# Optimized Control for Switched Reluctance Motor

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## Abstract

*The switched reluctance motor has become a competitive choice for several applications in electrical machine control system, because of its simplicity and robust construction. In this paper we will present a structure, modeling and simulation of 8/6 SRM based on closed loop hysteresis current control.*

*Due to the nonlinearity of the SRM hysteresis is a simple way in implementation, it allows in accordance of a closed loop to improve performance of the SRM.*

## 1. Introduction

SRM are very attractive for many industrial applications due to its simple fabrication, its high speed, its low cost and its better yield. Compared to AC/DC machines, SRM holds two main advantages:

- It is a very reliable machine as each phase is largely independent: physically, electrically and magnetically, compared to the phases of other machines;
- it can reach very high speeds (20,000 to 50,000 rpm) due to the shortage of conductors or magnets in the rotor;

Despite the simplicity of its fabrication and its good magnetic characteristics, the SRM is very unused. The complexity of its control and high torque ripple that is develops constitute its main handicap. This article treats, in a first time, the equations model the SRM, the structure of the inverter then the command structure simulated on Matlab / Simulink.

## 2. SRM MODEL

NOTATIONS
Vk : Phase voltage
Ik : Phase current
R : Resistance per phase
$T_{ek}$ : Electromagnetic torque
$\Phi_k$ : Flux in stator pole
$\boldsymbol{\omega_r}$ : Rotor speed
$\boldsymbol{\theta}$ : Rotor position
$L_k$ : Phase inductance
$T_L$ : Load torque
J : Rotor inertia
B : Coefficient of friction

We consider the basic structure of the SRM 8/6 shown in Figure 1.

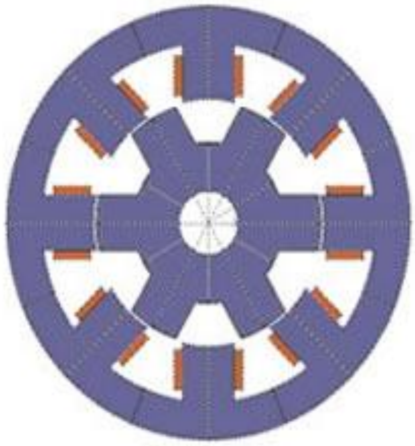

Figure 1. Structure of the 8/6 SRM

The voltages across the windings can be calculated by[1]:

By neglecting mutual effect, the stator pole flux is defined as the product of the inductance of one phase and current there through.

.

$$\boldsymbol{\Phi_k(\theta) = L_k(\theta, i) I_k(\theta) \qquad k = 1, 2, 3, 4\,.} \qquad (2)$$

The rotation speed of the SRM is given by:

$$\boldsymbol{\omega_r = \frac{d\theta}{dt}} \qquad (3)$$

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By replacing the flux, and the speed by expression (2) and (3), the equation (1) becomes [2] :

$$V_k = RI_k(t) + I_k(t)\frac{dL_k(t)}{dt} + L_k(t)\frac{dI_k(t)}{dt} \quad (4)$$

The mechanical equation of the SRM is written:

$$j\frac{d\omega_r}{dt} = T_e - T_L - B\omega_r \quad (5)$$

When the magnetic circuit is not saturated, the electromagnetic torque is given by:

$$T_{ek} = \frac{1}{2}\frac{dL_k}{d\theta}I_k^2 \qquad k = 1, 2, 3, 4. \quad (6)$$

We note that the sign of the torque does not depend on the current direction. For an engine torque, the phase must be supplied when the inductance is increasing, and to obtain a brake torque, the phase must be supplied when the inductance decreases.

The average torque can be written as the superposition of torques of each motor phase:

$$T_e = \sum_{k=1}^{4} T_{ek} \quad (7)$$

## 3. Inverter structure

The asymmetric bridge shown in Figure 2, is the basic for the SRM, it allows the direct recovery of energy towards the source. It uses two main switches per phase. The two per phase recovery diodes ensure the return of the energy accumulated during the active phase to the source.

