A SPEED CONTROL STRATEGY FOR SWITCHED RELUCTANCE MOTOR

Ioan-Felician Soran, Istvan Sztojanov, Dragoş Ovidiu Kisch, Sever Paşca

Electrical Engineering Department, University Politehnica of Bucharest,
313 Splaiul Independentei, 060032 Bucharest, Romania,
phone: +4021 348 1735, e-mail: ioansoran@yahoo.com

The article describes how to set up a speed control strategy with a good dynamic for a Switched Reluctance Motor (SRM) fed by a voltage source. The article states that before establishing the strategy, it is appropriate to obtain a map of control angles limits (θ_{ON} and θ_{OFF}) in order to enable the current extinction at any work speed. The article also proposes a study of torque production in the second quadrant of $\Omega - M$ frame to facilitate an efficient braking.

Keywords: speed control, switched reluctance motor, control techniques

1. INTRODUCTION

The models of a 6/4 SRM are straightforward because an apparently simple equation can describe the performance of an active phase:

$$u = Ri + \frac{d\psi}{dt} \tag{1}$$

Since the mutual inductance between the phases is very low, the same equation is also valid for a simultaneous conduction of two phases. The control of such a machine demonstrates that the simplicity is a trap because the flux $\psi(\theta, i)$ is strongly nonlinear. The performance is strongly dependent on the control strategy. The subject is still present in the literature, as there is not a unique and efficient solution to the list of issues: good dynamic in the four quadrants of $\Omega - M$ reference frame, reduced torque ripple, optimisation of losses (winding losses and eddy currents losses), noise minimisation etc. There is a lot of interesting survey articles which present the state of the art in SRM control. We have used for this purpose the charts [1] and [2]. According to them, there are the following important categories of control strategies:

- **Flat-topped currents methods** were the first control methods, improved by the use of $m_e - i - \theta$ functions obtained by calculation or experiment.
- **Torque-sharing and current shaping (TSF) methods** propose to share the torque production between two phases which are in conduction in a part of the duty cycle. By using such methods, torque ripples are diminished.
- **Linearization and Decoupling Techniques – LDTs,** need a good nonlinear SRM model, with all possible nonlinearities. The phase decoupling is done by a state nonlinear controller that offers a quasi-linear performance of the phase which produces the great amount of torque at that moment.

– **Control techniques for a large area of speed** use a split of phase current in a flux component and a second component dependent on rotor position. The algorithms based on this idea can minimize the torque ripples or losses.

The paper presents a complete non-linear model of SRM that takes into account the saturation of magnetic circuit and rotor position. This model offers the $m_e - i - \theta$ functions and a suitable form of equations for numeric integration.

The proposed method controls the torque production in order to ensure a high dynamic of an SRM drive. The nonlinearities of the phase flux are taken into account with an equation that has a simple form. The magnetization characteristics have the form given in Fig. 1. They are described with a good precision [3] by the equation (2):

$$\psi(\theta,i) = \frac{i}{a_1(\theta) + a_2(\theta)\cdot i + a_3(\theta)\cdot i^2} \tag{2}$$

where $a_1(\theta), a_2(\theta), a_3(\theta)$ are continuous functions of rotor position angle θ.

The idea of separating the effect of current and position is not a new idea, it can be found in [4], but the form (2) has some essential advantages, like the identification of $a_1(\theta), a_2(\theta), a_3(\theta)$ functions and a simple form of $i = F(\psi, \theta)$ function.

The torque production was investigated in connection with the safe conditions of current extinction in the first and second quadrant of the $\Omega - M$ reference frame. A map of extreme values for θ_{ON} and θ_{OFF} at any speed and any sign of torque was identified and drawn. The proposed control strategy uses this map to ensure the necessary torque in a dynamic conduct.

