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Simulation of Switched Reluctance Motor for Performance Analysis Using MATLAB/SIMULINK Enviroment and use of FPGA for its control

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ABSTRACT : This paper presents modeling, simulation and analysis of Switched Reluctance motor. A Matlab/ Simulink environment to simulate switched reluctance motor is described. From its linear model, its dynamics is described and discussed in detail. All simulations are completely documented by their block diagrams and Explaination of special Matlab functions and parameters makes the model easily understandable to the reader. Based on the developed model, simulation studies are performed . In the past, either a linear or nonlinear model with predefined parameters of SRM was used for close-loop control. In spite of the nonlinear nature of the SRM, its linear model represents the dynamic behaviour of SRM with very good approximation. Therefore, for the sake of simplicity, this study represents a linear model of SRM. For FPGA implementation, this model is simulated in a Matlab Simulink environment using a Xilinx System Generator implemented in Xilinx Spartan-3AN XC3s14an FPGA nanoboard.

Keywords: Switched Reluctance Motor (SRM), Current Controller, Speed Controller, Linear Model, PI Controller, FPGA (Field Programmable Gate Arrays), System Generator

I. INTRODUCTION

The electrical drives are very important part of an industry. The requirement of drives depends upon the available mains and load characteristics. Because of its simple and robust structure, high torque to inertia ratio, high thermal capability and high speed potential ,reliabitity ,brushless variable speed drive using SRM has become popular relative to other drives and represents an economical alternative to PM brushless motors in many applications [6]. However, the SRM suffers from noticeable torque ripple and acoustic noises that prevent its use in high performance drives [11].

The operational principles of the SRM are quite simple and straightforward, but the proper control of the SRM is not sufficiently completed. The inherent nonlinearity of a SRM makes torque production highly dependent upon the geometry of the poles, which is characterized by the dependence on both stator current and rotor position.

Switched Reluctance Drive (SRD) is a stepless speed regulation system, which is composed of SRM, converter and controller. In order to produce the maximum torque from a motor at a given speed, the combination of motor - converter should be determined. However, control strategy , converter's topology and optimized design of SRM have crucial influence on performance of SRD. Thus, dynamic simulation of the whole SRD has become very important [1, 2].

In general, Computer Aided Design (CAD) tools are employed for this purpose. Some researchers have previously studied in various subjects such as different motor shapes, control strategies and converter types [3, 5], but the studies are not completed. On the other hand, very few simulation studies of the SRM have been achieved with circuit-based languages such as Spice, Simulink [4, 5].The electrical and mechanical circuit equations are realized by using the Matlab-Simulink program [5]. Mostly, working on a simulink model instead of an actual machine is cheaper, easier and more practical [6, 7].

This paper presents a simplified linear model for closed loop control of SRM, which uses the fundamental mathematical functions to describe the saturation of the flux linkage depending on the winding current and rotor position. The model requires a minimum of pre-calculated or measured input data. This model can be used with any control technique like PI control,Hysteresis Control and Voltage Control. But here PI controller is used. For FPGA implementation, this model is simulated in a Matlab Simulink environment using a Xilinx System Generator implemented in Xilinx Spartan-3AN XC3s14an FPGA nanoboard. Design of the developed controller for the Switched Reluctance Motor is simulated via a Simulink full digital platform. The resulting design has a flexible and modular structure where the designer can customize the hardware blocks by changing the number of inputs, outputs, and algorithm when it is compared to the designs implemented using classical microcontrollers and digital signal processors. With its flexibility, other control algorithms can easily be programmed and embedded into the FPGA.

II. SWITCHED RELUCTANCE MOTOR

In Switched Reluctance Motor the torque is developed because of the tendency of the magnetic circuit to attain the minimum reluctance i.e. the rotor moves inline with the stator pole thus maximizing the inductance of the excited coil.. When a rotor pole is aligned with a stator pole, there is no torque because field lines are orthogonal to the surfaces (considering a small gap). If one displaces the rotor of its position, there will be torque production that will tend to bring back the rotor toward the aligned position. If current is injected in the phase when in the unaligned position there will not be torque production (or very little). If one displaces the rotor of the unaligned position, then a torque tends to displace the rotor toward the next aligned position. The magnetic behavior of SRM is highly nonlinear. But by assuming an idealistic linear magnetic model, the behavior pattern of the SRM can be easily studied without serious loss of integrity from the actual behavior pattern. SRM, when compared with the other ac and dc machines has some advantages and limitations [7].

