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THREE PHASE SWITCHED RELUCTANCE MOTOR CONTROL USING TWO POWER SOURCES

BY

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Abstract. This paper presents the control strategy of an ideal 6/4 switched reluctance motor (SRM), using two power sources of different voltage amplitudes (U_n and $5U_n$). Each stator phase inductance presents a linear variation (triangular shape) and also the absence of ferromagnetic circuit saturation phenomenon. To maintain each stator phase current and also the rotor angular velocity between certain prescribed limits, some hysteresis type controllers were utilized. For reducing the current ripple, the Soft Switching technique was adopted. The first power supply has the nominal voltage value of 230 V. The second power source provides a voltage value of about five times higher, respectively 1,150 V. At the beginning and also during each energizing cycle of any stator phase, the low value voltage is being applied to the terminals of each winding. Thus, the stator phase current increases from zero to the reference value in an appropriate period of time, being then maintained around the extent limits. At the end of each energizing cycle, the high value voltage is applied with reverse polarity to the terminals of the stator phase winding. In this way, the current decreases in a time period of approximately 5 fold lower than in some classical situations. By applying this technique, an almost ideal stator phase current waveform is obtained for low and medium rotor angular speeds (≤ 314 rad/s). A series of results, obtained using the Matlab/Simulink working environment, for different operating regimes of the SRM, are also presented.

Key words: SRM; control; converter; voltage.

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1. Introduction

Switched reluctance motors has a number of advantages that distinguish them from other types of electrical machines among which include: simple construction, robust feature, no rotor windings, no permanent magnets in the constructive structure, its own characteristics – high tolerance, small cost and the possibility of operating at high temperatures (Biro *et al*., 2005).

Many structures of static power converters have been developed over time to enable different ways for energizing and de-energizing the stator phases of the switched reluctance motors, and also allowing an adequate control of the stator phase current and rotor angular velocity, respectively.

According to the requirements, various static converter topology were made, with: q, $q + 1$, $1.5q$ and $2q$ power semiconductor devices (where q is the number of phases of the SRM). Fig. 1 shows the classification of static power converters used for energizing the stator phases of switched reluctance machines, depending on the number of power semiconductor devices and the possible operating modes (Krishnan, 2001; Ahn *et al*., 2010; Liang *et al*., 2010).

There are also static power converters configurations that do not fall under the classification of those who depend on the number of phases of the machine.

It is considered that most of the power converters have a DC power source connected to thereof input terminals. This source can be achieved either through accumulators or, in general, by using a rectifier provided with an additional element filter (capacitor) (Gairola *et al*., 2010; Ganguli, 2011).

By using these static power converter, the energy stored in the magnetic field of the stator phase of the machine can be used in various ways. A part of it can be converted into mechanical energy at the machine shaft, and the rest being dissipated either on its own windings resistance, or being transferred back to the DC power source (Irimia *et al*., 2012, 2011).

One of the most utilized power converters in classical control strategies is the asymmetric bridge static converter, whose structure is illustrated in Fig. 2 (Krishnan, 2001; Miller, 2003; Rolim *et al*., 2008). This type of converter includes two controllable power semiconductor devices (transistors, *T*1 and *T*2) and two discharge diodes (*D*1 and *D*2). It's structure allows three different commutation techniques to be applied: Hard Switching, Soft Switching and unipolar transistor commutation.

The Soft Switching technique implies that a transistor (*e.g.*, *T*2) to be maintained in conduction state (turned on) during the entire energizing cycle of a stator phase of the SRM, while the other transistor (*T*1) to be controlled *via* PWM pulses (AN1932, 2005; Monsef *et al*., 2013). This technique reduces the current ripple and also the electromagnetic torque ripple, thus being more advantageous than the Hard Switching technique.

The Hard Switching technique involves a simultaneous control of both transistors $T1$ and $T2$ *via* PWM pulses, during each energizing cycle (AN1932, 2005).

