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DISK-ROTOR SERVOMOTOR FED BY AN AC/DC CONVERTER

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În lucrare se prezintă modelul matematic al unui servomotor de curent continuu cu rotor disc şi al convertorului AC/DC de la care acesta este alimentat. De asemenea, se evidenţiază modul în care au fost determinaţi parametrii electromecanici ai servomotorului. În încheiere se prezintă o comparaţie între rezultatele obţinute în urma simulărilor şi a încercărilor experimentale precum şi o analiză a influenţei ansamblului convertor-servomotor asupra reţelei de alimentare.

In the paper the mathematical model of a disk-rotor servomotor is presented along with that of a AC/DC converter. The identification method used for the motor's electro-mechanical parameters is also presented. Finally, a comparison between the simulated data and experimental results along with an analysis of the converter-DRSM assembly influence over the supplying network is made.

Keywords: numerical modeling, disk-rotor DC servomotor, fully controlled AC/DC converter

1. Disk-rotor servomotor modeling

One of the main particularities of the disk-rotor servomotor (DRSM) [1] mathematical model is that the excitation flux $(k\phi_e)$ is constant in time, due to the fact that this machine is equipped with permanent magnets on the stator.

In the followings a brief presentation of the mathematical model for this particular type of DC motor [2] is presented. Dynamic regime is described by the equations (1):

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$$u_A = R_A \cdot i_A + L_A \cdot \frac{di_A}{dt} + e \qquad m_s = m_{sarc\_ax} + M_{fc} + B \cdot \Omega$$
$$e = (k\phi_e) \cdot \Omega \qquad (1)$$
$$m = m_s + J \cdot \frac{d\Omega}{dt} \qquad m = (k\phi_e) \cdot i_A$$

The numerical model of the DRSM was implemented in Matlab-Simulink [3]. Table 1 gives details on the symbols used in describing the corresponding mathematical model.

Table 1

Notations for the mathematical model of DRSM

Symbol and measurement unit	***Significance***
u_A [V]	Supply voltage
R_A [Ω]	Rotor resistance
i_A [A]	Rotor current
L_A [H]	Rotor inductance
e[V]	Back electromotive force (back emf)
m[Nm]	Electromagnetic torque
m_s [Nm]	Load torque
J[kgm^2]	Total inertia momentum
Ω[rad/s]	Angular rotor speed
m_{sarc_ax} [Nm]	Load torque considered at the motor shaft
M_{fc} [Nm]	Coulomb friction torque, non-dependent of speed
B[Nm/(rad/s)]	Viscous friction coefficient
$(k\phi_e)$[Vs]	Excitation flux

A detailed explanation concerning the manner in which the expression of the load torque m_s was determined [4] follows. When the machine is working without load (no-load) then this torque represents the total losses in the machine and has three components:

- M_{fc} – Coulomb frictions (non dependent on speed);
- $M_{fv} = B \cdot \Omega$ – viscous frictions (proportional with the speed);
- $M_{ra} = C \cdot \Omega^2$ – air frictions (proportional to the speed squared).

Usually the last term is small enough so it can be neglected. In the following presentation this assumption is made. Consequently, in no-load and stationary conditions, the electromagnetic torque provided by the DRSM has the following expression:

$$M = (k\phi_e)\cdot I_{A0} = M_{fc} + M_{fv} = M_{fc} + B\cdot\Omega_0 \tag{2}$$

When the load is connected the electromagnetic torque expression, taking into account the previous notations, is given by:

$$M = m_s = M_{sarc\_ax} + M_{fc} + B\cdot\Omega \tag{3}$$

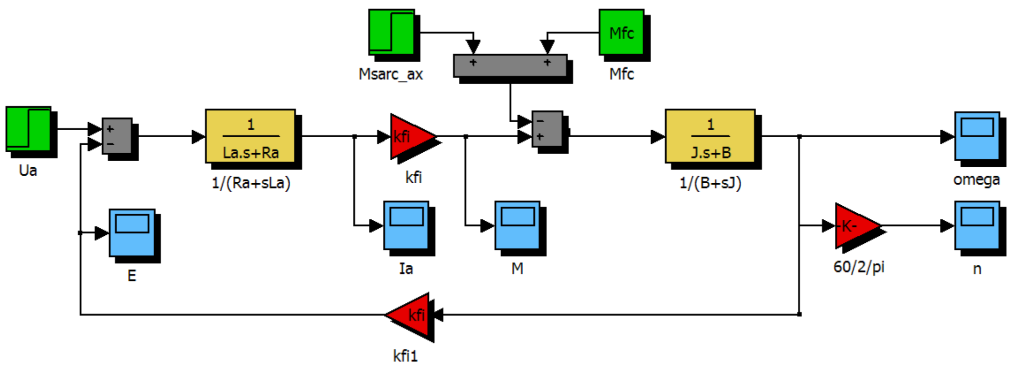

Fig. 1. Matlab – Simulink model for the disk-rotor DC servomotor

The model depicted in Fig. 1 was developed based on the equations presented in this paragraph.

2. Identification of the DRSM's parameters

In order to verify the accuracy of the Matlab – Simulink model for the DRSM its electrical and non-electrical parameters were determined from experimental measurements [5]. Some of the rated values of the motor were used in order to calculate the additional parameters $U_{An} = 106\ \text{V}$, $I_{An} = 8.9\ \text{A}$ and $n_n = 3150\ \text{rpm}$. Then the following quantities are derived:

- ✓ ***Rotor resistance*** was measured using a milliohm-meter. The obtained value is $R_A = 1.54\ \Omega$ and includes the electrical resistance of the brush-slide contact on the collector;
- ✓ ***Rotor inductance*** was determined by supplying the motor from an AC variable source. Measuring the impedance Z_A and knowing the previously measured resistance R_A a value of $L_A = 0.0007\ \text{H}$ was obtained for the inductance;

- ✓ ***Excitation flux*** was determined during a no-load experiment resulting in $(k\phi_e) = 0.28$ Vs;

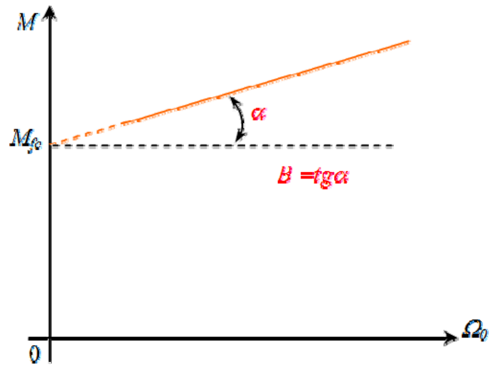

Fig. 2. Graphic construction used for the determination of the Coulomb friction torque and the viscous friction coefficient

- ✓ ***Coulomb friction torque*** M_{fc} ***and viscous friction coefficient*** B were determined by supplying the motor from a DC variable source during a no-load experiment. The voltage U_{A0}, the current I_{A0} and the speed were measured. For the latter a digital tachometer was used. With these values the electromagnetic torque $M = (k\phi_e) \cdot I_{A0}$ was calculated and the $M = f(\Omega_0)$ diagram was drawn (see Fig. 2) The intersection point between the straight line and the vertical coordinate is the Coulomb friction torque M_{fc} and the slope of the straight line is the viscous friction coefficient $B = tg\alpha$. In this way the values $M_{fc} = 0.139/2$ Nm and $B = 4.311 \cdot 10^{-3}/2$ Nm/(rad/s) were obtained.
- ✓ ***Inertia momentum*** J was determined using successive free breaking tests. In the case of free breaking ($m = 0$) the dynamic equation is [6]:

$$0 = M_{fc} + B \cdot \Omega + J \cdot \frac{d\Omega}{dt} \text{, with the solution } J = \frac{B \cdot t_f}{\ln(1 + B \cdot \frac{\Omega_i}{M_{fc}})} \quad (4)$$

The DRSM was brought at different speeds Ω_i and then the free breaking time t_f was measured. The final value for the inertia momentum was obtained by using the mean value from all the tests. This value is $J = 0.001\,\text{kgm}^2$ and was obtained after pursuing 20 different tests.