This paper presents simulation for 60-kW 6/4 SRM. Table 1. gives the specifications of Motor usd for MATLAB simulation.

Table 1. SRM Specifications.

Number of rotor poles	6
Number of Stator poles	8
Aligned Inductance	23.6e-3 H
Unaligned Inductance	0.67e-3 H
Saturated Aligned Inductance	0.15e-3 H
Stator resistance	0.05 Ohms
Inertia	0.05 Kg.m.m
Friction	0.02 N.m.s
Maximum Current	450 A
Maximum Flux Linkage	0.486 V.s

A. Construction

The physical appearance of a Switched Reluctance motor is similar to that of other rotating motors (AC and DC) etc. It has doubly salient construction. Usually the number of stator and rotor poles are even. The windings of Switched Reluctance Motor are simpler than those of other types of motor. In an SRM, only the stator presents windings, while the rotor is made of steel laminations without conductors or permanent magnets. This very simple structure greatly reduces its cost. Motivated by this mechanical simplicity together with the recent advances in the power electronics components, much research has being developed in the last decade.

The winding of opposite poles is connected in series or in parallel forming no.of phases exactly half of the number of stator poles. Therefore excitation of single phase excites two stator poles. The rotor has simple laminated salient pole structure without winding. This is the advantage of this motor as it reduces copper loss in rotor winding. The stampings are made preferably of silicon steel, especially in higher efficiency applications. For aerospace application the rotor is operating at very high speed, for that cobalt, iron and variants are used. The air gap is kept as minimum as possible, especially 0.1 to 0.3mm.The rotor and stator pole arc should be approximately the same. If the rotor pole arc is larger than the stator pole arc it is more advantageous.

B. Generalized Equation of Motor

Through careful derivation,one can find the voltage equation of every particular phase as,

$$V = r\,i + d\psi / dt \quad ...(1)$$

Where, $\psi = Li = N\varphi$ ...(2)

r = winding resistance

L = Nonlinear equivalent inductance

For $r = 0$

$$V = L\,di/dt + i\,(dL/d\theta)\,(d\theta/dt) \quad ...(3)$$

$$V = L\,di/dt + i\,\omega\,(dL/d\theta) \quad ...(4)$$

C. Development of Torque

The general expression for the torque produced by one phase at any rotor position is,

$$T_d = [\delta W' / \delta\theta]\ i = \text{Const} \quad ...(5)$$

Since W' = Co-energy = $1/2\ F\ \phi = 1/2N\ I\varphi$ ...(6)

This equation shows that input electrical power partly increases the stored magnetic energy $(1/2L*i^2)$ and partly provides mechanical output power ($i^2/2 \times dL/d\theta \times \omega$), the latter being associated with the rotational e.m.f. in the stator circuit.

Neglecting saturation non-linearity,

$$L = \text{Inductance} = N\Phi / I \quad ...(7)$$

$$T_d = 1/2 i^2\ dL/d\theta \quad ...(8)$$

This equation shows that the developed torque is independent of direction of current but only depends on magnitude of current & direction of dL/d?.

$$T_e = \Sigma^{N}_{i=1} T_d = T_L + B\omega + Jd\omega/dt$$

Where, Te is the sum of the torque developed by all phases,N is the noumber of phases, and J and B denote the total inertia moment and the total damping ratio respectively.

D. Srm Linear Model

For various rotor angles, the magnetic flux versus current is given in Fig. 1. In Fig. 1, the slope of the curve in the linear region without saturation represents the valueof the related inductance.The value of inductance varies not only with θ rotating angle, but also with the current through winding due to the saturation feature of magnetic material [7, 9].

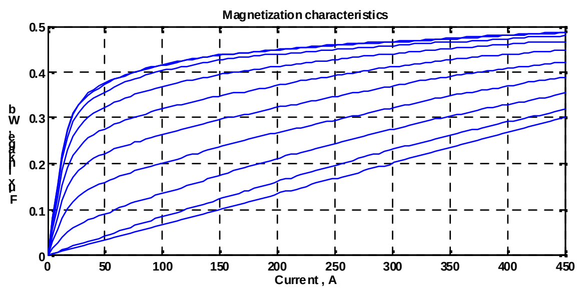

Fig 1. Flux Vs Current for different Rotor Angle.

