Proceedings of the 2012 International Conference on Industrial Engineering and Operations Management
Istanbul, Turkey, July 3 – 6, 2012

Simulation and Determination of the Laws Control of the SRM for the Integrated Starter Generator Application

M. Boudouda
GMP-CReSTIC Laboratory
University of Champagne-Ardenne
9, Rue du Québec 10023 Troyes Cedex - France

F. Naceri and S. Belkacem
Department of Electrical Engineering
University of Batna, Algeria

Abstract

This paper deals with the design of an integrated starter generator system for a car flywheel based on the Switched Reluctance Machine (SRM) technology. First, we discuss about the starter generator problematic following the results of our bibliography research, and secondly, we briefly remained generalities about the SRM and the determination of the laws control. In addition, we have designed the converter associated to the machine using (Matlab/Simulink) software in order to identify the laws control and to adapt to the operating modes (motor, generator, booster, brake). Finally, simulations of the open and closed loop model were performed on the converter with machine (SRM).

Keywords
Switched Reluctance Machine (SRM), Starter-Generator, law control, Matlab-simulink, Dspace

1. Introduction

The demands of the European automotive sector to reduce fuel consumption and pollutant emissions necessitate an optimized exploitation of electrical energy [1]. In this type of system, an electrical device should function as both a motor and generator [2], operate at high power variations under very wide speed range. In addition, this application must be embedded in a car. This implies that the physical envelope is highly constrained (limited to the space available under a hood) and the temperature could vary from -30°C to +130°C .Moreover, the end users require that these solutions should be reliable, robust and inexpensive. For this application, the switched reluctance machine appears because of its robust structure, a better solution than other types of machines, such as asynchronous machines or the wound rotor of synchronous machines [3]. That is why the work presented here suggests evaluating the potential of this technology. Initially, the paper presents the problem of the starter/generator based of the switched reluctance machine (SRM). Then, we detailed the constitution, the principle and the SRM structure. Finally, simulations were carried out in order to validate technical specifications for all operating modes (starter, generator, booster, braking) and to determine the laws control on open loop, then closed loop [4]. .

2. Starter Generator Problematic

During the last few years, the automotive manufacturers have been interested in combining the starter and the generator into one unit [5]. The concept of this integrated starter/generator system is to use an SRM that incorporates the flywheel mounted on the crankshaft between the engine and the gear box [6] which is shown in Figure 1.

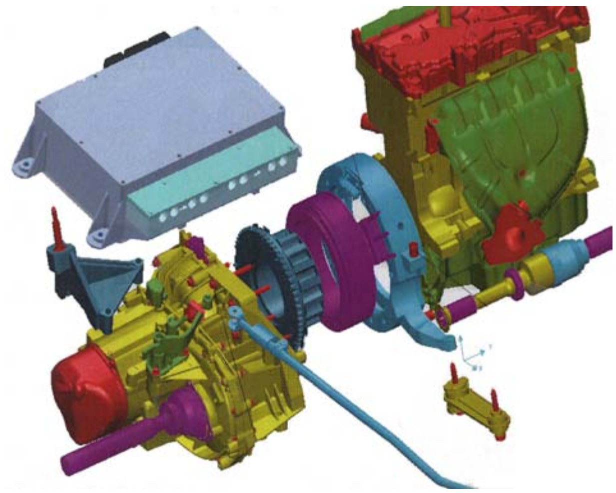


Figure 1: The flywheel mounted on the crankshaft

A. Choice of the Starter Generator based on the switched reluctance machine

The SRM was chosen for the structural simplicity, low cost, robustness, capability to develop high torque at low speed and good efficiency. It is successfully used in many applications such as: electric traction motors, starter-generators for aircraft engine [7], high speed application. However, it has some disadvantages auto-control necessity, high current ripple and a consequently noise

B. Integrated Starter Generator Functions

This system must ensure the following operating modes:

- Starting: From 0 to 100rpm, the system should ensure the starting of the engine during a time not exceeding a few milliseconds, then the SRM must provide a high torque about 160Nm in order to activate the thermal engine pistons
- Generator: From 800rpm the SRM should function as a traditional alternator in order to recharge the engine battery and provide the power for the accessories: headlights, and various actuators (Figure 2). It must deliver a constant power of 3KW between 800-6000rpm.
- Booster : Stop and Go function for urban traffic, i.e. the restarting of the thermal motor in order to decrease the pollutants emissions
- Braking : Assisting the engine in decelerating

3. Switched Reluctance Machine

A. Constitution of the SRM

This type of switched reluctance machine [8], has a toothed rotor with Nbtr: number teeth of the rotor and a toothed winding stator with Nbts: number teeth of the stator. This machine does not comprise the excitation circuit (see fig.1). The two pole parts are carried out by sheet stacking of ferromagnetic material.

B- Flux- Position- Amps- Turns diagram

In the Switched reluctance machine, the flux varies versus the rotor position and the amps turns injected into a phase: $\boldsymbol{\Phi = \text{function}\ (N_s.i,\ \theta\ ).}$ As shown in Figure 3, we represent the characteristic of the machine and this form of the inductance (or of permeance) [9].

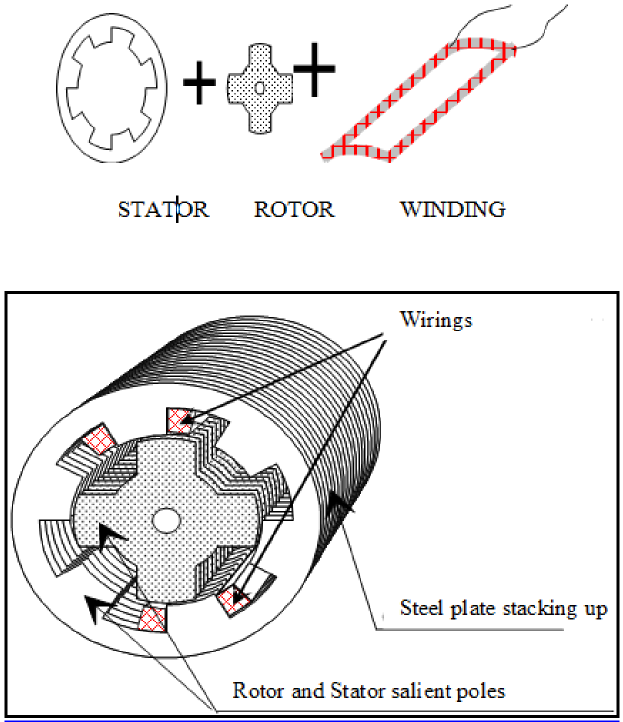


Figure 2: Constitution of the SRM

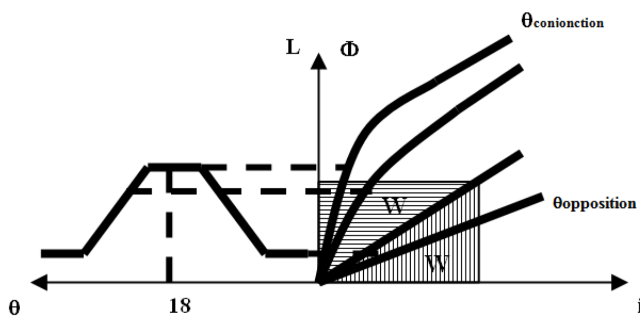


Figure 3: Flux- position- amps-tour diagram

The notions of Energy and Coenergy are defined by

Energy: $\boxed{Wem = \int i \cdot \partial\Phi}$ *Eq.. 1-1*

Coenergy: $\boxed{Wcem = \int \Phi \cdot \partial i}$ *Eq.. 1-2*

Which is represented the hatched surfaces on the Figure 3.

