Research of Transition Processes of Single-Phase Collector Motor With AC Voltage Controller Model Created on Project Design Data

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***Abstract*— A model of an single-phase collector motor with alternating current supply and voltage regulation using one thyristor (half wave phase control) or two thyristors (full wave phase control) in MATLAB Simulink has been developed and further investigated on the basis of results of project design calculation, while all necessary motor parameters for mathematical models have been obtained. This model is based on existing models of universal motor and thyristor in the MATLAB Simscape library using real data. The obtained model has enabled to investigate the mechanical characteristics of the motor with alternating current supply and voltage regulation using one or two thyristors for different thyristor firing angles. The influence of the armature circuit inductance on the shape of the regulated supply voltage in the motor start and operation mode using the AC voltage controller is investigated. The importance of controlling the armature circuit inductance in the process of design calculation and the ways of reducing inductance are proved. It is shown that complex design reduction of the armature inductance and the use of RC-snubber allows to provide the lowest ripple of the motor supply voltage.**

Keywords—alternating current, mathematical model, single-phase collector motor, thyristor, triac, project design

I. Introduction

Contemporary developments in the field of modeling, analysis and synthesis of electromechanical systems demonstrate a significant interest in the research of singlephase collector motors (SPCM) with AC supply. This motor type is a type of universal motor, but it is designed and operated from AC power. The main upsides of such motors are the possibility to obtain high rotation speeds reaching the mark of tens of thousands of rpm, the simplicity of the design, the possibility to obtain significant torque, relatively small size and light weight, the AC-powered operation. In addition, AC SPCMs enable an easy, economical and smooth change of the motor speed over a wide range by means of using quite simple electronic control schemes. Such schemes guarantee relatively high efficiency, good starting torque at low starting currents and fairly low cost.

That is why modern household appliances (vacuum cleaners, washing machines, mixers, blenders, etc.) and hand-held power tools (drills, chainsaws, hand saws, etc.) are driven by a variety of AC SPCMs speeds with rotation speeds from 5000 to 30,000 rpm and are powered from the network with the industrial frequency of 50 Hz and standard voltage of 220 V. Options for applying such motors with the power ranging from a fraction of watts to several kWt have been discussed in [1].

A comprehensive analysis of other research works [2] has revealed that the problem of accurate modeling of different operation modes of AC SPCM has not been sufficiently researched, mainly due to the lack of their real parameters. Such parameters as power, speed and nominal voltage can be normally obtained from the datasheet of a particular motor, which appears to be largely insufficient. For example, the universal motor mathematical model has been researched in [3], but the studies have been carried out by means of using only approximate parameters.

The absence of real AC SPCM parameters does not allow to adequately research the mathematical model of the motor or create a model of a certain real speed control system. For example, the motor model powered by a voltage inverter was studied in [4], but it is not clear from the article where the parameters of the motor under consideration were obtained from. The influence of modulation indicators on the harmonics of the current and voltage of the universal motor powered by a single-phase PWM inverter was investigated in [5], but the article lacks explanation as to where the parameters of the motor under research were obtained from.

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devices with different types of their loads and analyze them with the help of modern approaches to describing such complex objects [6]. This article will also provide the comparison of the results obtained for the half wave phase control AC SPCM supply scheme and for the full wave phase control one. The mechanical motor characteristics at different power options and the values of the firing angle of the thyristors are of particular interest. In the design calculation of the AC SPCM, the parameter of the armature circuit inductance is determined as the result after all other calculations. However, this parameter significantly affects the switching processes and the voltage ripple of the motor supply. The correlation between active and inductive resistance of the armature circuit arouses interest in terms of switching processes in power thyristors.