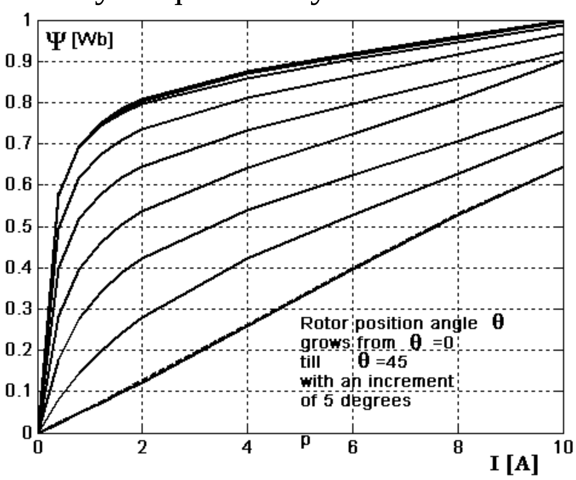

Fig. 1. The magnetization characteristics of SRM

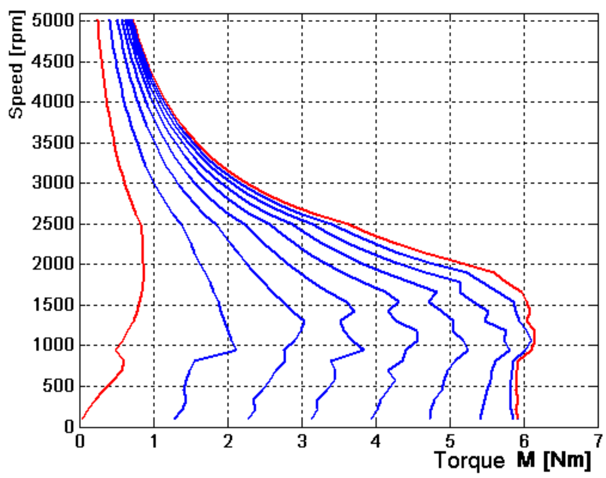

Fig. 2. Mechanical characteristics in the first quadrant of $\Omega - M$ frame

The above characteristics describe a machine of rated power P_N = 1 kW, rated speed n_N = 2000 rpm and rated voltage U_N = 240 V.

The mechanical characteristics of SRM are given in Fig. 2 in the first quadrant of the $\Omega - M$ frame. The parameter of family is the turn-on angle θ_{ON}. The duty cycle is variable because the turn-off angle θ_{OFF} is constant for a given speed according to the map of extreme value of the angle. To ensure the phase current's turn-off, the maximum value of the control angle θ_{OFF} moves slightly from 86°, for 500 rpm to 70° for high speeds such 5000 rpm.

2. Control at Low Speed

The phase current evolution is strongly dependent on speed because of the induced voltage by rotation. The phase voltage equation (1) can be developed in order to outline its components:

$$u = Ri + \frac{d\psi(\theta,i)}{dt} = Ri + \frac{\partial\psi(\theta,i)}{\partial i}\frac{di}{dt} + \frac{\partial\psi(\theta,i)}{\partial\theta}\frac{d\theta}{dt} \tag{3}$$

The component

$$\frac{\partial\psi(\theta,i)}{\partial\theta}\frac{d\theta}{dt} = \Omega\frac{\partial\psi(\theta,i)}{\partial\theta} \tag{4}$$

represents the induced voltage by rotation.

At low speed, the current derivative is high and the phase current has to be limited by a hysterezis current controller. The maximum value of duty cycle

$$\Delta\theta_c = \theta_{off} - \theta_{on} \tag{5}$$

can have significant values of nearly 35 – 38 degrees. Taking into account the ideal duty cycle for a 6/4 SRM, at low speed, the conduction of two phases can be superposed in order to grow the developed torque. The current extinction is produced by a negative phase voltage. The duration of the current extinction, the so called "train", is reduced as we can see in Fig. 3.

