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Circuit-Field Model Of Switched Reluctance Motor

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***Abstract*— the paper presents the field-circuit model of a switched reluctance motor of 6/4 poles. The system of Differential equations enabling to carry out calculations for steady and transient states at single-pulse or (PWM) supply is given. The characteristics of flux linkages and torque were obtained from the field calculations. Basing on the circuit calculations there were obtained the waveforms of speed, currents and electro-magnetic torque at single-pulse supply during the motor starting as well as the waveforms of currents and torque at PWM supply. The motor speed-torque characteristics for different turn-off angles of the winding voltage were determined when assuming the constant speed at single-pulse supply**

Keywords—filed circuit ;Switch reluctance;single Phase; winding Voltage.

I. INTRODUCTION

Great interests in switched reluctance motors as well as numerous publications dealing with them appearing lately are due to the development of power electronics and increased possibilities of control systems that decide on the operating properties of such type of a motor. Because of their advantages SR motors can in many cases replace induction, brushless and synchronous with permanent magnet motors used so far. It especially refers to the drives with adjustable speed. A switched reluctance motor can be fed:

- In the single-pulse mode from a DC voltage source.
- From a controller with pulse width modulation (PWM) with the following type of control voltage, current (with a hysterics current controller) and torque.

The choice of the motor control way depends on the user's requirements. The control conditions may be optimized in order, for example, to achieve minimal torque pulsation, to limit currents, to minimize power losses in windings. The design of the SRM electromagnetic circuit is performed together with the design of its control system for the given parameters. In order to design the motor winding and magnetic circuit it is necessary to know the stator current waveform. This current as well as its rms value depends on the transistor commutation angles in the supply system (Fig.1).

The SRM properties (its characteristic and current waveforms) can be determined basing on two methods:

- Simplified analytical relationships of the current and torque waveforms are formulated when assuming the linear magnetic circuit, basing on the analysis of inductance distribution harmonics for various rotor positions [5].
- Computer programs enabling field and circuital calculations are used. The current and torque waveforms are obtained from the solution of the system of nonlinear differential equations describing the motor steady and transient states.

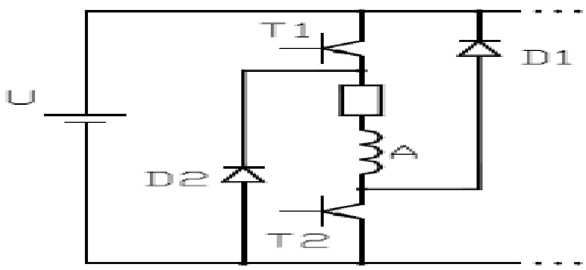

Fig.1. Controller circuit for one motor phase.

The research works performed nowadays dealing with the drives with SR motors are focused on the following problems:

- Modeling and optimization of switched reluctance motor construction and control.
- Choice of such a way of control which decreases torque ripples.
- Application of control systems basing on fuzzy logic.
- Elimination of rotor position sensors.
- Use of digital signal processors (DSP).

The field-circuit model of a 3-phase switched reluctance motor of (6/4) poles (Fig.3) enabling to calculate the motor properties for steady and transient states. The possibilities of calculations for various ways of motor supply are shown. The exemplary calculations were made for the designed electromagnetic circuit of a motor of the structure presented in Fig.3. There were assumed: supply voltage 36 V, rated torque M=1.5 Nm, and speed n=2100 rpm.

II. THE MOTOR MODEL.

In the considered model 3-phase winding with one phase coils connected in series and the supply system shown in Fig.1 were assumed. The following assumptions were made for the mathematical model: each phase can be treated separately; losses in the motor core, mechanical as well as eddy current losses can be neglected. At the single-pulse supply two stages can be distinguished in the operating cycle of each winding phase:

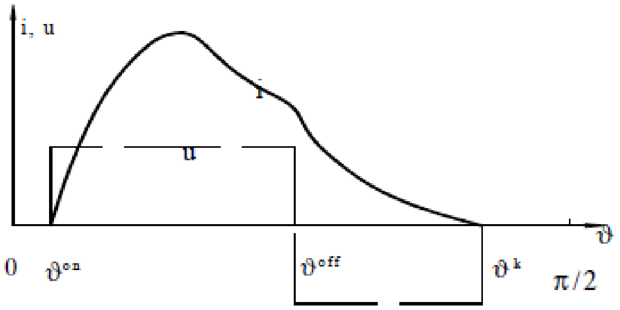

Fig.2. Phase current and voltage vs. rotor position.