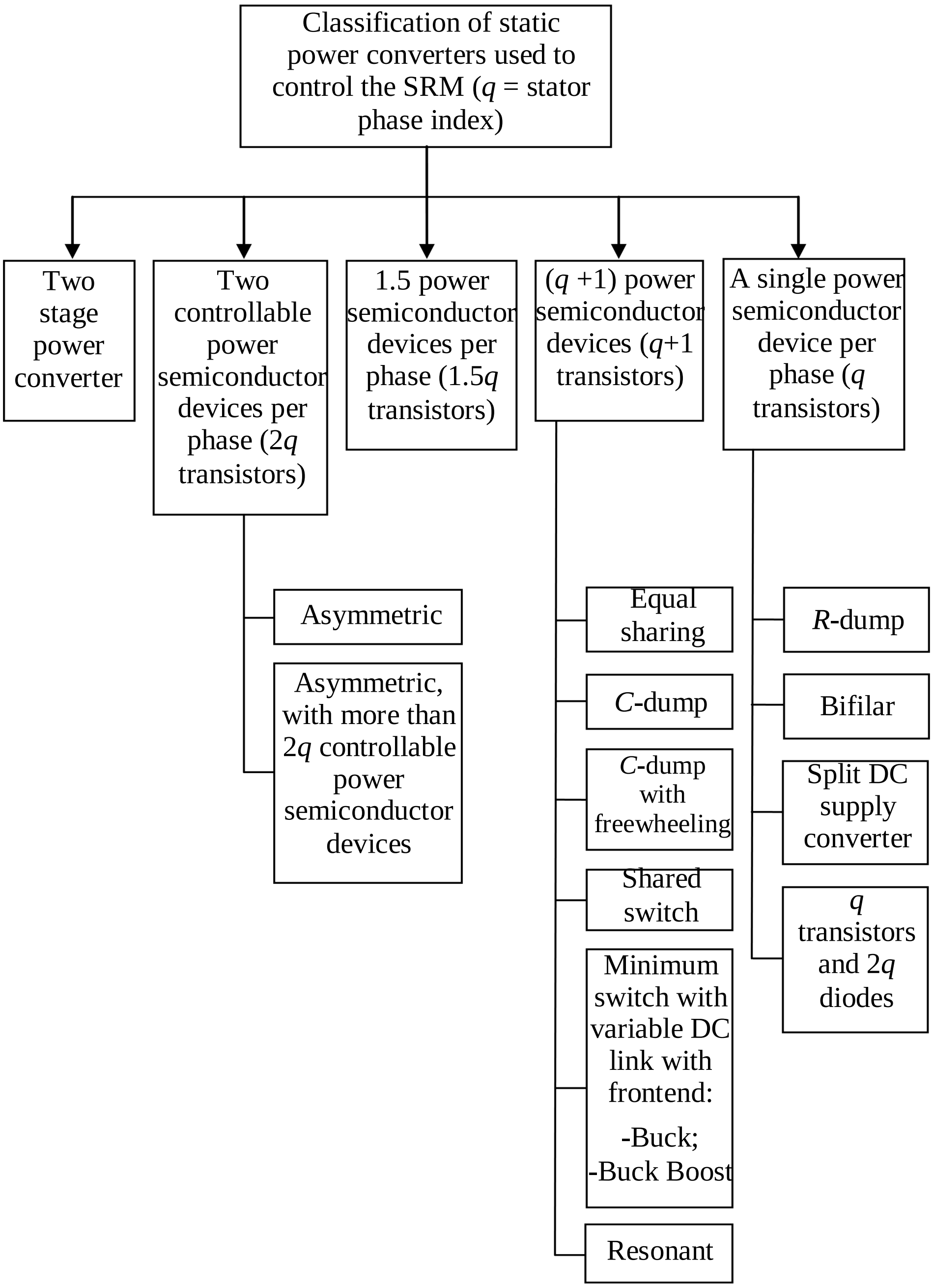

Fig. 1 – Classification of static power converters used to power the stator phases of the SRM (Krishnan, 2001; Ahn *et al*., 2010; Liang *et al*., 2010).

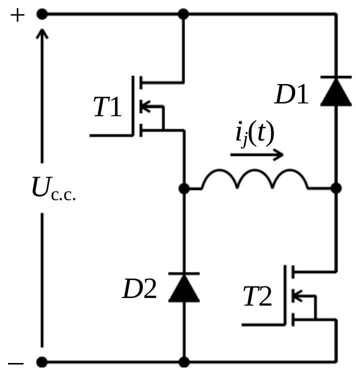

Fig. 2 – The structure of the asymmetric bridge power converter (Krishnan, 2001; Miller, 2003; Rolim *et al.*, 2008).

By modifying the Soft Switching strategy it can be obtained negative voltage polarity at the terminals of any stator phase winding of the SRM, for each negative values related to the corresponding error of the set current. This is done by comparing two signals, a triangular carrier wave of a given frequency and that a control modulating wave. This control strategy, which is referred as unipolar switching, provides an output voltage at the terminals of the static power converter of the same polarity as the current error (corresponding to the control signal). In this way, the switching frequency is doubled, which also contributes to mitigating the current ripple and thus the torque ripple (Krishnan, 2001).

2. The SRM Equations, Parameters and Simulink Block Diagram

The eqs. constituting the mathematical model of the switched reluctance machine which was implemented using MATLAB/Simulink software package and its relating parameters are shown as follows.

2.1. The SRM Equations

The voltage equation of each *j* stator phase is given by Faraday's law

$$u_j = R_j i_j + \frac{\mathrm{d}\phi_j(i_j,\theta)}{\mathrm{d}t} = R_j i_j + L_j(i_j,\theta)\frac{\mathrm{d}i_j}{\mathrm{d}t} + e_j(i_j,\theta,\omega_r), \tag{1}$$

where: $u_j(t)$ is the voltage applied to the terminals of the stator phase winding, [V], R_j – the phase resistance, [Ω], i_j – the current through the winding, [A], Φ_j – the flux linkage, [Vs], θ – rotor angle, [rad], L_j – phase inductance, [H], e_j – back-EMF (electromotive force), ω_r – rotor angular velocity, [rad/s] and j = 1, 2, 3 (or *a*, *b*, *c*) – the phase distinctive index.

Total magnetic flux of *j* stator phase is described by the relation (Biro *et al.*, 2005)

$$\phi_j(i_j,\theta)=\phi_\sigma(i_j,\theta)+\phi_{mj}(i_j,\theta)=L_{\sigma j}(i_j,\theta)i_j+L_{mj}(i_j,\theta)i_j, \tag{2}$$

where: $L_{\sigma j}(i_j,\theta)$ is the stator phase dispersion inductance, [H] and $L_{mj}(i_j,\theta)$ – the useful phase inductance, [H].