Special attention has to be paid to the maximum value of control angle θ_{OFF} that permits a safe extinction of the current at every speed. At low speed, "the current train" is short enough and θ_{OFF} can be placed close to 90°.

In Fig. 3 the torque harmonic content is reduced. We can extend the definition of THD by considering the useful value of the mean torque as "important". The *harmonics content* ***hc*** will be:

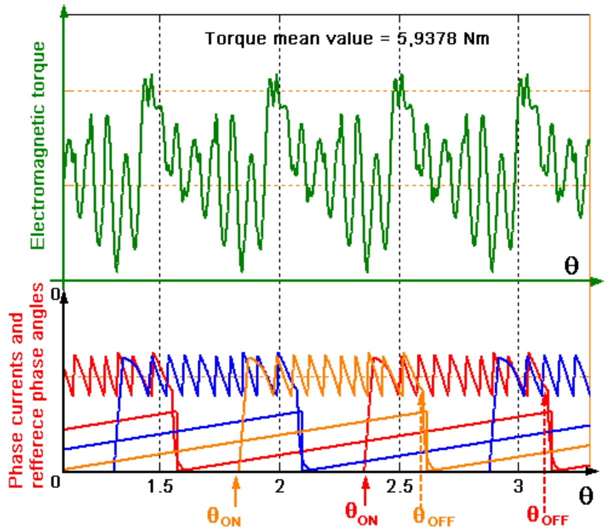

Fig. 3. Phase currents at low speed

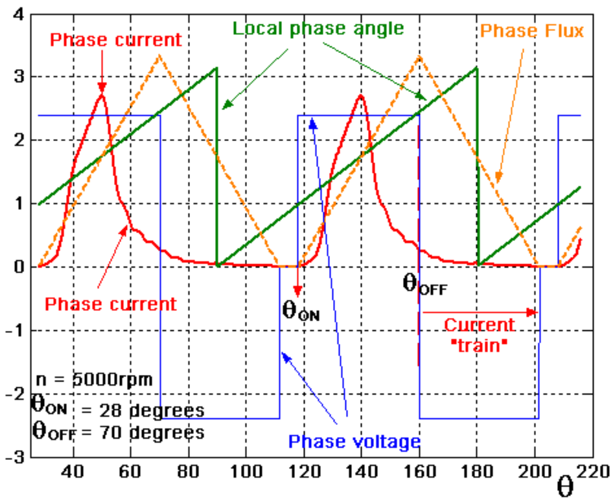

Fig. 4. Current evolution at n = 5000 rpm

$$hc_M = \sqrt{1 - \frac{M_0^{\ 2}}{\sum_{k=1}^{\infty} M_k^{\ 2}}} \tag{6}$$

For extended phase conduction, the harmonics content is low. In Fig. 3 we have *hc* = 0.3874. For low electromagnetic torque, the control angle θ_{ON} will progress, the duty cycle will be smaller than the ideal value of $\Delta\theta_c = 30^\circ$ and the harmonics content will increase.

3. CONTROL AT HIGH SPEED

At high speed, the induced voltage by rotation becomes more and more important. The consequences of this growth are visible at the beginning of the duty cycle: the current cannot grow at the limited value by current controller, but it remains under this limit. The current slope has the form given by equation (7) where it is obvious that for a constant feeding voltage $u = U_0$ the voltage component (4) diminishes the current slope.

$$\frac{di}{dt} = \left[\frac{\partial\psi(\theta,i)}{\partial i} \right]^{-1} \left[u - Ri - \frac{\partial\psi(\theta,i)}{\partial\theta}\frac{d\theta}{dt} \right] \tag{7}$$

On the other hand, at the extinction command by θ_{OFF}, the "current train" passes into the region where the flux slope $\frac{\partial\psi(\theta,i)}{\partial\theta}$ becomes negative. Therefore, the quantity between brackets can become a very small negative quantity and the current extinction will be in danger!

$$-U_0 - Ri - \Omega\left(-\frac{\partial\psi(\theta,i)}{\partial\theta} \right) \tag{8}$$

This becomes obvious in Fig. 4 which presents the current evolution at high speed.