Each phase inductance was displaced by an angle θ*s* as [7, 9].

$\theta s = 2\pi(1/Nr-1/Ns)$

where *Nr* and *Ns* are the number of rotor and stator poles, respectively.

When the motor has equal rotor and stator pole arcs, ?r = ?s, one has the following angle relations

?*x* = (?/ *Nr*- ?*r*)

?*y* = ?/ *Nr* which are indicated in Fig. 2.

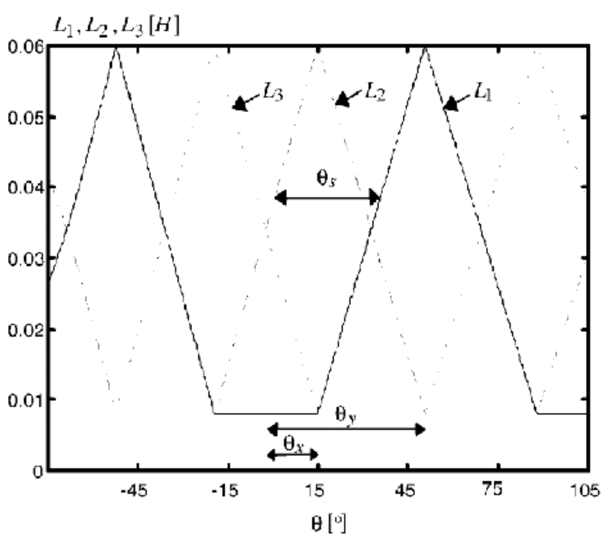

Fig. 2. Inductance Profile of each Phase.

III. PROPOSED MODEL

From Above equations of SRM the model for simulation is developed. Fig. 2.

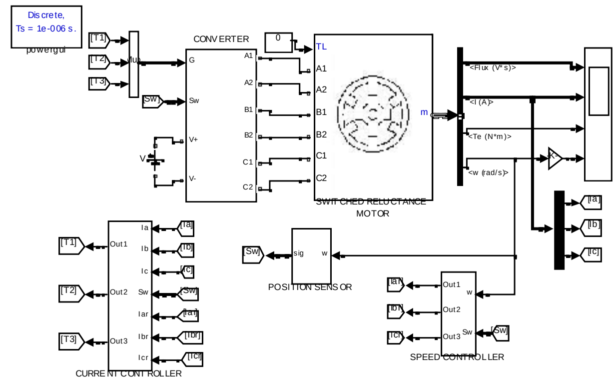

Fig. 3. Complete Simulation Model of SRM Drive System.

The whole model is divided into several independent blocks, such as position sensor block, converter block, speed controller block, current control block etc. Detailed implementation of various subsystems blocks are introduced in follows.

A. Position Sensor Block

The function this block is to work out the angle of rotor position angle relative to reference zero angle in an electric cycle. For a 3-phase 6/4 SRM, each phase inductance has a periodicity of 90 degrees. Therefore, it is appropriate to transform the rotor position angle coming from the mechanical equation so that it is modulo 90 . Here, modulo 90 is realized by virtue of rem function in MATLAB/ SIMULINK as shown in Fig. 4.

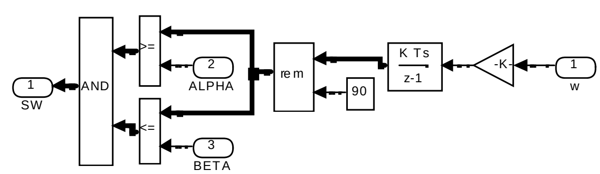

Fig. 4. Inside of Position Sensor Block.

B. Converter Block

An Asymmetric bridge converter is adopted here, it's function is implemented by using MATLAB/SIMULINK.The simulation model of converter block for one phase is shown as Fig. 5. It has two power switches and two diodes .Step motion of Switched Reluctance Motor is realized by switching on or off phase windings. The choosing of conduction angle is crucial to the power and torque ripple of SRM.