4. Geometry of the Starter Generator

Figure 4 shows the geometry of SRM. Figure 5 illustrates the saturation phenomenon which occurs when current values exceed 100amps. Electromagnetic characteristics:

- q = 3 Number of phases
- Ns = 10 Number of wires per phase
- Nbdr = 16 Rotor tooth number
- Nbds = 24 Stator tooth number
- Pn = 3 kW Nominal power

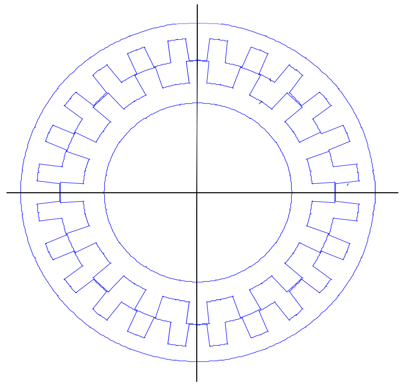


Figure 4: Geometry of SRM 24/16

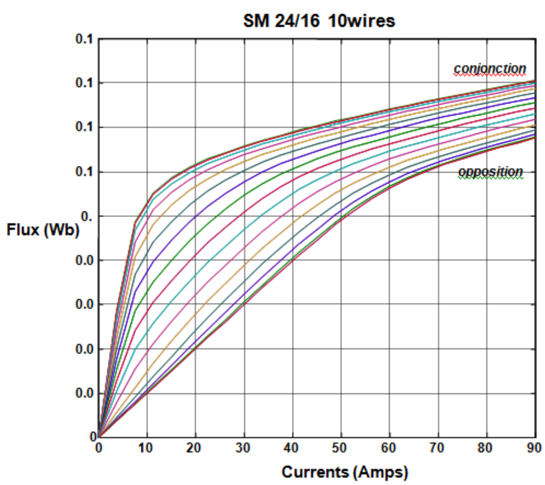


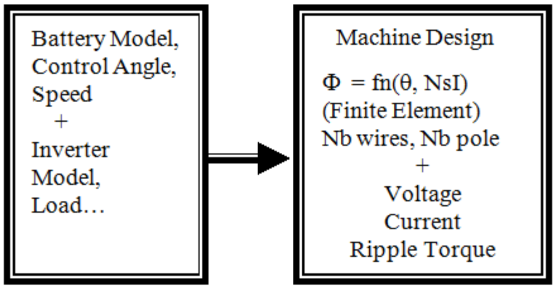
Figure 5: Flux- position- amps- turns SRM 24 /16 diagram

5. **Simulations**

This part presents our simulation model of the switched reluctance machine (starter/generator). We explain the determination of the control angles [10] in order to identify our strategic command for each operating mode. We also developed the control parameters for the look up tables for the closed loop system.

A. Simulation principle

The purpose is to simulate the function of the switched reluctance machine in motor and generator operating mode from static data Flux = function (position, current) calculated by finite elements. Schematically, we numerically solve the principal equation for different control angles, for input speed under a battery voltage, while taking into account a number of other sensitive parameters of the Electro technical system. The principle schematic is as follow:



Electrical Equation

The following equations describe the voltage (V) applied into the machine phase [9] :

$$V = r \cdot i + \frac{d\Phi(\theta, i)}{dt} = r \cdot i + Ns \cdot \frac{d\phi(\theta, i)}{dt}$$
$$V = r \cdot i + Ns \cdot \left[\frac{di}{dt} \cdot \frac{\partial \phi(\theta, i)}{\partial i} + \frac{d\theta}{dt} \cdot \frac{\partial \phi(\theta, i)}{\partial \theta} \right]$$
$$\omega = \frac{d\theta}{dt} = \frac{\omega_e}{Nbdr}$$

Eq.. 1-3

In the linear case: $\phi = L(\theta)i$ and the last equation can be written as :

$$V = r \cdot i + Ns \cdot \left[L \cdot \frac{di}{dt} + i \cdot \omega \cdot \frac{dL}{d\theta} \right]$$

Eq.. 1-4

The inductance variation term versus the position i **.ω.(dL /dθ)** is called counter electromotive force (e.m.f).