1. For the angle range (ϑ_{on} / ϑ_{off}) both transistors T1 and T2 are turn-on and the supply voltage U is applied to the winding.
2. For the angle range (ϑ_{on} / ϑ_{off}) both transistors T1 and T2 are turn-off and the reversed supply voltage (-U) is applied to the winding through the diodes D1 and D2.

In the case of supply from PWM controller the transistor T2 is turn-on, whereas the T1 transistor is chopped with a fixed duty-cycle within the period (ϑ_{on} / ϑ_{off}). The canonical forms of the differential equations describing the SR motor with a load are as follows:

$$\frac{d_{i_K}}{dt} = \frac{1}{a(\vartheta, i_K)}[u_K(\vartheta) - R_{iK} - wb(\vartheta, i_K)] \qquad (1)$$

$$\frac{dw}{dt} = \frac{1}{j}(M_e(\vartheta, i) - M_0) \qquad (2)$$

$$\frac{d\vartheta}{dt} = w \qquad (3)$$

Where:

$$a(\vartheta, i_K) = \frac{d\psi_K}{di_K} \qquad b(\vartheta, i_K) = \frac{d\psi_K}{d\vartheta} \qquad (4)$$

$$M_e(\vartheta, i) = \frac{d}{d\vartheta}\int_0^1 \psi(\vartheta, i)di \qquad (5)$$

$$u_K(\vartheta) = \begin{cases} U & dla\ \vartheta_{on} \langle \vartheta \langle \vartheta_{off} \\ -U & dla\ \vartheta_{off} \langle \vartheta \langle \vartheta_x \\ 0 & in\ \ other..case \end{cases} \qquad (6)$$

- K=A,B,C–winding phase- winding resistance

  i_K current flowing through the K-th phase

Winding, ϑ rotor position angle , *w* - angular speed of rotor , ψ_K - flux-linkage of the K-th phase winding *j* - moment of inertia , M_e - electromagnetic torque , M_0 -load Torque.

In order to solve the system of equations (1÷3) one should determine the waveform of the supply voltage u_K of the particular phase windings in relation to the rotor position (6) and the assumed way of control. In each step of integration one must calculate the electromagnetic torque (5) and partial derivatives of the flux-linkages of the particular windings (4).

The motor operating characteristics are determined for the steady dynamic state (w =const). Than the system of equations (1/3) can be simplified to the one nonlinear differential equation (7) for the k-th winding voltages. In this equation the known characteristics for example of phase inductance $L_K(\vartheta, i_K)$ are used. The differential equation is given by:

$$\frac{di_K}{dt} = \frac{u_K(\vartheta) - Ri_K - wi_K \dfrac{dL_K(\vartheta, i_K)}{d\vartheta}}{L_K(\vartheta, i_K)} \qquad (7)$$

As a result of solving the numerical equation (7) the current time waveform is obtained. The rms current value is calculated, as it is essential from the point of view of winding design. The electromagnetic torqueses correspond to these current waveforms. One can determine the relation between the torque and the current as well as the rotor position: by means of field calculations (for example Maxwell tensor method) basing on the distribution of the magnetic flux density in the air gap (normal and tangential components) or from the magnetic field energy and the known inductances.

III. FIELD CALCULATIONS

The field calculations were carried out by the finite element method using the OPERA-2D program. In the calculations the zero boundary conditions (A=0) at the stator outer and rotor inner diameters were assumed. From the calculations the distributions of the magnetic vector potential in the machine were obtained (Fig.3) for various rotor positions and different currents. They were used for calculations of the flux-linkages, inductances, static torque, and flux density components in the air gap.

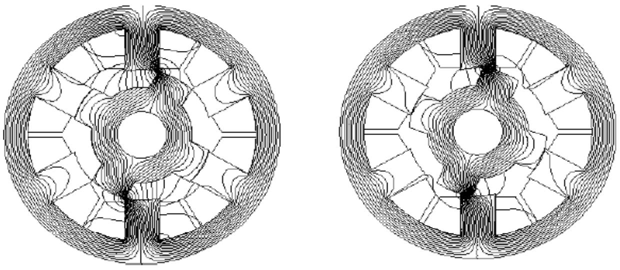

Fig.3. Vector potential distribution when supplying one of the phase winding I=10 A for different

The calculations of the end winding leakage inductances were made analytically. The obtained values were added to those determined from the field calculations. For the calculated points the approximation by means of the spline functions was made. That way the distributions of the flux linkage (Fig4a) and the torque (Fig.4b) as a function of the current and rotor position were obtained. These functions were used for circuital calculations. Fig.3. Vector potential distribution when supplying one of the phase winding I=10 A for different.