The torque has high harmonics content and the ratio Torque/Current will be small. This is the reason why a good control strategy will maintain the control angle θ_{OFF} at its upper limit and the torque control will act upon control angle θ_{ON}.

4. BRAKING THE ROTATION

For a good dynamic response in the braking period, a negative torque has to be developed. It is not enough to develop a smaller torque than the load torque! Both control angles have to "move" in the area of phase "local angle" $0 < \theta < 45^\circ$. At this point, the usual current control of first quadrant of $\Omega - M$ frame is not more efficient. The hysteresis controller doesn't limit the current by applying $u = 0$ because the flux derivative against angle is not positive anymore. Fig. 5 shows current growth beyond the "old limit" of 6 A in spite of applied voltage $u = 0$.

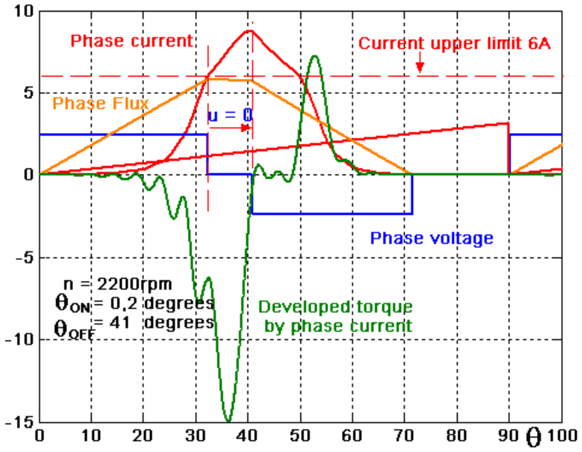

Fig. 5. Current evolution for negative mean torque

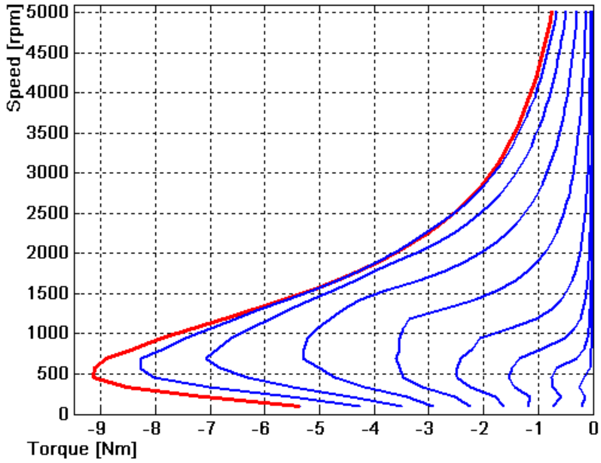

Fig. 6. Mechanical characteristics in the second quadrant of $\Omega - M$ frame

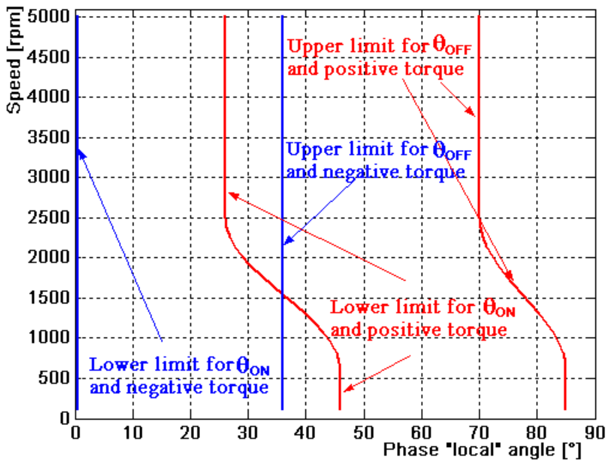

Fig. 7. Allowed zones for control angles

This evolution leads to greater absolute values of torque in the quadrant II of $\Omega - M$ frame, as shown in Fig. 6, which is positive for machine dynamics.