B. Presentation of the simulation model

In this part we will explain the principle of our simulation model and the role of different blocks Figure 5 presents the complete model used for the different simulations and connection between the main diagrams blocks. The (srm3ph) block presents the SRM model functioning on motor and generator. This one was designed by (Flux 2D, Flux 3D) software and calculated by finite element, in the output of this block, we recover the 3 added currents, flux and the torque. Then the currents has been injected in the current limitation block (dmic3ph) compared to the order value which is the maximum value. Each given speed corresponds to a position injected in the input of the machine model. All the data processed by (com3ph) block has the following inputs:

- Rotor Angle : Motor position
- $\theta_{ON}, \theta_{FW}, \theta_{OFF}$: From these angles and for each operating mode (Starter – Booster – Generator - Braking), the laws control are released.
- M/G : To select between functioning mode (1 : Motor– 0 : Generator).
- Bottom_Cmd In : The input value of the current limitation (Chopping Current).

In the output of this block , we recover the laws control which are injected to the inverter power bridge (block adts3ph) and the (batt+Filtre1) block which represents our battery state model and the parameters , efficiency and average values (capacitor , battery power , battery current) are displayed during the simulation. On the other hand, the efficiency and average currents values (MOS, Diode) and (MOS and Diode) losses of the inverter are calculated with (Power Device Calculator) block. However, in this case we don't design the load of the engine equipment, we oriented our model of the possibility to use our machine us a starter and generator

6. Simulations Results

Simulations were carried out from Matlab programs and the design developed with Matlab Simulink [11].

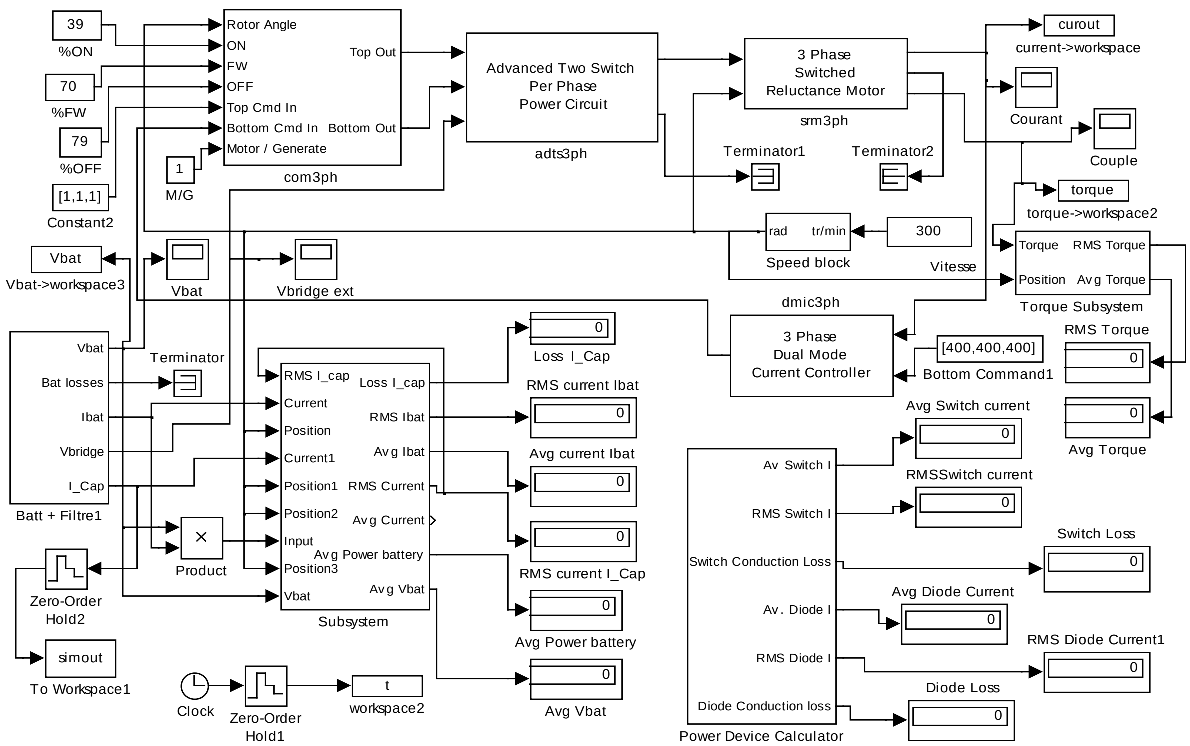


Figure 6: Block diagram of the open loop control

A. Open loop simulations

The problematic of the open loop simulations of proposed machine is in the following terms

- To find θ_{ON} ,θ_{FW} ,θ_{OFF} control angles which us to define the control parameters of our machine
- Simulations of our battery model with different values of capacity and resistance

B. Wave forms

The simulation results in open loop model of the system to enable us to study different operating modes. We did a many simulations with different control parameters in order to determinate the operating envelope.