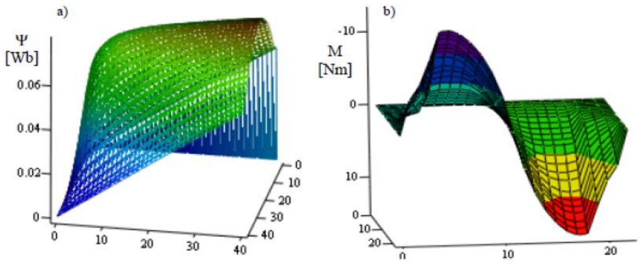

Fig.4. Flux-linkage (a) and static torque, (b) as a function of current and rotor position.

IV. CIRCUITAL CALCULATIONS

The circuital calculations were carried out by means of the MATHCAD procedures for solving differential nonlinear equations. For the transient states the system of differential equations (1-3) was solved, whereas for the steady states the equation (7). It is possible to obtain the waveforms of the chosen quantities for various ways of motor control when assuming the supply conditions.

A. Simulation results of the transient states at single pulse supply.

Fig.5 shows the calculated time waveforms of speed (Fig5a), electromagnetic torque (Fig.5b), Phase currents (Fig.5c) during the motor starting at the single

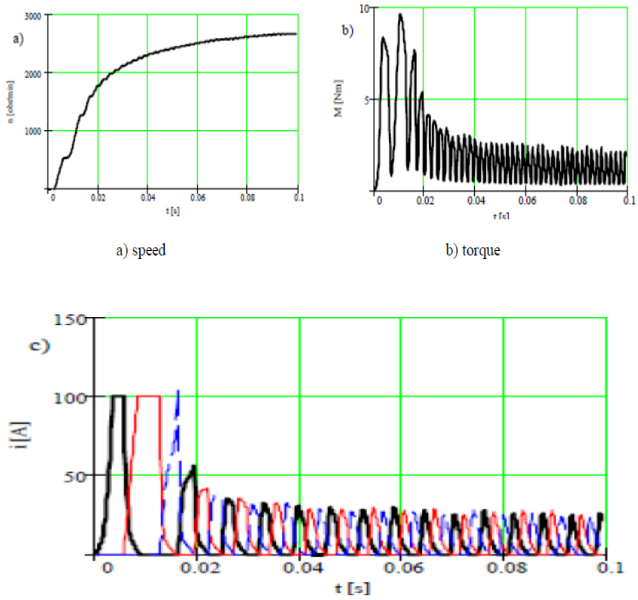

Fig.5. Time waveforms: a) speed; b) torque; c) phase currents during the motor starting For M =1.5Nm ϑ_{on} =0 deg, ϑ_{off} =30 deg

Pulse control, turn-on angle $\vartheta_{on} = 0$, turnoff angle off $\vartheta_{off} = 30$ deg and the current maximum value limit. From the presented waveforms it can be seen that great values of currents and electromagnetic torque occur at the single pulse supply at the Initial instants of the starting. Hence, it is advisable to limit this current in practical realizations.

B. Simulation results at the constant speed and single pulse supply.

When designing, choosing the winding and motor operating characteristics it is sufficient to analyses motor steady state when assuming the constant speed. Solving the nonlinear differential equation (7) for the chosen winding at the fixed control angle one obtains the current waveform. Then, one calculates numerically the current rms value, the source output active power, electromagnetic torque and its average value. Fig.6 presents the current waveforms versus the rotor position for one of the windings at single pulse supply for different turn-off angles and various speeds. The calculations results reveal the strong influence of the speed and control angles on the values as well as time waveforms of the current and electromagnetic torque. The single supply is more advantageous at high speeds. From calculations for various control and load conditions it is possible to obtain the motor operating characteristics. For the fixed load torque they make it possible to determine for instance the range of the speed and currents at the control angle changes. The motor speed - torque characteristics $n = f(M)$ for different turn-off angles are shown in Fig.7a. The characteristics $I_{RMS} = f(M)$ presented in fig.7b allow for determination of the phase currents for various loads and turn-off angles. So, they are necessary at the motor design stage.