The rotor angular velocity is given by relation

$$\frac{\mathrm{d}\theta}{\mathrm{d}t}=\omega_r. \tag{3}$$

The torque, T_j, produced by the energized phase, is given by the derivative of the magnetic co-energy, W_{cj}, as a function of the angle θ which characterizes the position of the rotor, that is (Biro *et al.*, 2005)

$$T_j=\frac{\partial W_{cj}(i_j,\theta)}{\partial\theta}=\int_0^{i_j}\frac{\partial\phi_j(i_j,\theta)}{\partial\theta}\mathrm{d}i_j. \tag{4}$$

The eq. of motion (balance of couples) is the usual one

$$T_e=\frac{J}{p}\cdot\frac{\mathrm{d}\omega_r}{\mathrm{d}t}+T_L+\beta\omega_r. \tag{5}$$

where: T_e is the electromagnetic torque developed by the machine, [N.m], J – moment of inertia, [$\mathrm{kg}\cdot\mathrm{m}\cdot\mathrm{m}$], p – number of pair poles, T_L – the load torque, [N.m], β – friction coefficient.

For the analysis of nonlinear electromechanical energy conversion it must be taken into account the saturation of the ferromagnetic circuit (Krishnan, 2001). The co-energy, W_{cj}, and the magnetic field energy, W_{fj}, for each j stator phase are given by the following relations:

$$W_{cj}=\int_0^{i_j}\phi_j\mathrm{d}i_j, \tag{6}$$

$$W_{fj}=\int_0^{\phi_j}i_j\mathrm{d}\phi_j. \tag{7}$$

The relationship between energy (W_{fj}) and co-energy (W_{cj}), depending on magnetic flux and current, is shown in Fig. 3.

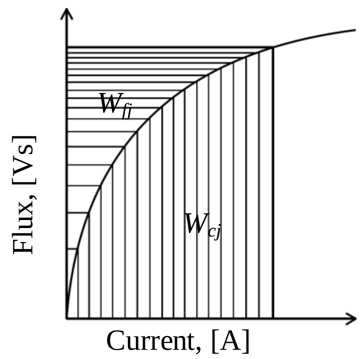

Fig. 3 – The relationship between energy (W_{fj}) and co-energy (W_{cj}), for a stator phase of the switched reluctance machine.

2.2 The SRM Parameters and Simulink Block Diagrams

The main Simulink block diagram corresponding to the mathematical model of the 6/4 switched reluctance motor, achieved through the equations previously described, is shown in Fig. 4.

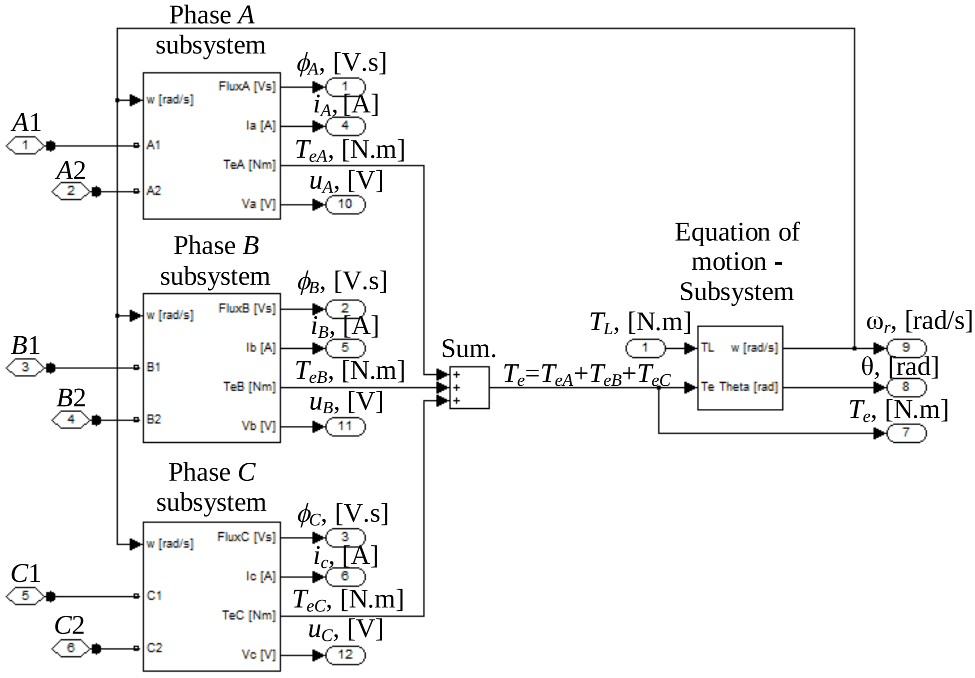

Fig. 4 – The main Simulink block diagram of the mathematical model corresponding to the 6/4 SRM.

The linear model of the SRM took into account the following aspects:

a) linear variation of the inductance profile of each stator phase;

b) triangular type form variation of each stator phase inductance;

c) saturation phenomenon of SRM ferromagnetic circuit, regardless of the magnitude of the current through each stator phase winding is ignored.

Considering these issues, the resulting parameters of the 6/4 SRM are presented in Table 1. Due to the lack of the saturation phenomenon of the ferromagnetic circuit, the aligned inductance (0.1 H) is ten times higher than the unaligned inductance (0.01 H), for any value of the stator phase current.