The main tasks set in this article are as follows:

- to analyze the main formulas of the design calculation of AC SPCM of arbitrary power and conduct necessary calculations for a specific example;
- to analyze the theoretical basis and develop the motor model in MATLAB Simulink based on the results obtained using the project design calculation powered by one or two thyristors;
- to investigate the transition processes of AC SPCM at motor start with one and two thyristors and different firing angles of thyristors, to obtain mechanical characteristics of the motor at various power supply options and firing angle values of thyristors, to investigate the influence of armature inductance on switching processes in motor start and operation modes and to determine ways of inductance reduction in the process of project design.

II. Project design calculation for AC single-phase collector motor

The AC SPCM was calculated over a long time [6] and was used in the design calculations of different motors from several watts to tens kilowatts. The AC SPCM calculation consists of major eleven steps [2].

To start the project design calculation of any AC SPCM, the following nominal parameters are required: 1. Power P_n , W. 2. Speed n_n, rpm. 3. Voltage U_n, V. 4. Frequency f_n, Hz. 5. Mode of operation (short-term, long-term, etc.).

This article takes into account only several major formulas necessary to create the mathematical model of the SPCM with AC supply.

Resistance of motor armature winding (75 °C):

$$R_a = 1.22 \frac{N_a l_{aw} \cdot 10^{-4}}{57 q_a} \qquad (1)$$

where: N_a - the number of conductors in armature, q_a - the cross-sectional area of conductor in armature, l_{aw} - the average length of winding.

Equivalent inductance of the motor armature section:

$$L_s = \frac{2 a w_c A_a A l_a b_b \cdot 10^{-3}}{I_a} \qquad (2)$$

where: a -pairs of parallel branches, w_c - number of turns in one section of the winding, A - linear load, I_a - nominal current, b_b - width of the brush, X_a - leakage flux magnetic conductivity of the armature winding section, l_a - armature core length.

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III. AC SPCM model

Differential equations, describing model of the researched AC SPCMs, are derived from the equivalent electrical and mechanical circuits of the motor [2] that are demonstrated in Fig. 1,

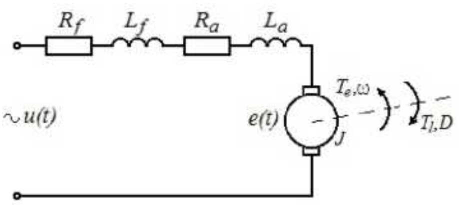

Fig. 1. Equivalent electrical and mechanical circuit of AC SPCM: *u(t)* - supply voltage, *i(t)* - armature current, *e(t)* - the self-induction EMF, *T(t)* - electromagnetic torque, *T(t)* - load torque, *m(t)* - angular speed of the motor, *J* - machine and load moment of inertia, *D* - viscous friction coefficient

Motor equivalent electrical circuit shown in Fig. 1 can be expressed using the differential equation below:

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This model is considered in [2] in more detail. The existing model of universal motor in the environment MATLAB Simulink library is also based on the equations under the study.

IV. Development and research of motor model with thyristors voltage controller based on results of project design

The development and investigation of motor model, shown in Fig. 1, requires the parameters of the motor. Our research results [2] enable to obtain all necessary motor parameters through the results of project design calculation derived from the set task for AC SPCM design and calculation.

Let us consider another case when the task for calculating the motor contains such data: P_n =550 W, P_{2n} =430 W, =11700 rpm, U_n =220 V, f_n =50 Hz,
prolonged mode of operation. We carried out the motors project design calculation using the formulas considered [2]. The obtained results to be further applied for creating a mathematical model are: R_a = 1.569 Q, Rf = 0.98 Q, L_a = 0.003585 H, L_f = 0.03485 H, $k*$ = 0.000191, k_a = 286.6, as calculated for nominal current I_a =3.3A.
Besides, the calculation of the motor magnetic circuit has been also carried out, which led to obtaining the magnetization characteristic of the AC SPCM.

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two (full wave phase control) thyristors and with the ability to simulate the change in load on the shaft (Fig. 2).