- To find θ_{ON} ,θ_{FW} ,θ_{OFF} control angles which us to define the control parameters of our machine

Simulations of our battery model with different values of capacity and resistance. Table 1 represents the data for simulation points in each operating mode.

Table 1. Simulation data

	Speed (rpm)	Motor Torque (rpm)	Motor Power (W)	Battery Power (W)
Starter	300	100.8	3166	8145
Booster	2000	28.73	6017	7780
Generator	3000	-21.03	-6622	-6028
Braking	2500	-26.56	-6993	-6302

Starter Mode :

From 0 to 850rpm, the system must ensure starting during a time not exceeding one hundred milliseconds and the SRM must provide a high torque (100Nm). Figure 6 shows the wave form of the 3 current phases in the case of a cold start operation (Rbat=35mΩ) with current limitation (600amps) and frequency (8Khz). In order to generate these currents in the SRM, it's necessary to supply these phases during the inductance decrease [12] by modifying the control parameters (θ_{ON} , θ_{FW} ,θ_{OFF}).

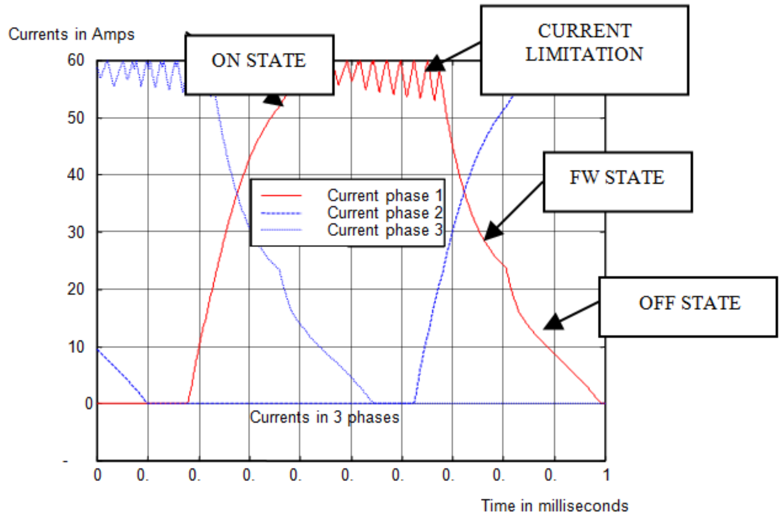


Figure 7: Waveforms of the starter phase current

Note that in starting mode, we are interesting to obtain average torque greater than 100Nm. Figure 8 shows the waveforms of the battery voltage corresponding to the power or required torque within our constraints and the minimum voltage, which should not drop below 21V (min Ubat> = 21V). So if we decrease the battery voltage Ubat (less than 21V), we reduce the torque ripple.

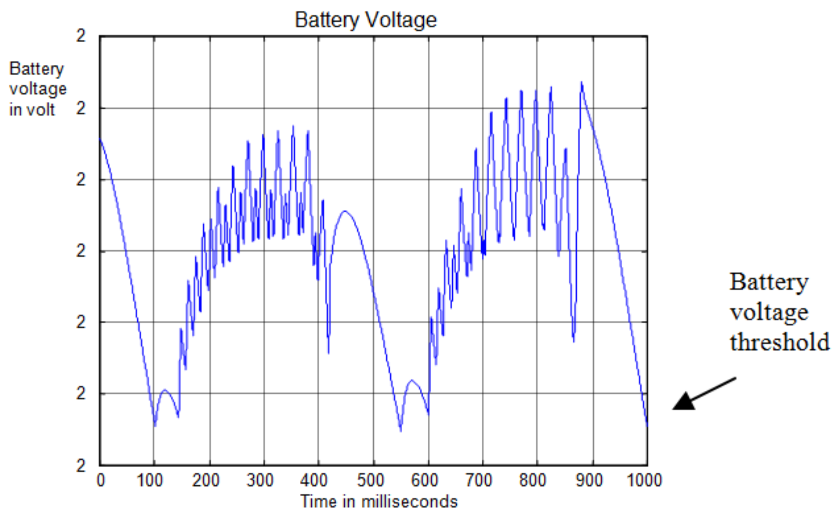


Figure 8: Wave forms of the starter battery voltage

- Generator Mode:

In this mode, the motor turn between 700 and 6000 rpm and should provide a 40.5V voltage on the continue network with a good efficiency and battery power 6KW. Regarding the currents we can distinguish 3 ranges; An up current area, an increase current area due to the counter-electromotive force of the inductor variation, and then decreasing current until its extinction in the process of free wheeling.
The waveforms of the currents are shown bellow.

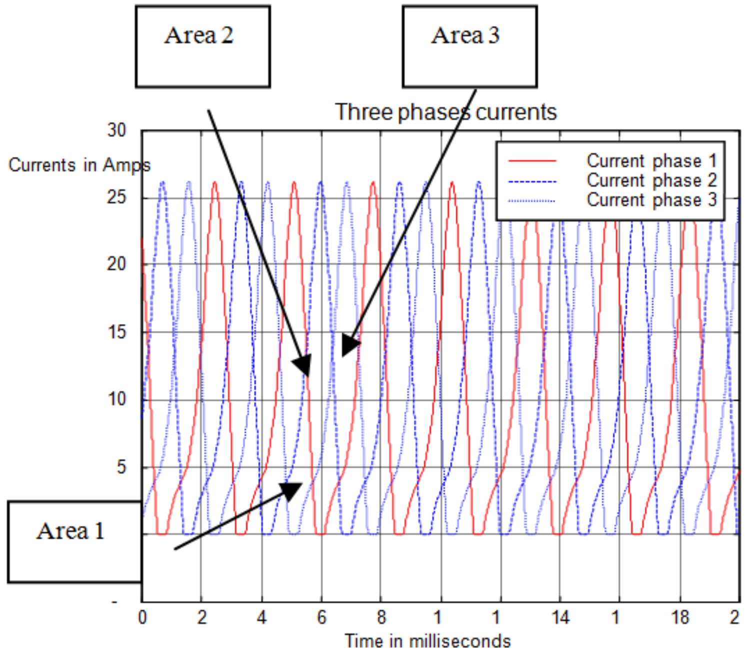


Figure 9: Waveforms of the generator phase current

The voltage waveform shows the various voltage resistive drops. Also regarding the simulation on generator mode, our purpose was to find the control parameters that allow us to maintain the battery voltage, low ripple of the battery voltage (Ubat) and the power battery delivered.(see Figure 9).

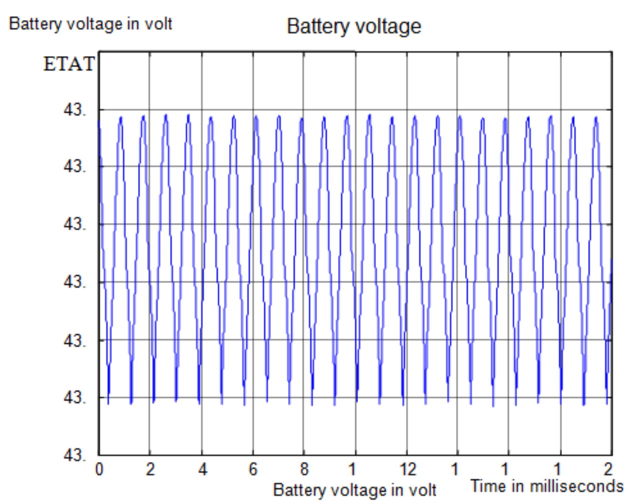


Figure 10: Waveforms of the Generator battery voltage

C. Closed loop simulations

Initially, the open-loop simulations identified a range of control parameters on the basis of some predetermined angles by manual calculation for different modes. It is from this angle that we created our look up tables and located them in our closed-loop system [13]. The diagram of the closed-loop simulation is the same as open-loop diagram except that the adjustment of laws control is done by using the block (Generator Control Law). In this case, speed is re-injected at the input block, and the torque order too, which takes the following values: 0 à 100% for motor mode and 0 à –100% for generator mode. Each torque and speed value given enable us to determinate angles θ_{ON} , θ_{FW}, θ_{OFF} and the current limitation value (Chopping). The table below represents the simulation results in closed loop.