All the measurements and test were done using the experimental set-up shown in Fig. 3.

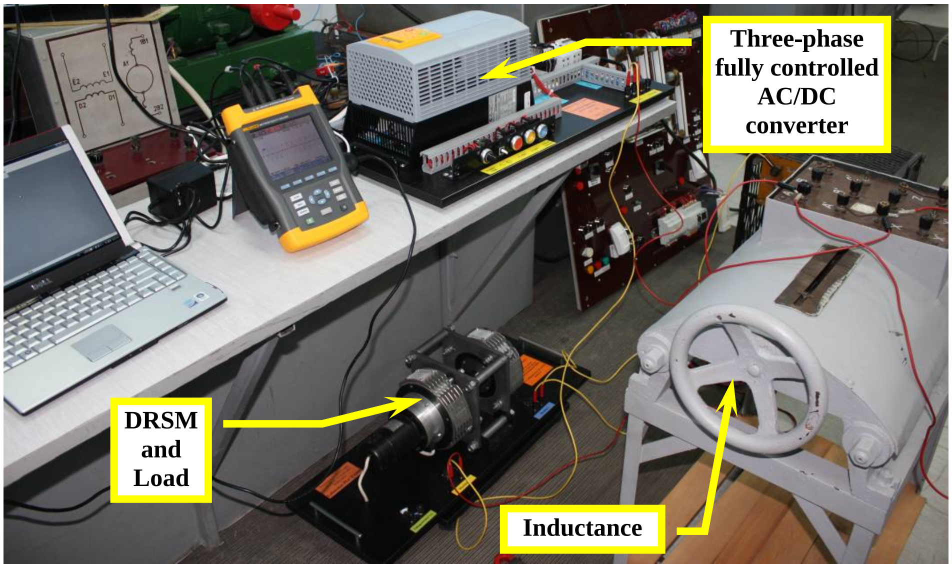

Fig. 3. Experimental set-up

3. Fully controlled AC/DC converter model

Theoretical concepts and the resulting model for the three-phase fully controlled AC/DC converter (bridge rectifier) are presented in this paragraph. These types of converters are commonly used in control systems and electrical drives based on DC machines.

In order to develop the Matlab – Simulink model for this converter, a three-phase voltage system was generated and based on the natural commutation points (the intersection points of the phase voltages) the control pulses for the 6 controllable semiconductor devices were generated. These pulses take into account that the conduction angle (angle of flow) for such a device is 120°.

The conduction for the controllable semiconductor devices starts with a delay angle α (control angle) with respect to the natural commutation points [7].

In addition, real commutation was taken into account. Such commutation is influenced by the inductances present in the circuit. These inductances are preventing instantaneous rises and falls of the currents.

The exact duration of the real commutation process is described by the commutation angle γ [7]. The rectified voltage during commutation is equal with the semi-sum of the phase voltages corresponding to the switching semiconductor devices [7].

In Fig. 4 the resulting model of the converter is presented. The voltage obtained for a control angle of $\alpha = 60^{\mathrm{o}}$ is presented in Fig. 5a ($\gamma = 0^{\mathrm{o}}$). Fig. 5b shows the voltage for the same control angle and a commutation angle of $\gamma = 10^{\mathrm{o}}$ (this value is far from a realistic situation and it was used only in order to verify the model).

The control impulses for the phase thyristors were implemented using Embedded MATLAB Function blocks [8]. There are two such blocks on each phase. Their input arguments are the control angle α, (and for the real commutation the commutation angle γ), the frequency and the clock signal (used in the process of transforming the time in degrees). The outputs of these blocks are the control impulses for the thyristors on each phase.