This careful analysis finally allows creating a very useful map for the control angles limits when the machine develops a positive or negative torque. This map is presented in Fig. 7.

5. SPEED CONTROL

The structure of speed control diagram has two control loops in cascade, the inner current loop with a hysteresis current controller. The outer loop has a PI speed controller with limited output signal. The significance of the output signal of a speed controller is a "necessary torque". There is equivalence between torque and control angle. Consequently, the output signal will be θ_{ON} control angle and its limited value will be about the half of the angle width between the limits given in Fig. 7. If a negative torque has to be produced, the output signal of the speed controller will be moved in the region of negative torque. The strategy ensures the control stability in a large area of load torques and speeds.

The dynamic of a speed control for an imposed $\Omega(t)$ is given in Fig. 8.

It has to be pointed out that the speed control in the first quadrant runs very well at any load torque with the same controller parameters Kp and Ki. It can be seen that the load torque of 2.5 Nm is very close to the torque limit at $250\ rad / sec \Rightarrow 2387\ rpm$ given in Fig. 2.

Very similar results can be obtained at speed reversal, as shown in Fig. 9. These excellent results were possible by using the extreme values permitted for positive and negative torques.

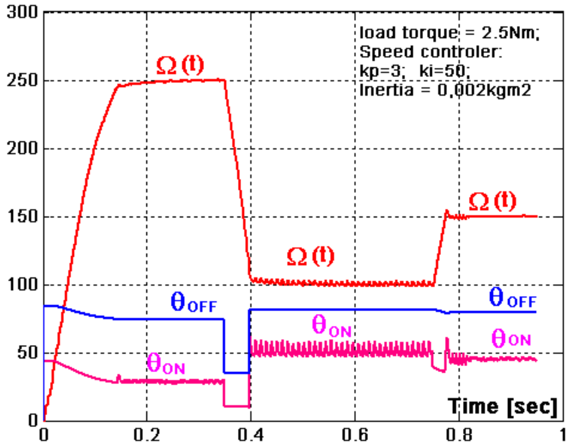

Fig. 8. Speed control in the first quadrant of $\Omega - M$ frame

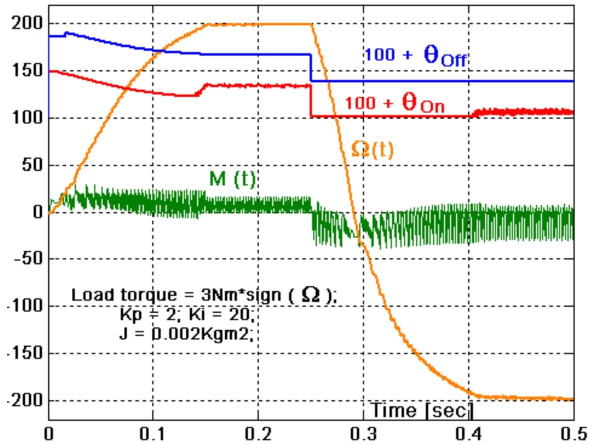

Fig. 9. Dynamic of speed reversal

6. Conclusions

A good dynamic of speed control can be obtained only by using the maximum permitted values of torque.

To obtain these limits for every permitted speed, a careful study of current evolution and extinction has to be done.

The authors propose the use of a control angles limits map for positive and negative torque before setting up a control strategy.

The proposed strategy is validated by virtual experiment (computer simulation).

The scope of the exposed strategy was only the dynamic of speed control. In the future, we intend to move from the command in a dynamic conduct to a command that minimizes the losses in a steady state operation.

7. Acknowledgment

The research concerning the dynamics of SRM was supported by Excellence Research Program CEEX No. 132/2006.

8. References

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