Table 1

Parameters of the Ideal 6/4 SRM

Parameter	Value
Stator resistance	0.1, [Ω]
Moment of inertia	0.001, [kg·m^2]
Friction coefficient, β	0.0002, [N·m·s]
Unaligned inductance	0.01, [H]
Aligned inductance	0.1, [H]
Maximum current	10, [A]
Maximum magnetic flux	0.1, [V·s]
Nominal Voltage	230, [V]

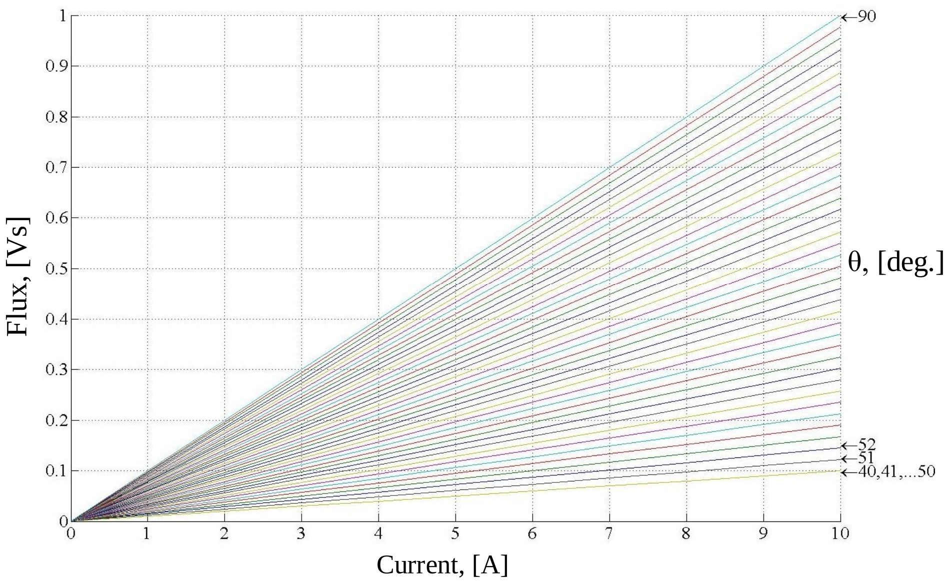

Fig. 5 – Phase magnetic flux *vs.* the phase current and rotor position angle.

Fig. 5 presents a graphic illustration of the stator phase magnetic flux, ϕ_j, [Wb], depending on the phase current, I_j, [A], and rotor position angle, θ (varying from 40 to 90 geometrical degrees).

Fig. 6 is a 3-D representation of the stator phase magnetic flux ϕ_j, [Wb], depending on the phase current, i_j, [A] and rotor position angle, θ, (for a complete rotation of the rotor, from 0 to 360 geometrical degrees).

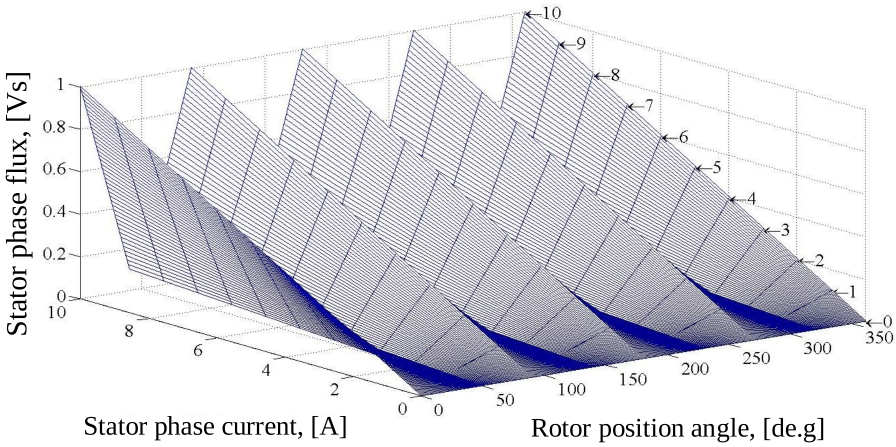

Fig. 6 – Stator phase magnetic flux *vs*. the phase current and the rotor position angle (3-D representation).

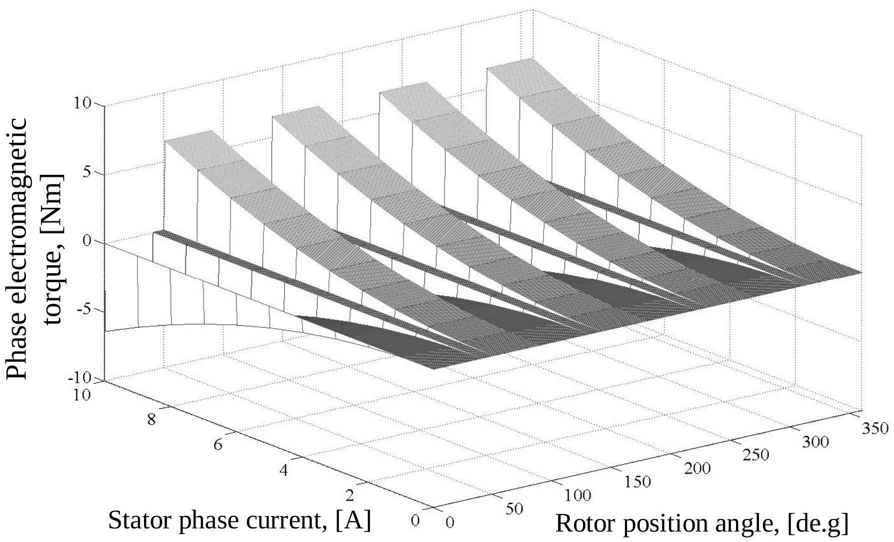

Fig. 7 – A 3-D representation of the electromagnetic torque developed by a stator phase of the machine, *vs.* the phase current, *i.e.* the rotor position angle.

Fig. 7 shows, in three-dimensional form, the electromagnetic torque, T_{ej}, [N.m], developed by a stator phase of the SRM, depending on the current, i_j,

[A], flowing through that winding and also depending on the mechanical position angle θ, [deg.], considering a full rotation of the rotor (360°).

