpm with the polarization change system of the field circuit supply DC voltage, $p = 10$

Lack of steady-state operation in the process of synchronization started above the synchronous speed makes it difficult to control the course of this process. The characteristic operating point of the motor, whose appointment is not difficult, is a change in the rotational speed from over to under synchronous speed. A significant increase in the probability of an effective and gentle motor synchronization out of over the synchronous speed provided by the use of the transistor switch [7], allowing the changing of the polarization of the field circuit supply DC voltage [8]. The polarization of this voltage is selected at the instant when the motor reaches the synchronous speed, providing conditions in which the DC current is added to the corresponding value of the field current caused by the AC voltage induced in the field magnet winding [4]. This increases the resultant value of the field current, thereby increasing the pull-in torque. The calculation results of the synchronization process realized by switch-
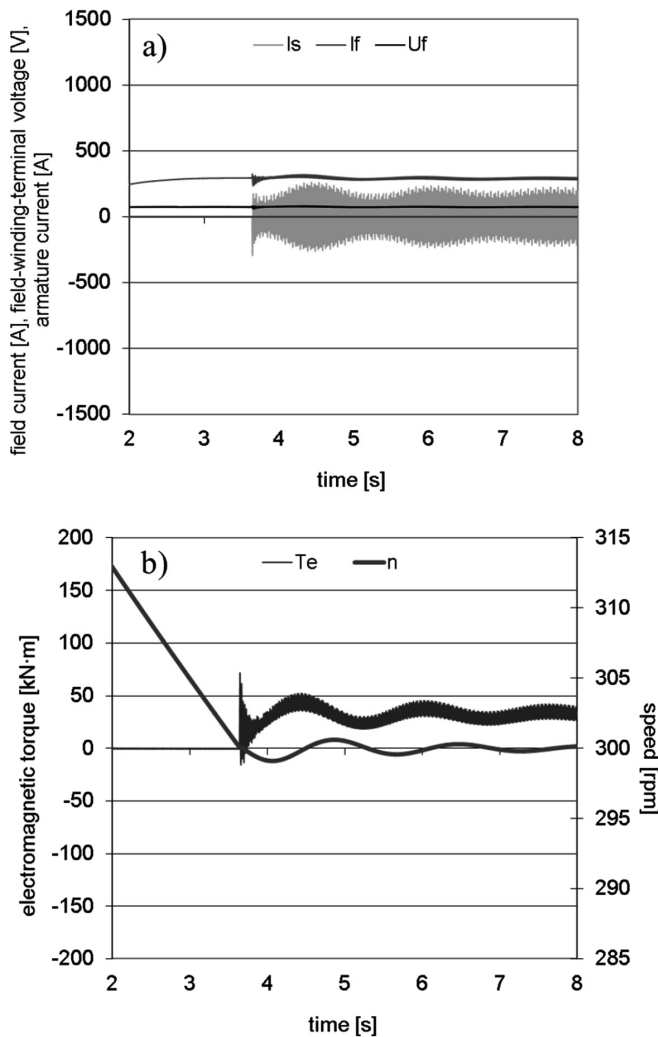

Fig. 4. Waveforms of the quantities during motor synchronization started at: $n \approx 300$ rpm and initial angle of the rotor 10 deg, $p = 10$

ing the rated value of the field voltage at the instant when the motor reaches the synchronous speed with the polarization change system of the field circuit supply DC voltage, for the same operating conditions as before, are shown in Fig. 3.