Explanation of the table content:

The speeds (80, 160, 320, 640 rpm) correspond to the cold starting mode, for which the required torque value is the maximum (Tmax >=100Nm) then, we simulated with the torque values (80%Tmax, 40%Tmax, 20%Tmax, 10%Tmax). We did the same for the speeds (1280 2560 5120 rpm), which correspond to the booster mode operation at constant power 6KW and for which the torque value to be calculated by the following equation:

$$P = T * \omega \Rightarrow T = P/\omega$$

Example: for the speed 1280 rpm $\Rightarrow$ ω = (1280 2*pi)/ 60 = 134.04 rd/sec
Torque = 6000/ 134.04 = 44.76Nm

This means that for each speed the look up table dimension is (7X5), each speed value versus the torque gives the θ_{ON}, θ_{FW}, θ_{OFF}, Chopping parameters, which allow us to generate the control laws and to implement them in the block "Generator Control Law". Furthermore, if we want to simulate a value of speed that is not in the table, the block model provides an interpolation until desired values are found.

Speed (rpm)	80	160	320	640	1280	2560	5120
Tmax (Nm)	106.9	105.8	99.05	72.55	44.76	22.38	11.28
ON	56	54	52	40	37	21	23
OFF	90	88	89	77	87	72	71
FW	100	98	99	87	92	80	83
Chop	600	600	600	600	600	600	600

A. Look up tables model

Figure 11 shows the "Generator Control Law" block diagram which generates the control laws. It contains the starter and generator look up tables [14]