3. SRM Control Principle Using Two Power Sources

Fig. 8 presents the main block diagram of rotor angular velocity and stator phase current control of the 6/4 SRM, when using two power sources of different voltage amplitudes. Each current and, respectively, angular velocity control loops is provided with a hysteresis type regulator, for maintaining the specified parameters within their prescribed values. The current error, ε_j, it is obtained by comparing the actual current, $i_j(t)$, through each stator phase winding with the reference value. The value of the resulting current error establishes the output value (0 or 1) of the hysteresis type controller. In the same way, by comparing the actual rotor angular velocity with the prescribed value, the speed error, $\varepsilon_{\omega r}$, results, which determines the output value of the corresponding hysteresis regulator. By comparing the output results of both the current and the speed hysteresis regulators through a logic gate (AND in this case), it is obtained the final result for the Gate Drive System. The gate drive system gives the appropriate signals to the power semiconductor devices (IGBT – Insulated Gate Bipolar Transistor) from the converter structure. The static power converter has a special topology, which allows two different voltage sources to be interchanged across the terminals of each stator phase winding, by predetermined control logic. The position sensor gives the actual angular velocity (dθ/dt) and by integrating it, results the rotor position angle, θ, which is then compared with the turn-on and turn-off angles for establishing the right interval for energizing the corresponding stator phase (Irimia *et al.*, 2013).

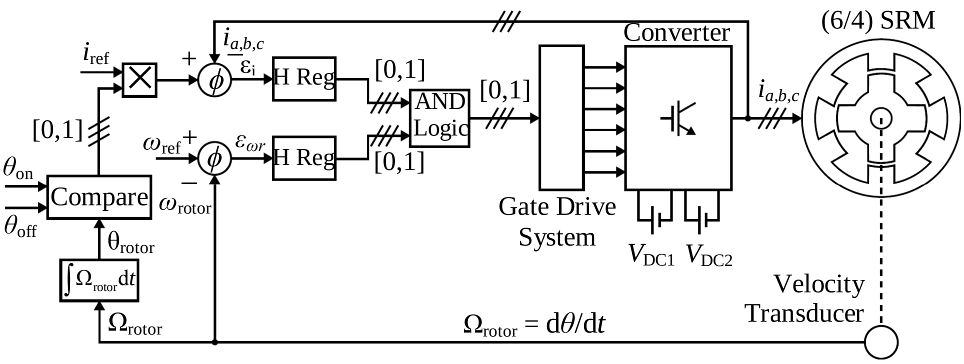

Fig. 8. The block diagram corresponding to the rotor angular velocity and phase current control loops of the SRM, when using two different power supplies (Irimia *et al.*, 2013).

By adopting the control technique with two different voltage values for energizing the stator phases of the 6/4 SRM, the resulting waveforms are illustrated in Fig. 9.

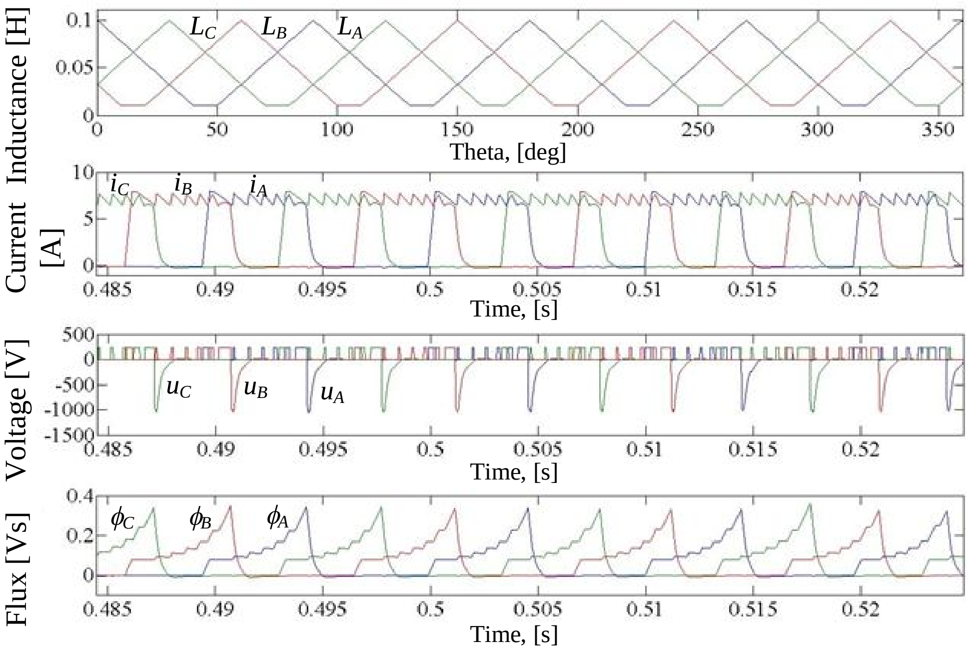

Fig. 9 – Waveforms corresponding to the operating regime of the 6/4 SRM, controlled by two different voltage values.

4. Simulink Control Scheme of the 6/4 SRM

The main control scheme of the SRM comprises (Irimia *et al*., 2013):

a) the rotor angular velocity and the stator phase current control loops, each being provided with hysteresis type regulators (controllers);

b) the rotor position sensor;

c) two power sources with different voltage values (1 and 5U_n);

d) the special topology static power converter and the associated control logic for the IGBTs;

e) the ideal 6/4 switched reluctance motor.