The synchronization process out of over the synchronous speed can also be realized from the supply network side of the stator of the excited synchronous machine. Switching the rated value of the field voltage is realized in the conditions of asynchronous operation, above the synchronous speed and switching voltages of the stator windings is executed at the instant when the motor reaches the rated synchronous speed. However, there is a problem of synchronizing the motor with the power network voltages. The electromotive forces induced through the rotor electromagnetic field in the phase armature windings do not allow uncontrolled switching of the windings on the supply voltages. The calculation results of the
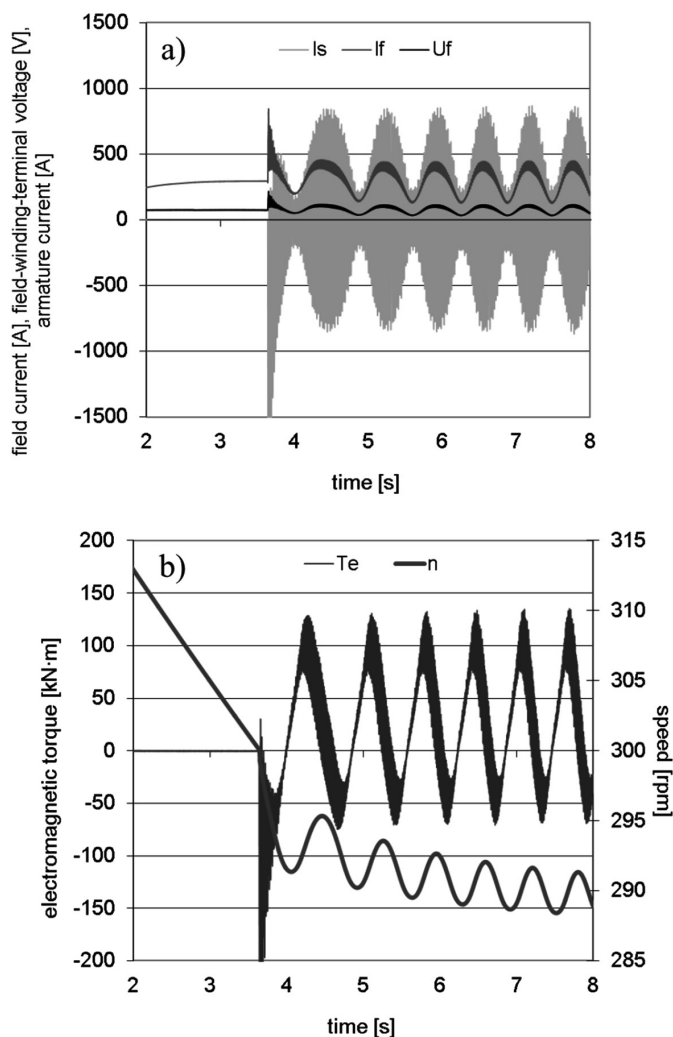
Fig. 5. Waveforms of the quantities during motor synchronization started at: $n \approx 300$ rpm and initial angle of the rotor 150 deg, $p = 10$

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switching process to a lower rotational speed of the two-speed synchronous motor for two different initial angular positions of the rotor are shown in Figs. 4 and 5.

The proposed synchronization method (Fig. 4) through controlled switching voltages of the stator windings provides effective synchronization and a considerable reduction of armature current, electromagnetic torque and rotational speed fluctuations – this reduces mechanical impacts on the transmission shaft. The synchronization process of the motor proceeds more gently (Fig. 4) than in the use of classical methods of implementation of this process and the field current forcing [7].

Accidental switching of the voltages to the stator windings (Fig. 5) may cause ineffective synchronization processes and result in adverse transients with significant risks to electrical circuits and the mechanical system. This issue requires further study.
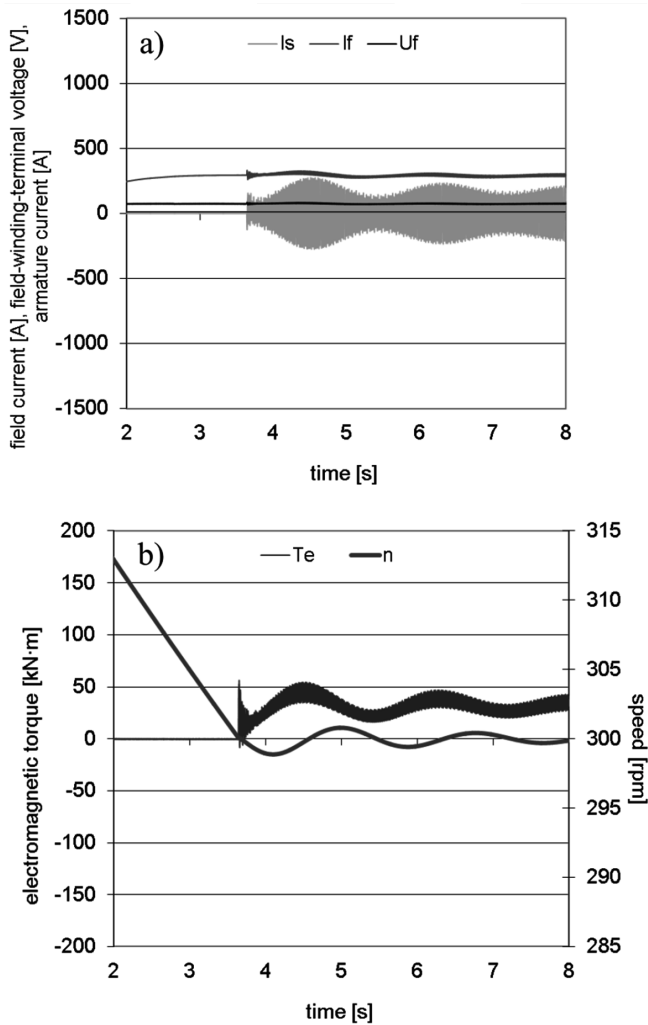