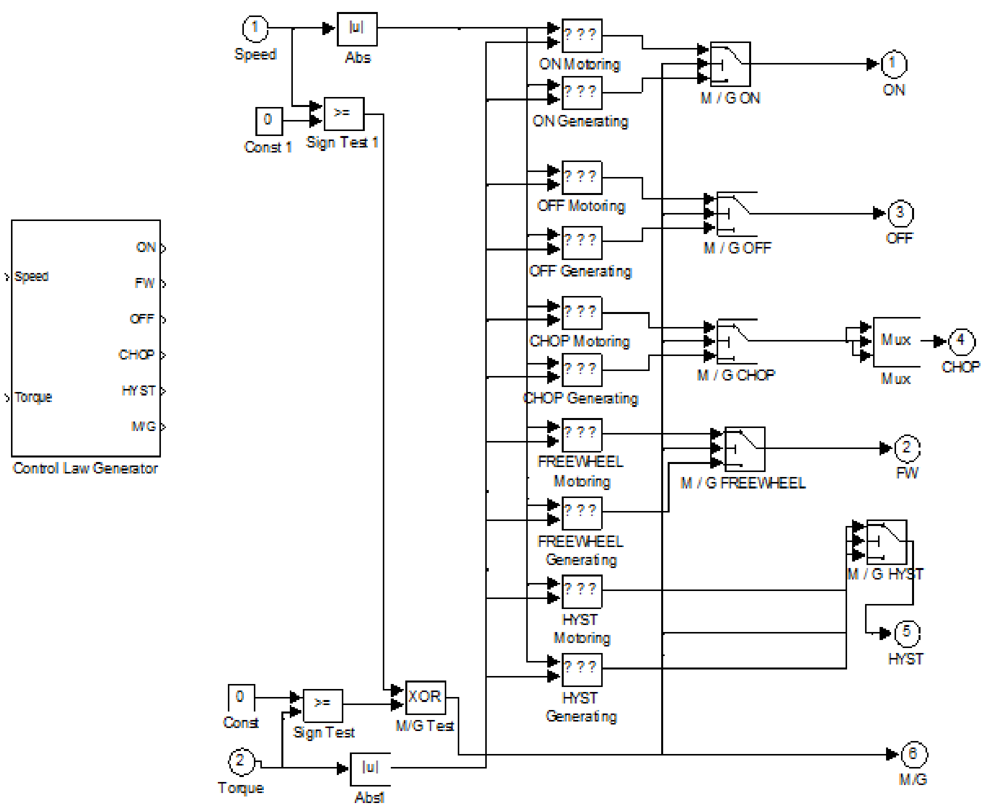


Figure 11: Look up table's schematic

7. Conclusion

The work carried out on this paper consisted of developing a calculation model on the Matlab/Simulink in order to explore the possibilities of the switched reluctance machine on the starter/generator mode and to simulate the operating machine in open loop and closed loop. This model is also used to study the influence of inductor waveforms on the laws control and the study has confirmed the relation between the currents and the inductor characteristics. At same time, this model has allowed us to make many simulations, which enabled us to confirm the compromise between our achieve design goals (maximum torque, power battery, etc.) and our constraints (threshold voltage battery, etc.) and especially to determined the laws control of the look up tables. Finally, all theses simulations enabled us to validate our design model and to verify experimentally the implementation of the look up tables of the laws control in the real time on the Dspace system (Hardware in the Loop) in order to check the tests and simulations results. Comparison between the experimental results and the simulations of the laws control will be presented in a future paper.

References

[1] Jawad faiz and K. Moayed zadeh, " Mode design of switched reluctance machine for starter/ generator of hybrid electric vehicle", Electric Power systems research, volume 75, Issues 2 – 3, August 2005, pp. 153 – 460.

[2] J.-P. Lecointe and R. Romary, " Five methods of statoral frequency determination: case of induction and switched reluctance machines", Mechanical systems and signal processing, Volume 18, Issue 5, September 2004, pp. 1133 – 1159.

[3] Liuchen Chang, " Switched reluctance motors: small motors of the next generation for automobiles ", Vehicular Technology Conference, 2003. VTC 2003-Fall. 2003 IEEE 58th on issue date: 6-9 Oct. 2003, Volume: 5, pp 3316 – 3320.

[4] A.V. Radun, C.A. Ferreira, E.Richter, “Two-channel switched reluctance starter/generator results” IEEE Transactions on Industry Applications, Issue Date: Sep/Oct 1998, Volume: 34 Issue 5, pp.1026 –1034.

[5] M. Gabsi, A. De vires, and Al, «A Switched Reluctance Machine for a car starter alternator system", Proceedings IEMDC 2001.

[6] Giuseppe S. Buja and Maria I. Valla «Variable structure control of SRM Drive », IECON’92, 9-13 November 1992,Vol. 1, pp. 482,487.

[7] M. Ali Akcayol and Cetin Elmas, NEFCLASS-based neuro fuzzy controller for SRM drive, Engineering Applications of Artificial Intelligence, Volume 18, Issue 5, August 2005, Pages 595-602

[8] Guy Grellet et Guy Clerc, " Actionneurs électriques ", Eyrolles 1999

[9] R. Inderka, M. Menne, and R. W. De Donker, “Generator Operation of a Switched Reluctance Machine Drive for Electrical Vehicles", EPE'99

[10] Szabó, L. and Viorel I.A., "On a High Force Modular Surface Motor,” Proceedings *of the 10th International Power Electronics and Motion Control Conference (PEMC '2002*), Cavtat & Dubrovnik (Croatia), 2002, on CD: T8 052.pdf.

[11] Stephen R. MacMin and William D. Jones, “A Very High Speed Switched Reluctance Starter / Generator for Aircraft Engine Applications", IEEE IAS Conf. , 1989, pp1158-1764.

[12] T. J. E. Miller, *Electronic Control of Switched Reluctance Machines.* Oxford: Newnes, 2001.

[13] R. Krishnan, Switched Reluctance Motor Drives. Boca Raton: CRC Press 2001.

[14] S. M, Lukic, A.Emadi, " State-Switching Control Technique for Switched Reluctance Motor Drives: Theory and Implementation", IEEE Transactions on issue date : 2010, pp 2932 – 2938.