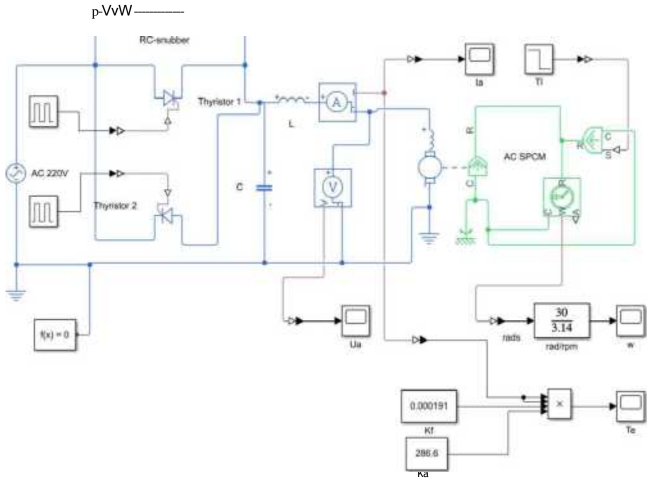

Fig. 2. Matlab Simulink model of AC SPCM with voltage regulation

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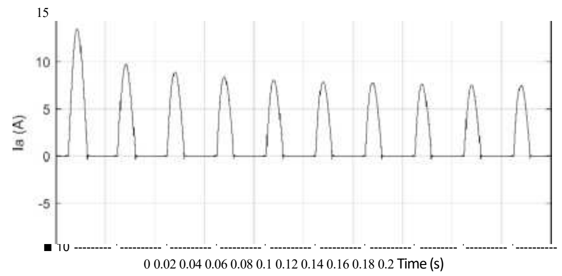

Fig. 3. Motor current at start with one thyristor (a=90°)

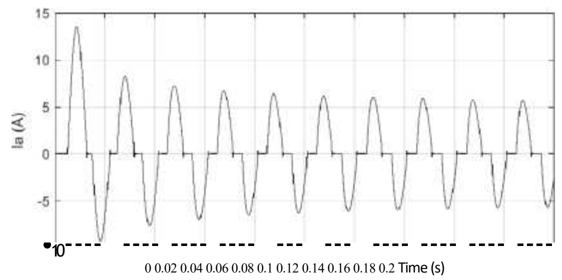

Fig. 4. Motor current at start with two thyristors (a=90°)

The transition process of supply voltage Ua and electromagnetic torque Te of AC SPSM at the start with Ti =
0. 348 Nm and power supply with one thyristor is shown in Fig. 5, 7 while the transition process for two thyristors is shown in Fig. 6, 8. The developed model enables to investigate the influence of capacitor C on the ripple of the supply voltage. The results for C = 0.1^F are shown in Fig. 5 and 6. Excluding C, the ripple amplitude was much larger. Figures 5 - 8 show the effect of change in the starting current on transition processes of motor voltage and torque .

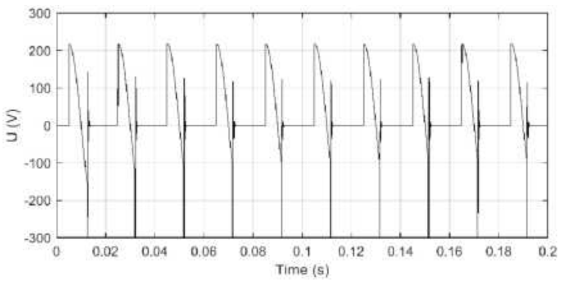

Fig. 5. Motor voltage at start (t=0) with one thyristor (a=90°)

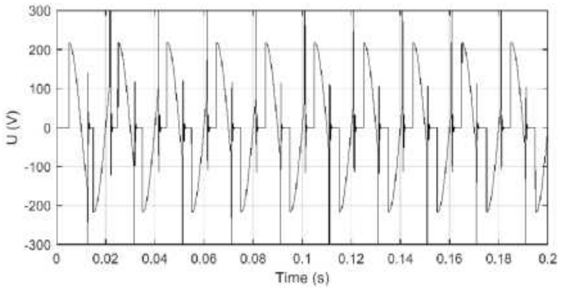

Fig. 6. Motor voltage at start (t=0) with two thyristors (a=90°)