The rotor speed, ω_r , and the amplitude of each stator phase current, i_j, [A], are controlled through hysteresis regulators, maintaining them within certain prescribed limits. The rotor position sensor provides the angle θ, which is obtained by integrating the angular velocity of the rotor, $\omega_r = \mathrm{d}\theta/\mathrm{d}t$ (Irimia *et al*., 2013). The power supplies are two ideal DC voltage sources, first one providing the nominal voltage value (230 V) and the second one providing a five times higher voltage level (1,150 V) (Irimia *et al*., 2013). The special topology static power converter was designed for interchanging the two ideal voltage sources at the terminals of each stator phase (Irimia *et al*., 2013).

The ideal three phase SRM, comprises 6 stator poles and 4 rotor poles, with radial magnetic field. Each stator phase inductance has a linear variation (triangular form) and also lack of ferromagnetic circuit saturation phenomenon.

The main Simulink block diagram corresponding to the control strategy with two distinct power sources is shown in Fig. 10 (Irimia *et al.*, 2013).

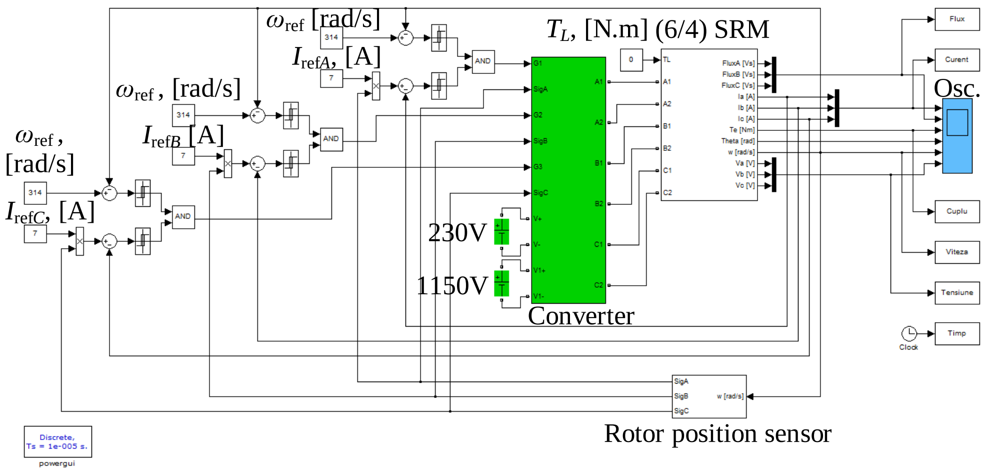

Fig. 10 – Simulink block diagram of the 6/4 SRM control system, using two different voltage sources (Irimia *et al.*, 2013).

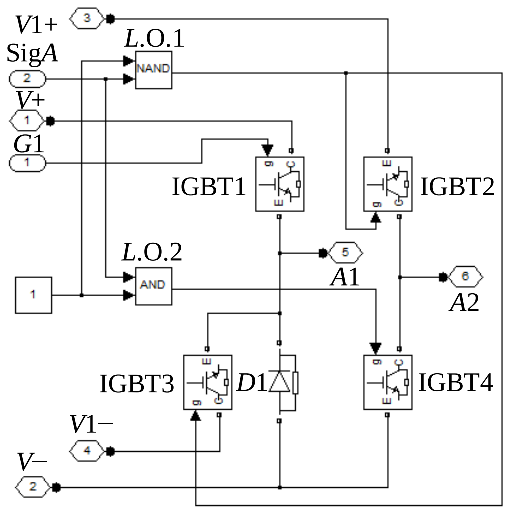

Fig. 11 – Simulink block diagram of the static power converter (special structure).

Simulink block diagram corresponding to the special topology static power converter is illustrated in Fig. 11. This static converter comprises four controllable semiconductor power devices of IGBT type, lettered from 1 to 4, and also one discharging diode, noted $D1$. This converter type also allows the implementation of both Hard Switching and Soft Switching techniques.

5. Simulation Results

Simulations was done through the software package MATLAB/Simulink, for different operating regimes of the ideal model corresponding to 6/4 variable reluctance motor. Some of these simulation results are presented as following.

Fig. 12 illustrates the waveforms of the magnetic flux of each stator phase, current through the windings, electromagnetic torque developed by the ideal SRM, angular velocity of the rotor and voltages at the terminals of any stator phase, during the start-up and the steady-state operating regime. In this case, the speed reference is set to ω_{ref} = 314 rad/s, the prescribed value of the stator phase current is I_{ref} = 7 A and the load torque, T_L = 3.1 N.m.