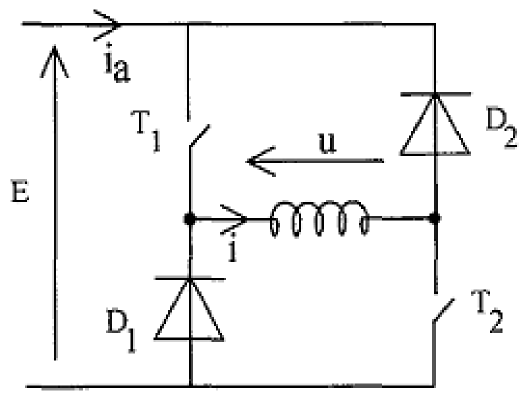


Figure 2. Structure of asymmetric bridge.

The power supply of the phase is done by closing and opening, simultaneously, the both switches at the beginning and at the end of a step. During the latter, and to control the current, T1 and T2 are controlled through a hysteresis loop.

## 4. SRM closed loop control structure

The proposed simulation model is shown in Fig.3:

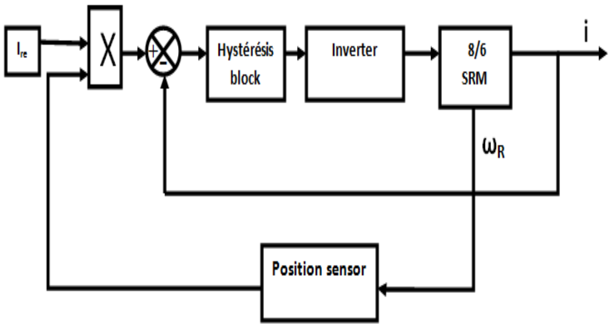


Figure 3. SRM control structure

The model is divided into several separate blocks, such as the position sensor, inverter, hysteresis block, etc. The detailed implementation of the various blocks is developed.

The current is controlled according the rotor position and a current reference. This reference is allows according to the load torque.



### A. Simulink SRM 8/6 model

The block representing the SRM, consists of a non-linear electrical model and a mechanical model. Figure.4 shows the construction of this block.

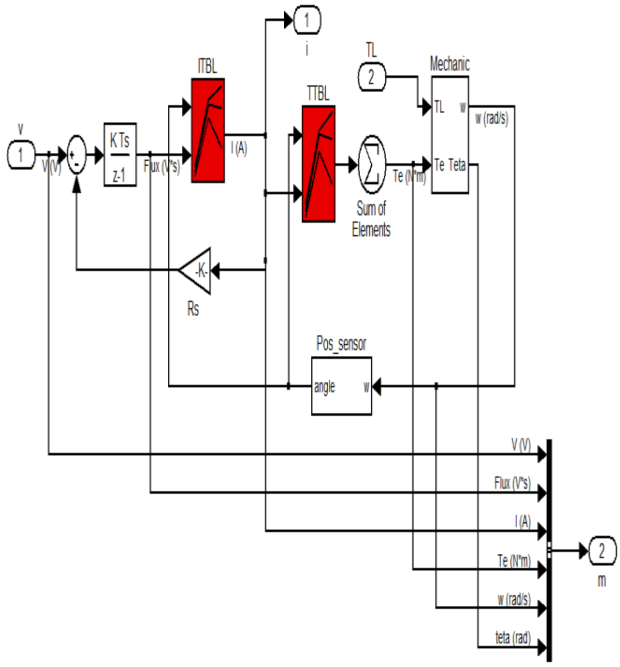


Figure 4. Electromechanical model of the SRM

The inputs of the SRM model are the tensions measured at the input of the connector. The magnetic flux in the windings is obtained by integrating the difference between the input voltage and the voltage drop in the winding resistance.

Controlled current sources are used to inject the current produced by the nonlinear function ITBL (i ( $\Phi$ , $\theta$ )) in the stator windings. The electromagnetic torques produced by each stator winding are obtained by the non-linear function TTBL (Te (i, $\theta$ )) and summed later to give the total torque produced by the machine.