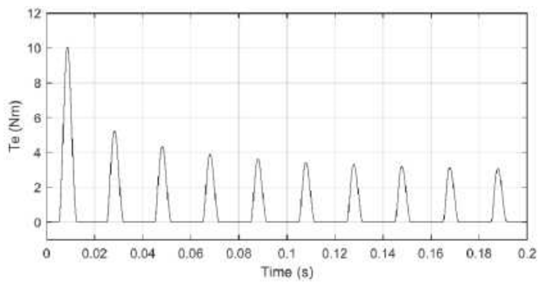

Fig. 7. Motor torque at start (t=0) with one thyristor (a=90°)

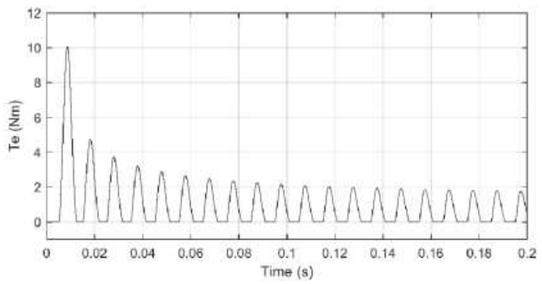

Fig. 8. Motor torque at start (t=0) with two thyristors (a=90°)

The analysis of the obtained results showed that the control of the AC SPCM voltage with the help of two thyristors provides lower ripples of the current («30%), electromagnetic torque («52%) in steady state, and, as a result, speed ripples. Reducing ripples of the current and the torque will reduce vibration and noise.

The transition process of AC SPCM speed of rotor rn at the start with ₃ Ti = 0.348 Nm and the power supply with one thyristor is shown in Fig. 9 (1), while the transition speed process for two thyristors is shown in Fig. 9 (2).

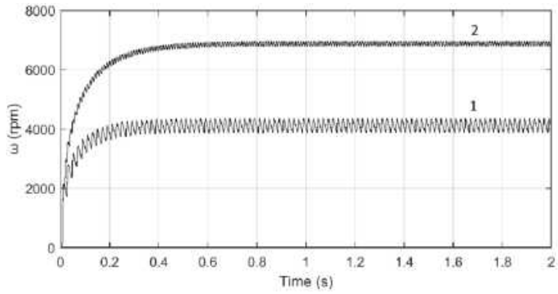

Fig. 9. Motor speed at start with one thyristor (1) and two thyristors (2)

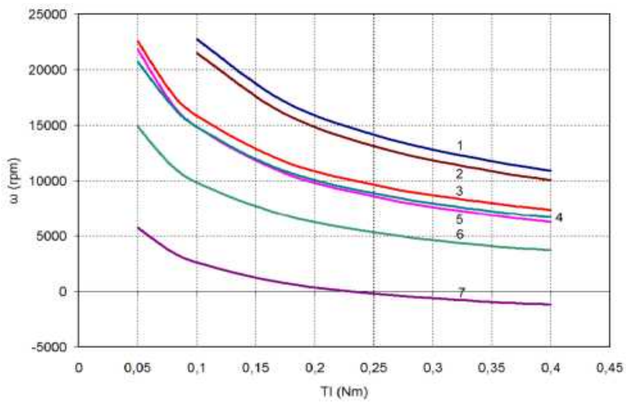

Fig. 10. Motor mechanical characteristics.

Let us consider the influence of the inductance of the armature circuit L_af on the voltage shape during starting the motor in Fig. 11 - Fig.13.