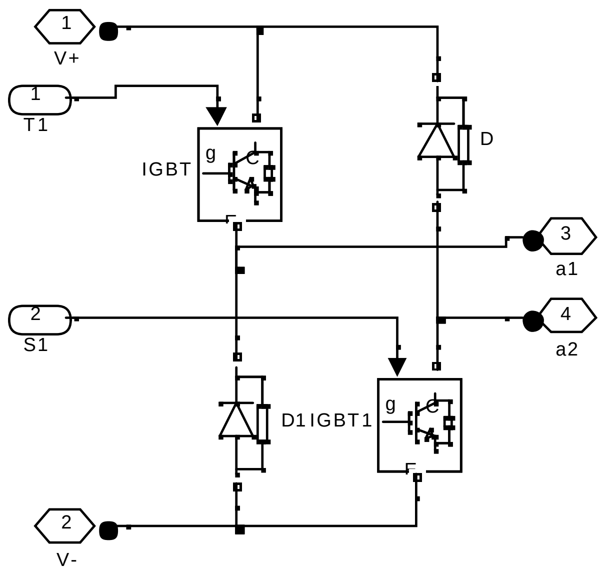

Fig. 5. Inside of Asymmetric-Bridge Converter for one leg.

C. Current Command Generator and Controllers

In the cascade control structure displayed in Fig. 3. the speed error existing between the rotor speed and its command is regulated by the speed controller [8] to yield the current command magnitude, and then multiplied by the commutation timing signal S1 to generate the current command for phase 1.

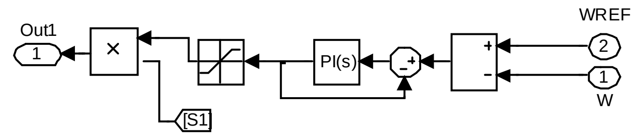

Fig. 6. Inside of Speed Controller.

Current controller [8] regulates the current feedback error to yield the control voltage for phase 1 which is compared with a triangular wave to create the PWM switching signal.Although any types of controller can be simulated by the proposed simulation environment, the proportional-plus-integral(PI) control type and Hysteresis type is adopted here. Detailed block diagrams to simulate the speed and current control loops are drawn in Fig. 5 and 6 respectively.

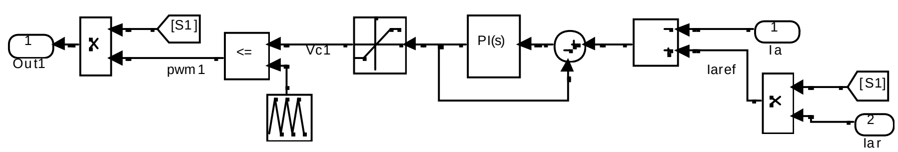

Fig 6. Inside of Current Controller for a Single Phase.

IV. USAGE OF XILINX SYSTEM GENERATOR IN THE CONTROLLER DESIGN

SRM have two kinds of controllers. One is pure analog electric circuit system, and the other is common microcomputer control system. Nowadays, In order to overcome disadvantsges [12] associated with analog and microcomputer control system, Field Programmable Gate Arrays (FPGAs) have been widely used as key components in implementing high performance processors. The speed, size and the number of inputs and outputs of a modern FPGA far exceeds that of a microprocessor or DSP processor. FPGA is ideally suited for making high-performance processors with a capability for implementing highly parallel arithmetic architectures [10, 13].

Here in this study ,the controller part of simulation model developed in Fig. 3 is analyzed by using a Matlab Simulink model. The control signals for the Converter in the related model are generated by the Xilinx FPGA chip. In this study, Xilinx FPGA application board is taken as a basis for a real time application. When the control algorithm design of the controller is completed in Matlab Simulink environment by using Xilinx System Generator, it can be translated automatically into VHDL programming language and then can be embedded into the Xilinx FPGA application board.

The difference in this design is that it includes not only the realization of the mathematical model to represent the natural behavior of the system controlled, but also the realization of the controller using FPGA. Xilinx blocksets used in the design obtained by the Xilinx System Generator can be added to the Matlab Simulink library and used by the Simulink Software. The block diagram of complete system model including the controller in Matlab/Simulink developed for Switched Reluctance Motor is shown in Fig. 8[10].

The sub-block called Spartan 3 represents the model of the FPGA based controller. Required control algorithms within the Spartan 3 block are designed digitally with Xilinx blocksets whose general view of the complete controller design is given in Fig. 8 and 10. Later, they are added to the Matlab Simulink library, and the realization of required controller is completed by running the Spartan 3 block together with the other Simulink blocksets in the system, namely, Switched Reluctance Motor and Converter blocks.