The electrical model is associated to the mechanical model which represents the mechanical dynamic of the SRM. It is obtained from the equation of motion (5). Figure 5 shows the Simulink block diagram of the mechanical model

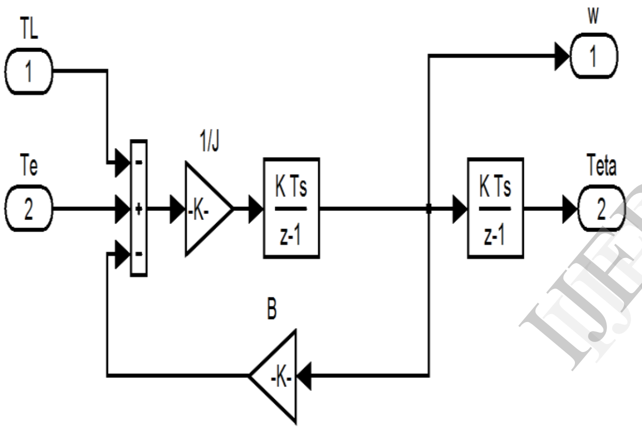


Figure 5. Matlab / Simulink Block of the mechanical model



## B. Position sensor block

The function of this block is to select the winding to supply, through the angle of the rotor's angular position from the referent angle zero in an electrical cycle. For a variable reluctance machine 8/6, each inductor has a periodicity of 60 ° (2π / 6 = 60 °), therefore, we must transform the rotor position angle [5], calculated from the mechanical equation, so that it is modulo 60 °. Modulo 60 ° is achieved with the real function in Matlab / Simulink as shown in fig.6:

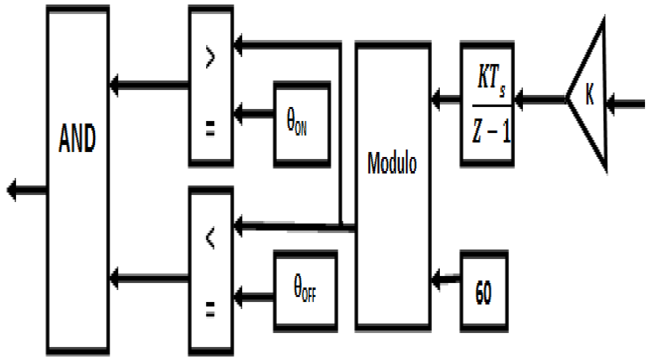


Figure 6. Position sensor Block

## C. Hysteresis Block

The control signal from the difference between the reference current and the measuring current is applied to the input of a hysteresis comparator, it is held between two forks IM and Im as shown in fig.7.

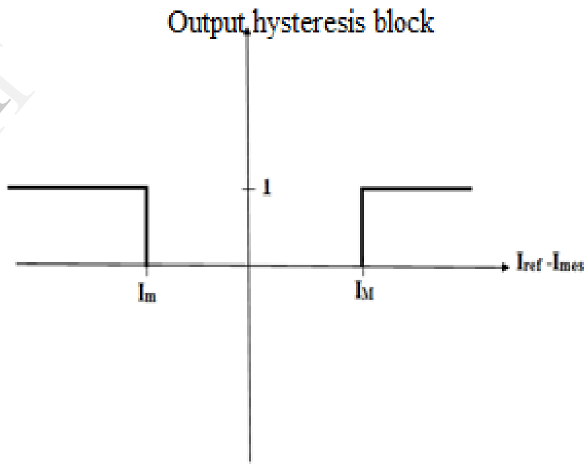


Figure 7. Transfer function

The Hysteresis block is performed by Matlab / Simulink with a comparator block "Relay" with which the hysteresis band is kept constant.

## D. Inverter block

As the studied machine has four phases, the inverter will include four asymmetric bridges [6], one for each phase, the phases are electrically independent.