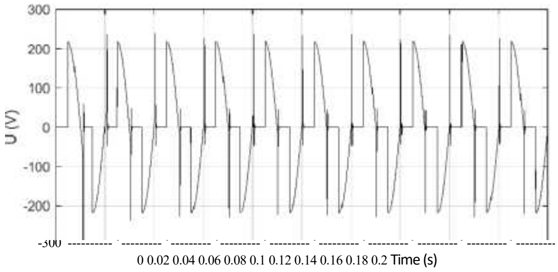

Fig. 11. Motor voltage at start (t=0) with two thyristors and *0.5Laf*

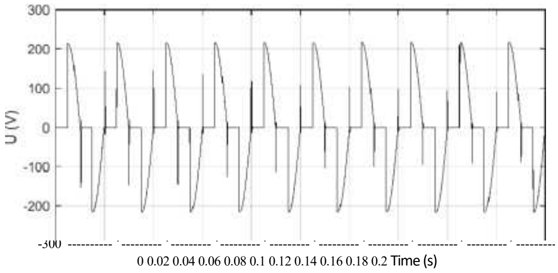

Fig. 12. Motor voltage at start (t=0) with two thyristors and *0.25Laf*

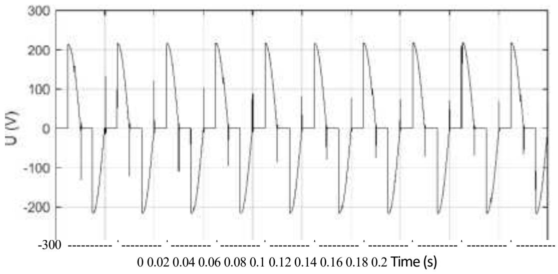

Fig. 13. Motor voltage at start with two thyristors $R_a+Rf=X_{La}f$ $(\sim 0.2L_af)$

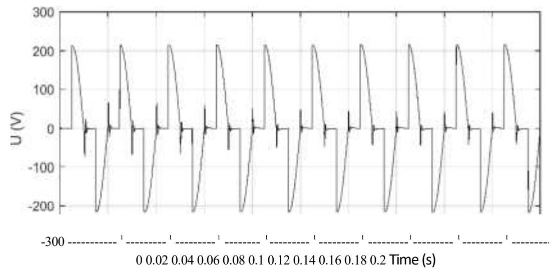

Fig. 14. Motor voltage at start with two thyristors $0.25L_af$ and RC-snubber

Additionally, let us consider the effect of RC-snubber (Fig. 2) on the operation of the AC controller (Fig. 14) for the case of 0,25 L_af . RC-snubber parameters are as follows:

C_s = 1^F, R_s = 1 Q.

The comparison of the voltage shape without a RC- snubber (Fig. 12) and with a RC-snubber (Fig.14) makes it possible to observe a 50% decrease in the ripple.

V. Conclusions

1. The theoretical fundamentals of the AC SPCM model with voltage regulation using one or two thyristors in MATLAB Simulink environment have been considered derived from the data that was obtained from the project design calculation, while all the motor parameters essential for creating the mathematical model were obtained. The model has been developed on the basis of a real scheme of voltage regulation as well as the models of the motor and the thyristor with application of real parameters.

2. The model of AC SPCM with voltage regulation using one thyristor or two thyristors in MATLAB Simulink environment has been investigated. This approach provides considerable scope for further exploration of this motor type practical application for different objects with different load types. Comparative analysis of the results that was obtained for the two power supply options has made it possible to draw the conclusion about the lower level of the current and torque ripples for AC voltage controller using two thyristors.

3. The obtained model made it possible to investigate the mechanical characteristics of the motor with alternating current supply and voltage regulation using one thyristor or two thyristors for different thyristor firing angles. The influence of the armature circuit inductance on the shape of the regulated supply voltage in the motor start and operation modes using the AC voltage controller is investigated. The importance of controlling the armature circuit inductance in the process of design calculation and the ways to reduce the inductance are proved. It is shown that complex design reduction of the armature inductance and the use of RC- snubber allows to provide the lowest ripple of the motor supply voltage.

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