The tests for the FPGA based controller are carried out using a Matlab Simulink Model. The system response for the positive and negative speed references and the loading and unloading performances are investigated through the simulations using the related model [10].

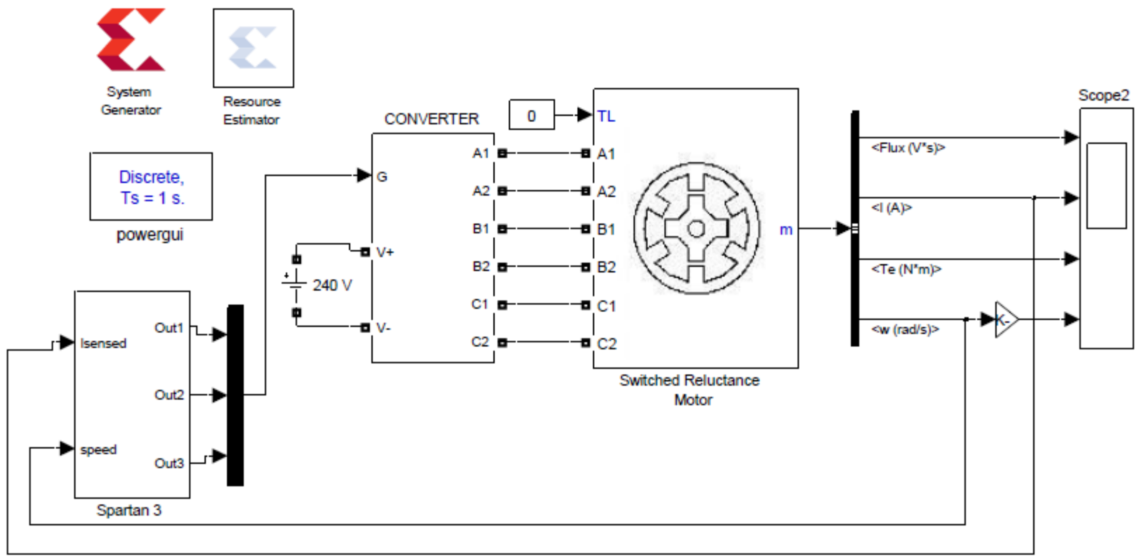

Fig. 8. The block diagram of complete system model including the controller in Matlab/Simulink.

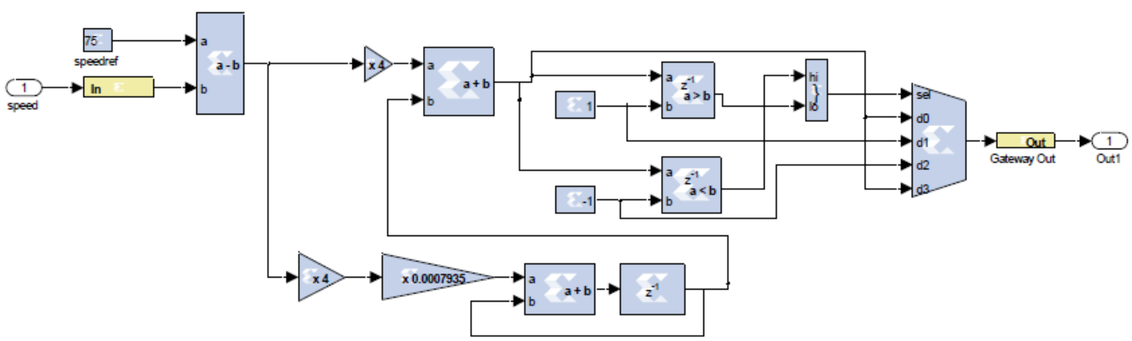

Fig. 9. Detailed Design of Speed Controller Block Using System Generator Tool.

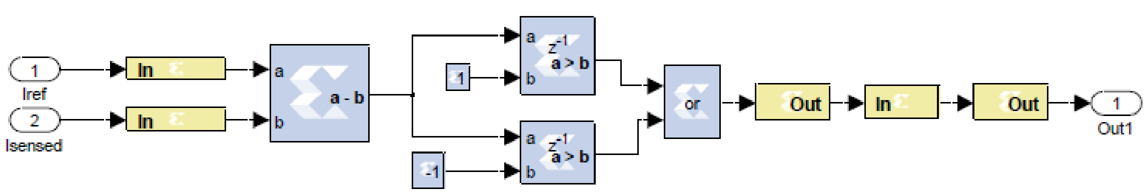

Fig. 10. Detailed Design of Current Controller Block Using System Generator Tool.