In the simulation by Matlab / Simulink we use IGBT for the switches T1 and T2

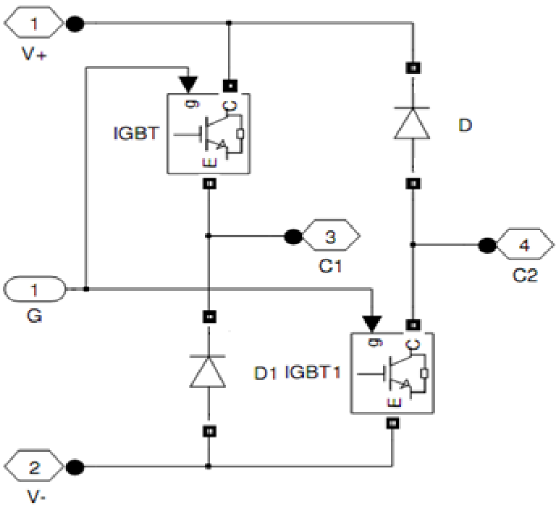


Figure 8. IGBT based asymmetric bridge.

## 5. Simulation results

The global simulation schema used on Matlab / Simulink is shown in Fig.9:

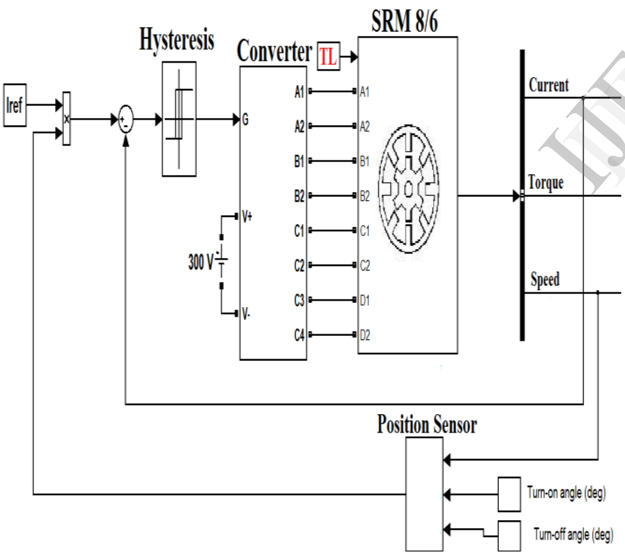


Figure 9. Complete schema of the simulation in Matlab / Simulink

The simulation results are obtained for a constant load torque TL=150N.m with $\theta_{ON}$ = 32.5, $\theta_{OFF}$ =52.5 and $I_{ref}$=250A $I_M$ =12.5A $I_m$=-12.5A SRM parameters are given in Table .1.

| | |
|---|---|
| Stator resistance (ohm) | 0.05 |
| inertia (Kg.m.m) | 0.05 |
| Friction(N.m.s) | 0.002 |
| Initial speed and position | 0,0 |
| unaligned inductance(H) | 0.67e-3 |
| aligned inductance (H) | 23.6e-3 |
| Saturated aligned inductance (H) | 0.15e-3 |
| Maximum current (A) | 450 |
| Maximum flux linkage (V .s) | 0.486 |

Table 1. SRM simulated parameters

The results obtained are presented in 'Fig10','Fig11', and 'Fig12':