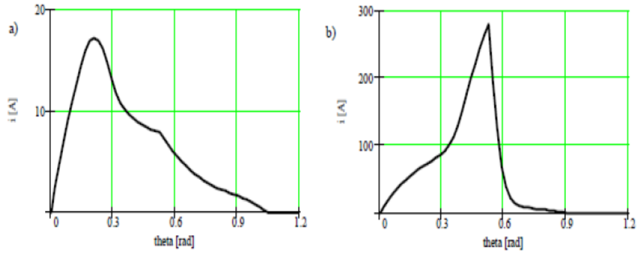

Fig.6. Currents vs. the rotor position at turn-on angle $\vartheta_{on} = 0$ deg; turn-off angle $\vartheta_{off} = 30$ deg and speed: a) n=4000 rpm, b) n=1000 rpm.

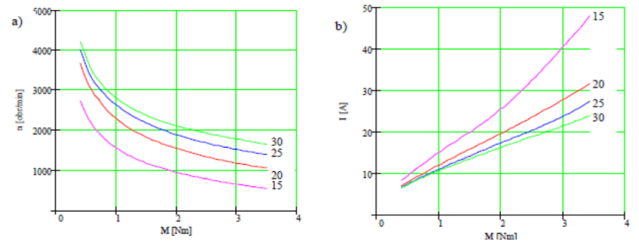

Fig.7. Characteristics at turn-off angle within $\vartheta_{off} = 15 \div 30$ deg, turn-on angle ϑ_{on} =0

a) speed-torque, b) rms current-torque

C. *Simulation results at constant speed and PWM supply*

It is possible to obtain the time waveforms of the phase current from the equation (7) when assuming properly the T2 transistor chopping frequency (Fig.1). The duty-cycle change of the chopping period influences the maximum and rms current values. The exemplary current waveforms (together with the winding voltage waveforms) and the torque waveforms versus the rotor position at the duty-cycle w=0.5 are shown in Fig.8a. At PWM supply one can influence the motor properties much greater by fixing the limits for the current minimum and maximum values at the given speed than by using the constant chopping frequency. The exemplary waveforms of the current voltage and torque are given in Fig.8. Basing on the calculations and the presented pictures one can draw a conclusion that the use of PWM supply results in decrease of the maximum values of currents and torques, in the smaller range of the current and torque changes and the lower torque ripples. So, one can considerably influence the motor sped-torque characteristics by changing the voltage duty-cycle (besides changing turn-on and turn-off angles) at PWM control.

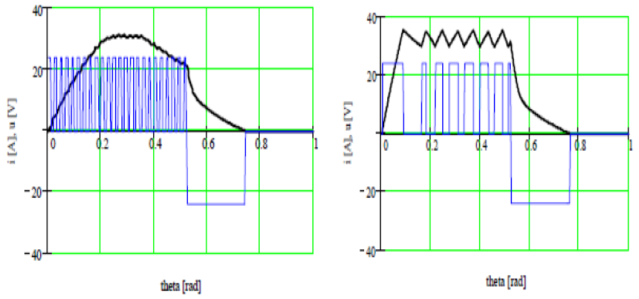

Fig.8.Phase current and voltage as a function of the rotor position, for:

a) ϑ_{on} =0 deg; ϑ_{off} =30 deg; n=1000 rpm; w=0.5,

b) ϑ_{on} =0 deg; ϑ_{off} =30 deg; n=1000 rpm; for the fixed current limits.

V. CONCLUSIONS

The field circuit model of a switched reluctance motor is presented in the paper. The computation possibilities that can be useful for motor design are shown. They allow for the determination of the motor operating properties in the steady as well as transient states at the single pulse or PW supply. The motor properties for different ways of control are compared.

REFERENCES

[1] Anwar M.N., Husain I.: Design of a Switched Reluctance Machine for Wide-speed Range Operation. Proceedings of International Conference on Electrical Machines. ICEM'2000, 28-30 August 2000, Espoo Finland, pp.1581-1585.

[2] Besbes M., Gabsi M., Hoang E., Lecrivain M., Grioni B., Plasse C.: SRM design for starteralternator system. Proceedings of International Conference on Electrical Machines. ICEM'2000, 28-30 August 2000, Espoo Finland, pp.1931-1935.

[3] Inderka R.B., De Doncker R.W.: Simple average torque estimation for control of switched reluctance machines. Proceedings of the 9th International Conference on Power Electronics and Motion Control EPE-PEMC 2000, Košice Slovak Republic, pp.5.176-5.181.

[4] Miller T.J.E.: Switched Reluctance Motors and their Control. Magna Physics Publishing and Clarendon Press Oxford. 1993.

[5] Záskalicky P.: Behaviour of the single-pulse operation switched reluctance motors. Prace Naukowe Instytutu Maszyn, Napędów i Pomiarów Elektrycznych Politechniki Wrocławskiej. Studia I Materiały. Nr 48. Wrocław 2000, pp.245-251.