V. SIMULATION RESULTS OF SRM

The Swicthed Reluctance Motor whose controller is embedded into a Xilinx Spartan-3 Field Programmable Gate Array (FPGA) by means of the Xilinx System Generator Toolbox, is simulated via a complete system modeled in Matlab Simulink environment, as shown in Fig. 7. Design details of the controller developed using Xilinx System Generator are provided in the preceding sections. Simulations are carried out for the 6/4 SRM .The machine is operated at no load. The results obtained from the simulation are as follows (Fig. 11–17).

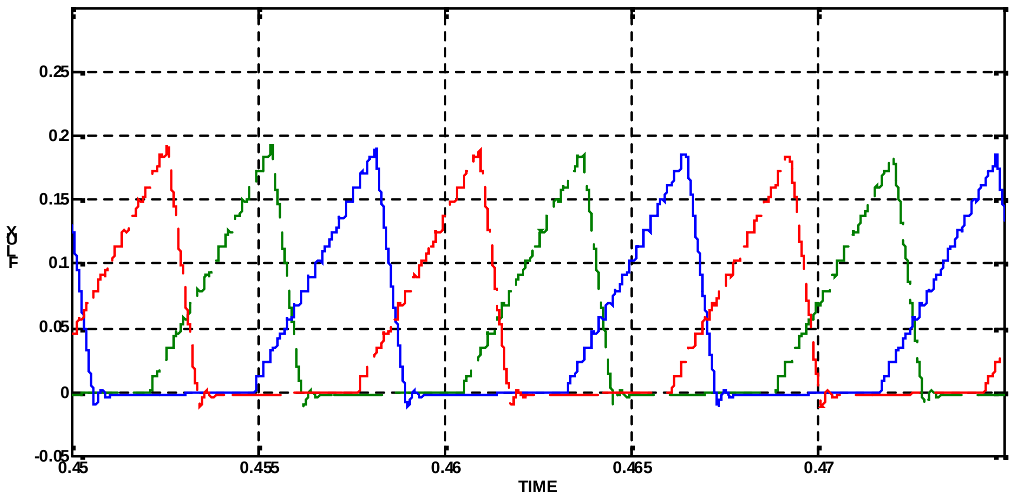

Fig.11. Flux Variation for three Phases of SRM.

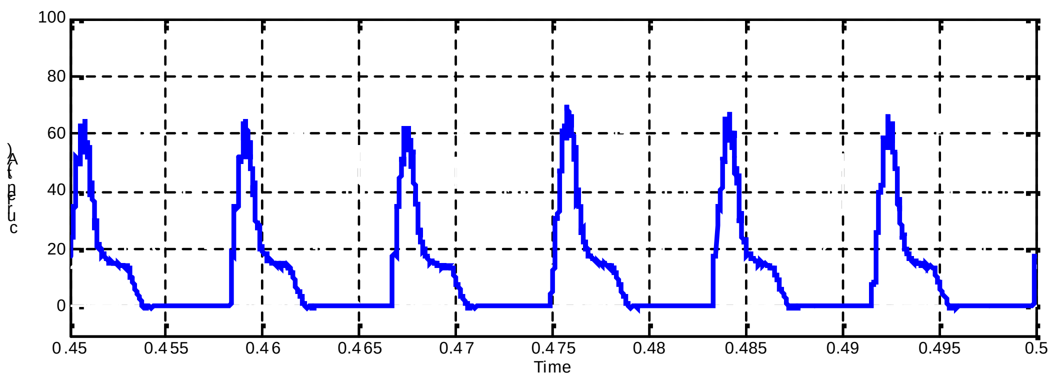

Fig.12. Current for Phase A.