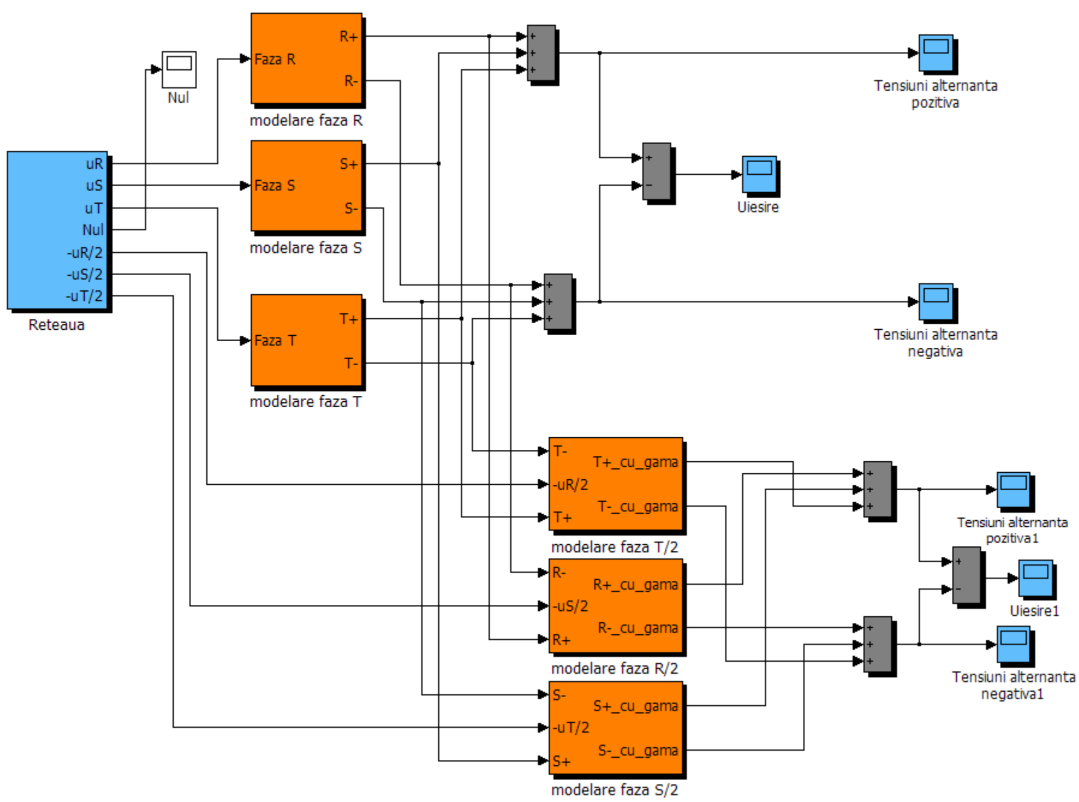

Fig. 4. Matlab – Simulink model for the three-phase fully controlled bridge rectifier

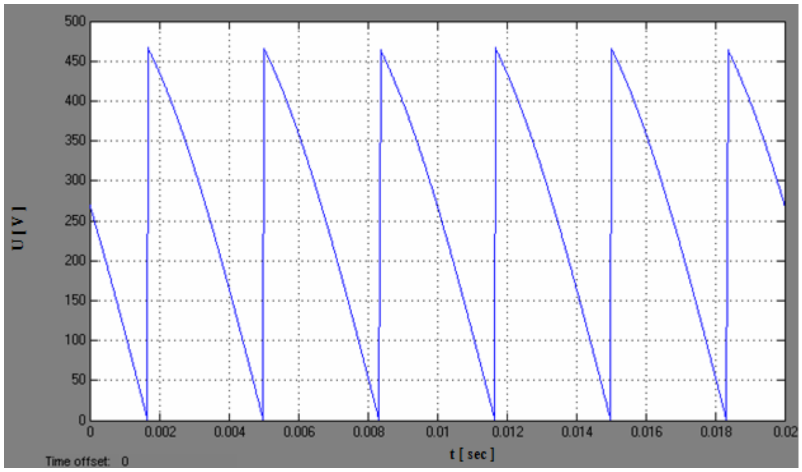

Fig. 5a. Converter's output voltage $\alpha = 60^{o}$, $\overline{U}_{med,\alpha} = 257$ V