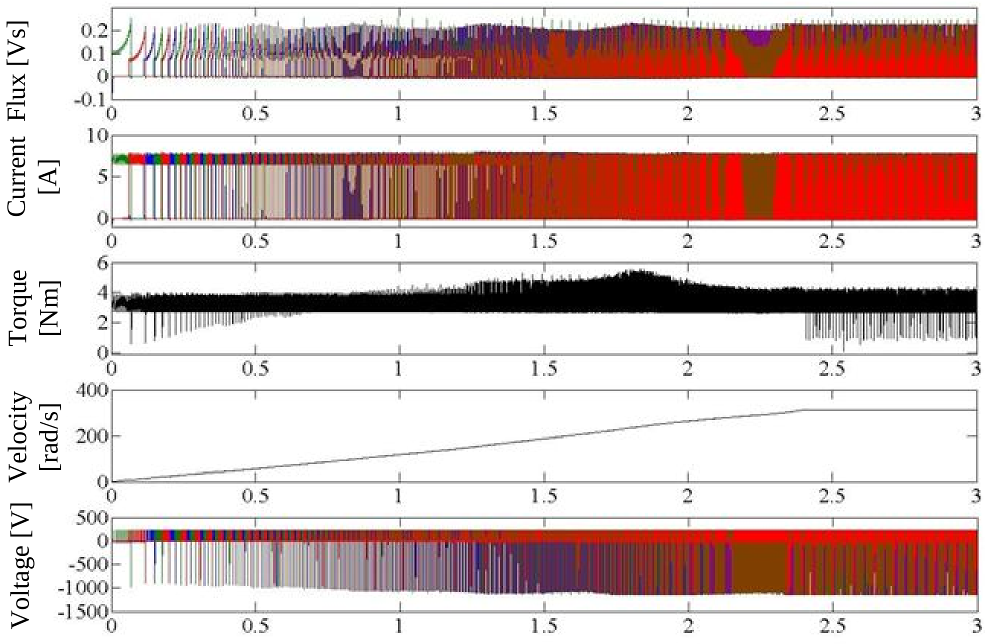

Fig. 12 – Waveforms corresponding to the start-up and steady-state operating regime of the ideal SRM, ω_{ref} = 314 rad/s, I_{ref} = 7 A, T_L = 3.1 N.m.

To highlight the co-energy transformed into kinetic energy at the motor shaft, Fig. 13 shows the electro-mechanical conversion cycle corresponding to a stator phase of the 6/4 SRM, in case of the steady-state operation regime, for the same conditions as mentioned in Fig. 12. The area delimited by the graph represents the co-energy transformed into mechanical energy.

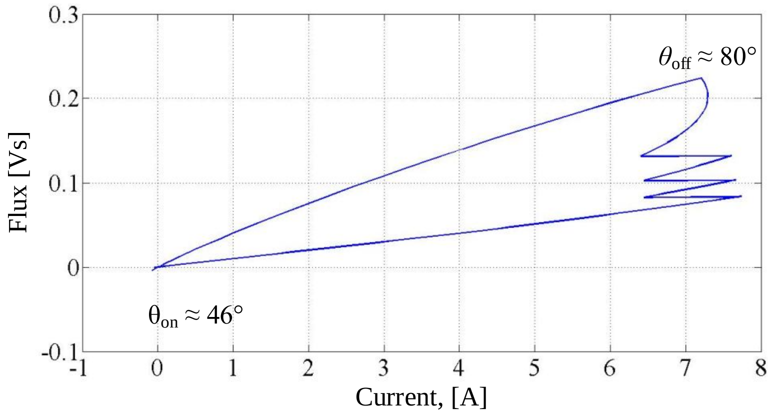

Fig. 13 – Electromechanical conversion cycle of one stator phase corresponding to the steady-state regime of the SRM, ω_{ref} = 314 rad/s, I_{ref} = 7 A, T_L = 3.1 N.m.

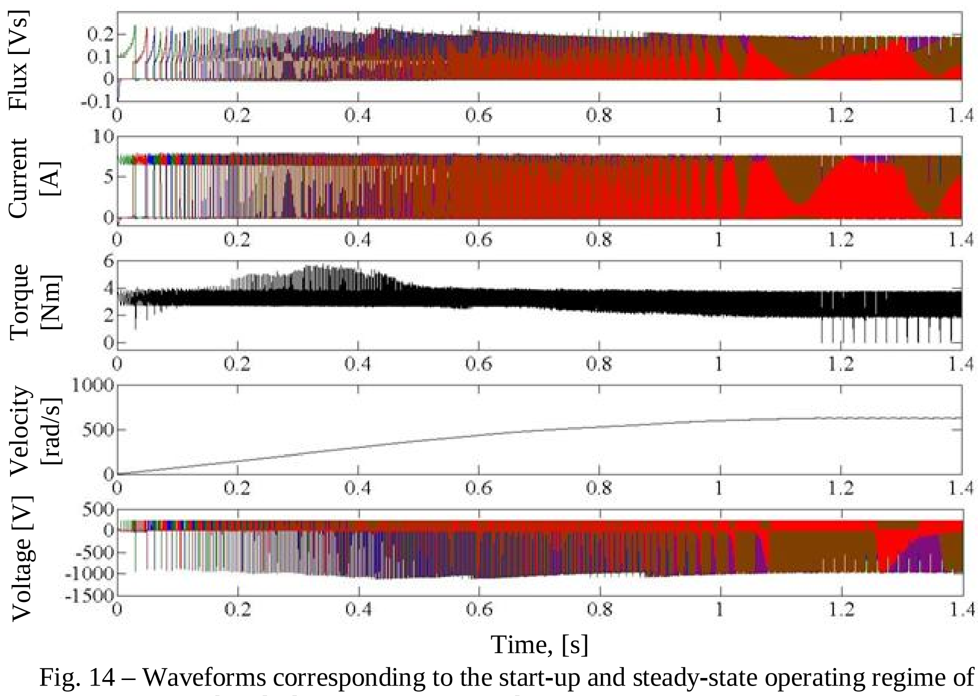

Fig. 14 – Waveforms corresponding to the start-up and steady-state operating regime of the ideal SRM, ω_{ref} = 628 rad/s, I_{ref} = 7 A, T_L = 2.5 N.m.

In Fig. 14 are shown the waveforms corresponding to the start-up and steady-state operating regime of the ideal SRM. In this case, the speed reference is ω_{ref} = 628 rad/s, the prescribed value of the stator phase current is I_{ref} = 7 A and the load torque T_L = 2.5 N.m.