Fig. 6. Waveforms of the quantities during motor synchronization started at: $n \approx 300$ rpm, initial angle of the rotor 10 deg and reduction value of the supply voltages by 15%, $p = 10$

 The field-circuit model of the motor was also used to calculate the processes of synchronization for the previously adopted operating conditions, taking into account the occurring periodic reduction value of the supply voltages. The periodic reduction of the stator voltages during the synchronization process by 15% (Fig. 6) and 20% (Fig. 7) was used in the calculations. In both cases (Figs. 6 and 7), the gentle synchronization process out of over the synchronous speed, realized by the controlled switching of power supply voltages to the stator windings, proceeds efficiently and smoothly.
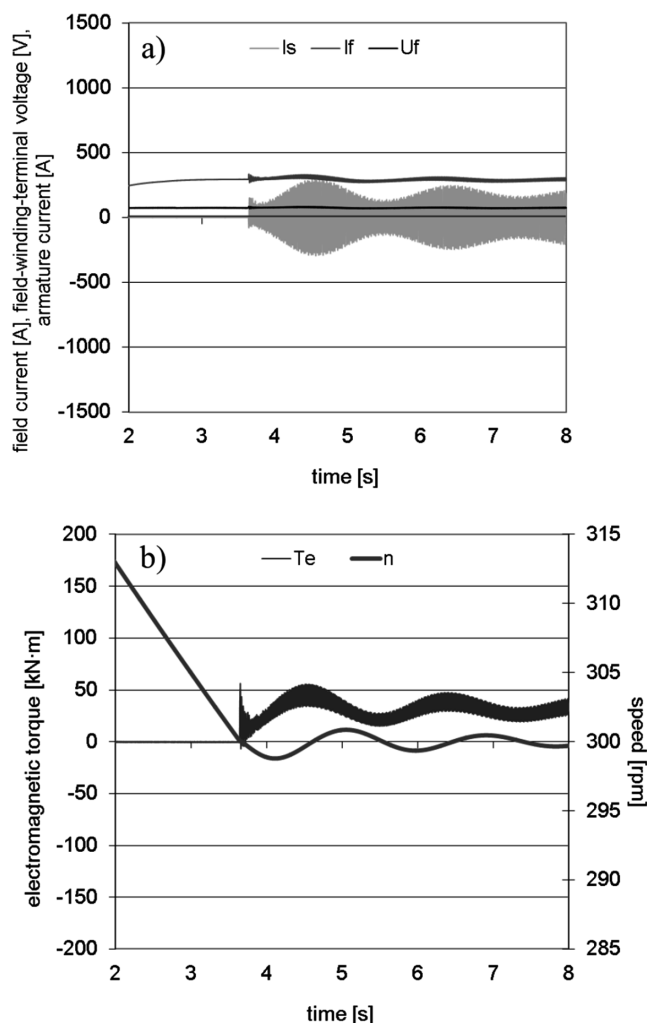

Fig. 7. Waveforms of the quantities during motor synchronization started at: $n \approx 300$ rpm, initial angle of the rotor 10 deg and reduction value of the supply voltages by 20%, $p = 10$

3. Conclusions

The synchronization process of the two-speed large-power synchronous motors out of over the synchronous speed, realized through switching the proper polarization of the field circuit supply DC voltage at the instant when the motor reaches the rated synchronous speed, proceeds effectively and gently, without using the field current forcing. The synchronization process out of over the rated synchronous speed realized through the controlled switching of voltages to the stator windings provides effective synchronization and a considerable reduction of armature currents and electromagnetic torque fluctuations. Due to the use of proposed synchronization methods, the motor can be synchronized when loaded with a torque higher than the torque at synchronization with classical methods of implementation of this process and field current forcing of 2.5 I_{fn}.

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