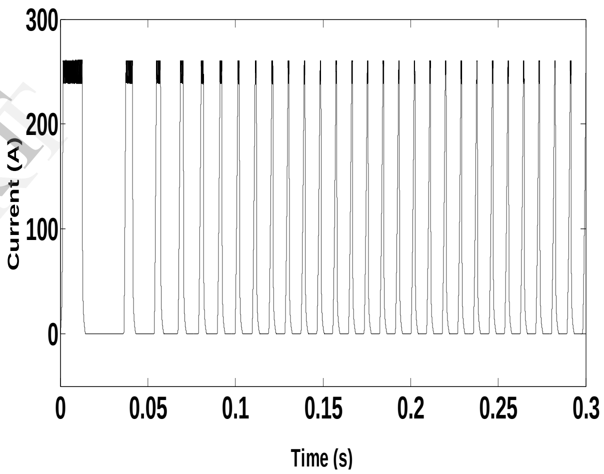


Figure 10. Current evolution at one phase

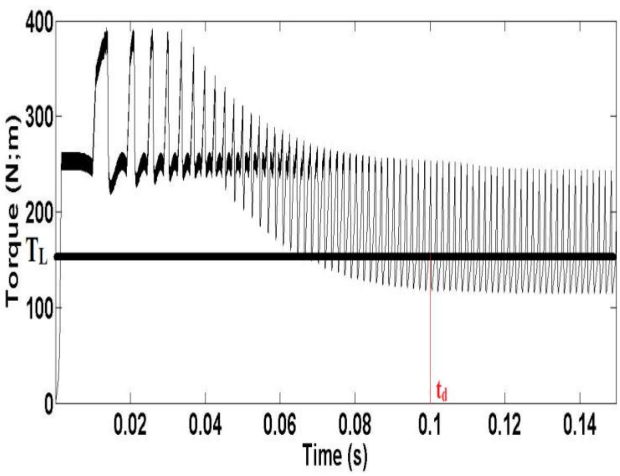


Figure 11. Torque evolution

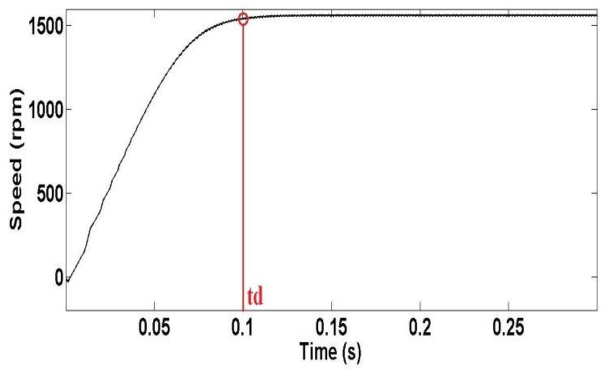


Figure 12. Speed evolution

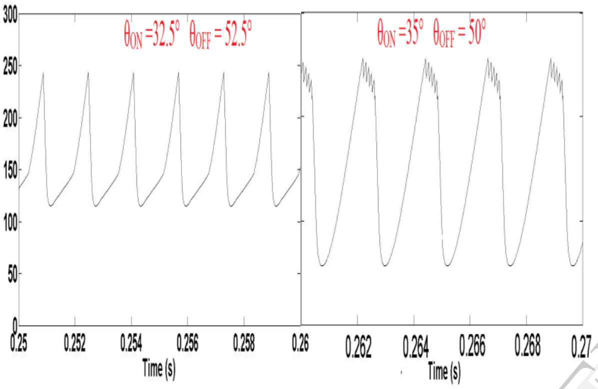


Figure 13. Torque ripples comparison for two values of $\theta_{ON}$, $\theta_{OFF}$

Interpretation of results:

The powers supply during the interval [$\theta_{ON}$, $\theta_{OFF}$]; where the inductance L increases, allows to achieve the maximum desired value of the phase current from the angle $\theta_{ON}$; The current increases linearly from zero. The use of Hysteresis, with a relatively narrow band, allows the regulation of the current. In this case, the current value is held in the desired band between IM and $I_m$ for low rotational speeds. Therefore the torque is kept constant during the conduction interval. A good choice of control angles $\theta_{ON}$ and $\theta_{OFF}$ is essential for proper motor control in this interval.

For the last interval where L is decreasing, a negative voltage is applied to accelerate the decay of the current and thus avoid the development of a negative torque.

The torque ripple and consequently the velocity oscillations are obviously due to the effects of the sudden switch in this command, which clearly introduces harmonics in the torque signal via the phase current.

Generally, it is noted that the angle corresponding to the power failure is longer than that corresponding to its establishment and this is due to the fact that the inductance is higher in conjunction than in opposition.

## 6. Conclusion

In this paper, we studied a switched reluctance machine 8/6, its inverter structure and its control by hysteresis. The SRM can be controlled by a non-linear and hysteresis-based command, but that would be with high torque ripple.

The application of this study on SRM 8/6 with load, has given good results in simulation, at the control accuracy and speed. But the torque ripples are not mastered, which leads us to seek solutions to stabilize the torque around its setpoint.

## 7. REFERENCES

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