Fig. 15 shows a zoom-in of the waveforms corresponding to the start-up and steady state operating regime of the SRM, for the same operating conditions as presented in Fig. 14. The waveform of the current is being elongated because of the high value of the back-EMF: $e_j = \omega \partial \phi_j (i_j, \theta) / \partial \theta$. If is desired to obtain a rectangular current waveform at high operating speeds as at the low speeds, each stator phase must be energized, at the beginning of any commutation cycle, with an appropriate voltage value that compensates the back electromotive force, e_j.

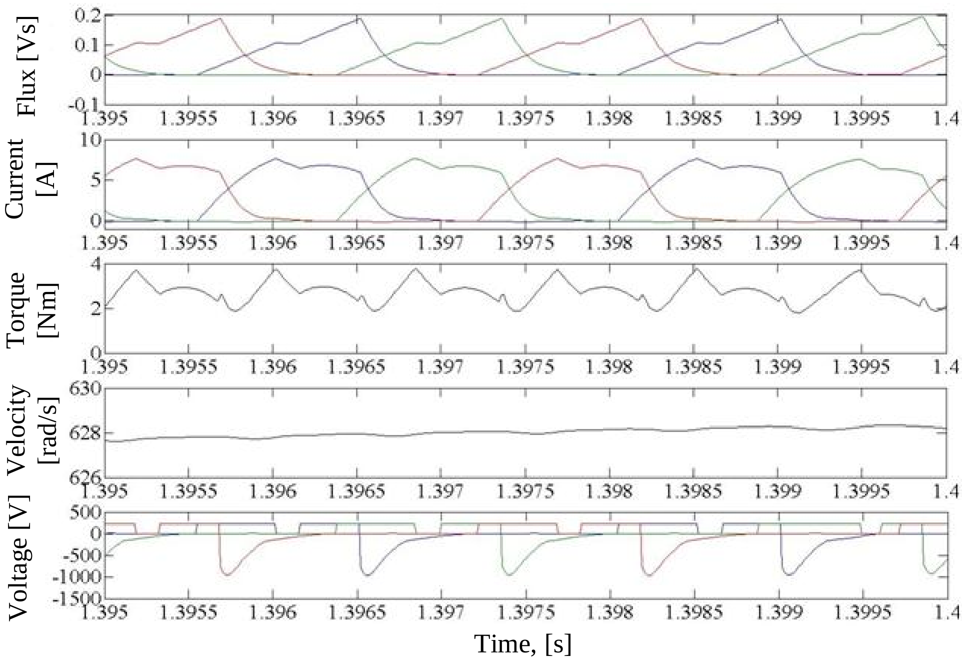

Fig. 15 – Zoom-in of the waveforms corresponding to the start-up and steady-state operating regime of the SRM, for the same conditions as in Fig. 14.

6. Conclusions

For energizing and, respectively, de-energizing each stator phase of the SRM during any commutation period, two distinct power sources with different voltage values (in this case: $U_1 = U_n = 230$ V and $U_2 = 5U_n = 1{,}150$ V) were utilized. By applying this method, the dynamic operating characteristics of the machine are significantly improved compared to other standard control techniques. Thus, the waveform of the current through each stator phase winding is better controlled, obtaining almost rectangular variation at low to medium operating speeds ($\leq$ 314 rad/s). Acceptable variations of the stator phase current are also achieved for higher working speeds ($\approx$ 628 rad/s). The current ripple is also reduced and, thus, the ripple of the resulting electromagnetic torque developed by the machine is proportionally minimized.

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COMANDA MAŞINII CU RELUCTANŢĂ VARIABILĂ TRIFAZATĂ UTILIZÂND DOUĂ SURSE DE TENSIUNE

(Rezumat)

Se prezintă comanda unei maşini cu reluctanţă variabilă trifazate (6/4) (SRM) (model idealizat) prin intermediul a două surse distincte de tensiune de amplitudini diferite (U_n, respectiv $5U_n$). Inductanţa fiecărei faze statorice are o formă de variaţie

liniară (profil triunghiular), iar circuitul feromagnetic al maşinii este caracterizat de absența fenomenului de saturație. Pentru a menține între anumite limite prescrise atât curentul prin fiecare înfăşurare de fază statorică, cât şi viteza unghiulară a rotorului, s-a utilizat câte o buclă de reglare prevăzută cu regulator de tip histerezis. De asemenea, pentru a obține o valoare cât mai redusă a riplului de curent, a fost adoptată tehnica (de comutație) Soft Switching. Prima sursă de alimentare furnizează la borne tensiunea nominală de 230 V. A doua sursă furnizează o valoare a tensiunii de aproximativ cinci ori mai mare, respectiv 1 150 V. La începutul, respectiv pe durata fiecărui ciclu de alimentare a oricărei faze statorice a maşinii, la bornele înfăşurării aferente se aplică tensiunea de valoare nominală. Astfel, curentul statoric creşte de la zero către valoarea de referință într-un interval de timp satisfăcător, fiind totodată menținut în jurul valorii prescrise prin intermediul buclei de reglare. La sfârşitul fiecărui ciclu de alimentare, la bornele înfăşurării de fază statorică se aplică, cu polaritate inversă, tensiunea de valoare ridicată. În acest fel, curentul descreşte într-o perioadă de timp de aproximativ cinci ori mai mică decât în situația clasică. Prin adoptarea acestei strategii de comandă, în cazul unor viteze unghiulare ale rotorului scăzute spre valori medii (≤ 314 rad/s), se obține o formă de undă a curentului de fază statorică apropiată de forma ideală dreptunghiulară. În lucrare sunt prezentate, de asemenea, o serie de rezultate obținute prin intermediul pachetului de programe MATLAB/Simulink, pentru diferite condiții de funcționare ale maşinii.