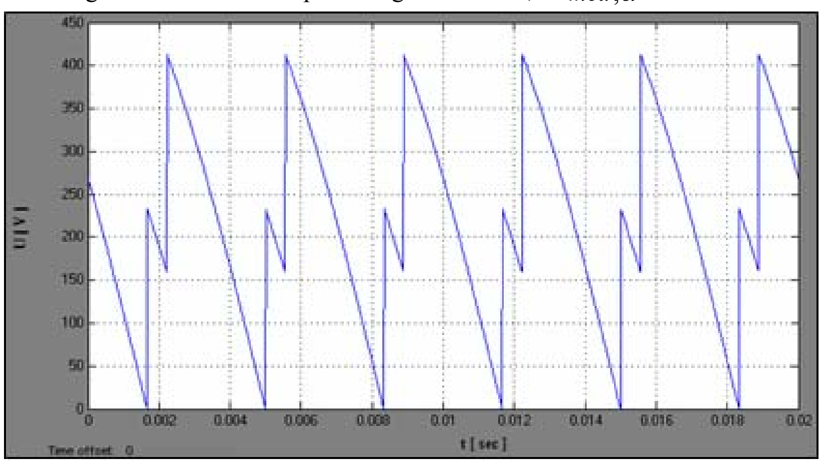

Fig. 5b. Converter's output voltage $\alpha = 60^{o}$, $\gamma = 10^{o}$

4. Dynamic regime analysis for the DRSM fed by a fully controlled AC/DC converter

In this section comparative study between the Matlab-Simulink model and the experimental results for a DRSM fed by a fully controlled AC/DC converter is presented. The load profile is composed by a no-load starting followed by a rated load coupling.

The experimental part consists of two tests: firstly, the converter supplies the DRSM in no-load regime and secondly, at time-moment $t_1 = 1.6$ s the rated load has been applied.

The simulation is performed using the Matlab-Simulink model presented in Fig.1 where the voltage supply block U_A is replaced with the model shown in Fig. 4.

The time variation of the current obtained during the Matlab-Simulink simulation corresponding to the previous presented operating regime is depicted in Fig. 6a. In comparison, the experimental current is presented in Fig. 6b.

In both cases the starting current during the no-load start-up is almost 8 times larger than the rated value. Due to the no-load operation, in about the same time with the speed, the current decreases and stabilizes at a value close to zero (the DRSM is a machine with low inertia moment).

When the load is present, the current increases to its rated value, $I_{An} = 8.9\ \mathrm{A}$, both in simulation and experiment.

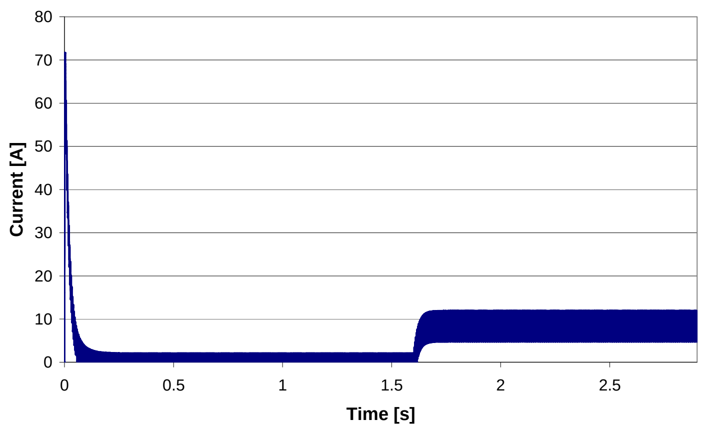

Fig. 6a. The current obtained with the Matlab-Simulink model

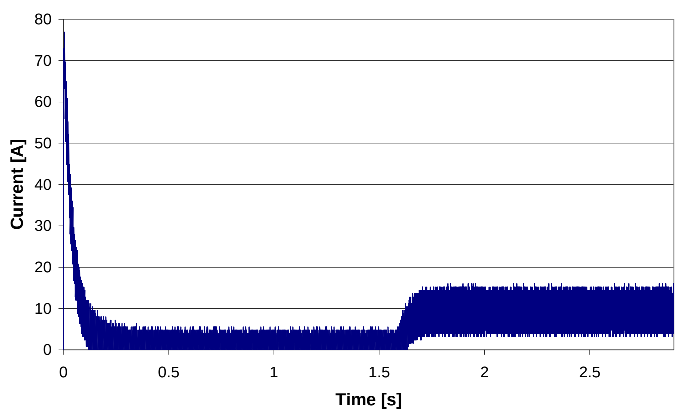

Fig. 6b. The measured current

The speed obtained from the Matlab-Simulink model simulation is shown in Fig. 7a. The experimental speed is presented in Fig. 7b. For both, simulation and experiment, the speed rises to the no-load value (4000 rpm), and after the load is applied it drops to the rated value.

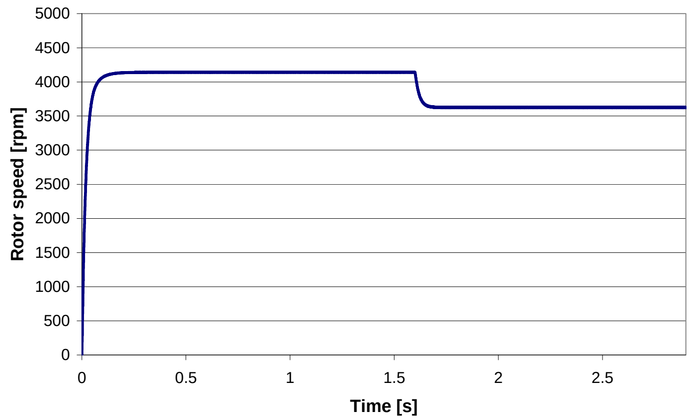

Fig. 7a. The speed obtained with the Matlab-Simulink model

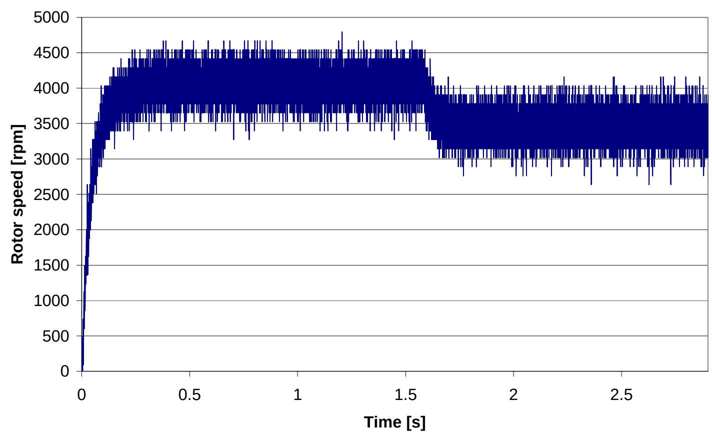

Fig. 7b. The measured speed

5. Influence over the network

For various load patterns of the three-phase fully controlled AC/DC converter-DRSM assembly, using the experimental stand presented in Fig. 3, the absorbed currents from the power line are recorded. After studying these currents, as predicted, it can be concluded that the most important effect over the network corresponds to the interrupt current operating regime. The current in this case is presented in Fig. 8a and its frequency spectrum is presented in Fig. 8b. The THD (Total Harmonic Distortion) value for this current is 126.7%, considering the first

19 harmonics [9]. Due to the high THD value, protective measurements for the other consumers have to be taken. These measurements must be in accordance with the existing directives on the power quality [10], [11] mainly due to the fact that current harmonics have a negative influence over the supplying voltage form. For low rated powers (as it is the case of the machine modeled in this article) these measures can be reduced by adding an inductance in series with the supplying circuit. On the other hand, for increased power there is the need for a shunt active filter.

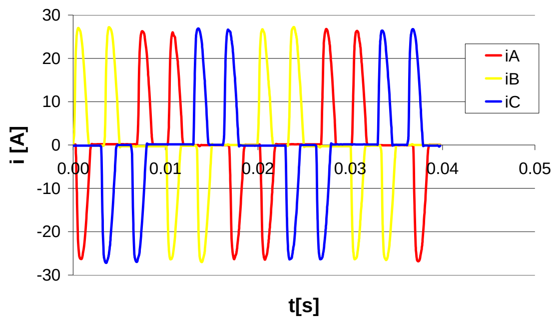

Fig. 8a. Currents absorbed by the converter in the interrupt current regime

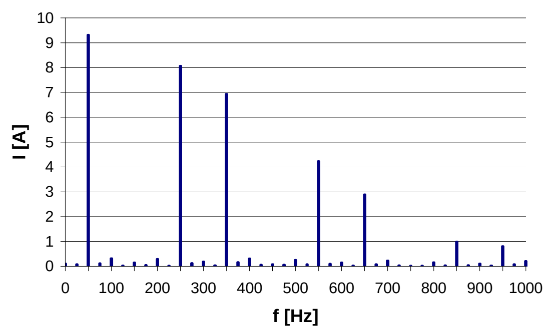

Fig. 8b. Spectrum of the current waveform in the interrupt current regime

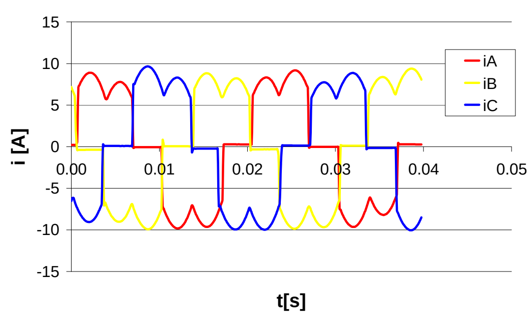

Fig. 9a. Currents absorbed by the converter in the non-interrupt current regime

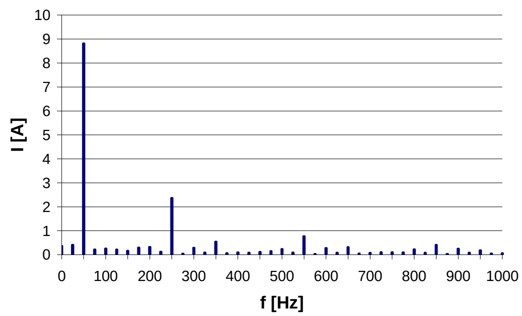

Fig. 9b. Spectrum of the current waveform in the non-interrupt current regime

When a series inductance is used the waveform of the currents is the one presented in Fig. 9a. Its FFT analysis is shown in Fig. 9b. The obtained THD is just 29.94%, taking into account the first 19 harmonics. The value of the inductance is $L = 0.047$ H .

6. Conclusions

This paper is focused on presenting the Matlab-Simulink models for a DRSM fed by a fully controlled three phase rectifier. The theoretical concepts that support the developed models are also highlighted. Consequently, the following issues are presented:

- the mathematical support needed for the development of the DRSM's model;
- the meaning and the measurement units corresponding to all the elements present in the model;
- the deriving of the total load torque m_S expression, referred to the driving shaft;
- the development of the Matlab – Simulink model for the DRSM;
- the applied methodology to experimentally identify the electromechanical parameters of the machine;
- the Matlab – Simulink model for the fully controlled three-phase bridge rectifier along with the specific output waveforms for a control angle $\alpha = 60^0$ and a commutation angle $\gamma = 10^0$;
- the Matlab – Simulink model simulation results for a no-load start-up of the DRSM and for a no-load followed by a rated load start-up;
- the influence of the converter-DRSM assembly influence over the supplying network and procedure to minimize this influence using only passive circuit elements (one of the authors' main contributions). Even if the power quality standards recommends that 50 harmonics should be used when the THD is calculated, in this case 19 harmonics were enough in order to show the high influence over the network of such AC/DC converters.

It can be observed that the presented case study shows a good agreement between the simulated and experimental results giving in this way a support for future work and tests.

The validation of the model has been performed by comparing the simulated waveforms and the time-constants during the dynamic and steady-state regimes.

The developed models (DRSM and fully controlled three-phase bridge rectifier) offer good results and can be used during the teaching process in order to offer a better understanding of the specific phenomena.

7. Acknowledgment

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