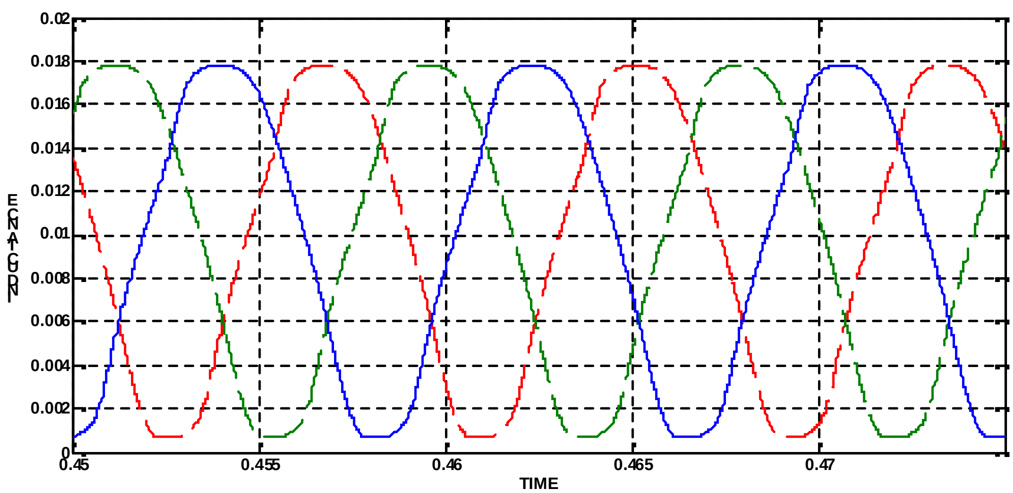

Fig. 13. Inductance Variation for Three phases of SRM.

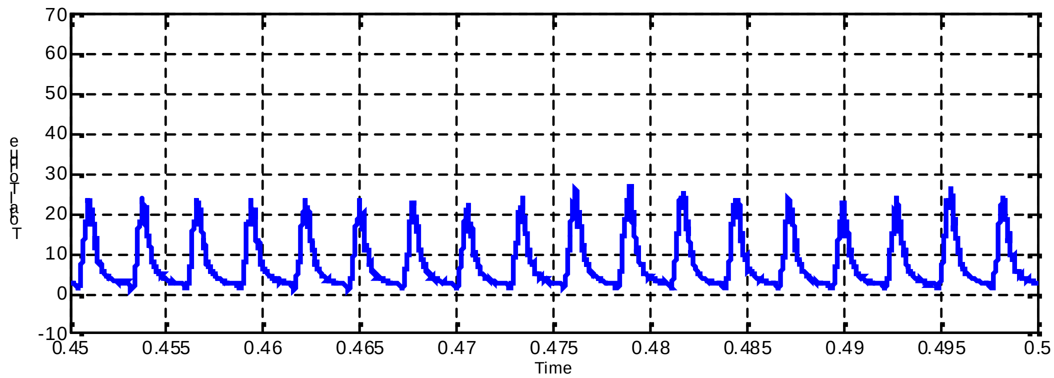

Fig.14. Total Torque Generated.

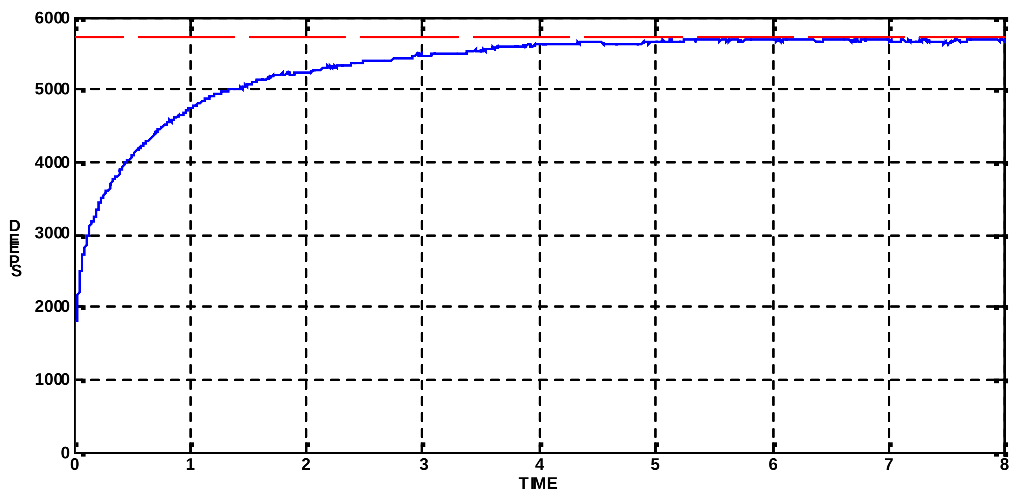

Fig.15. Reference Speed and Actual Speed of SRM.

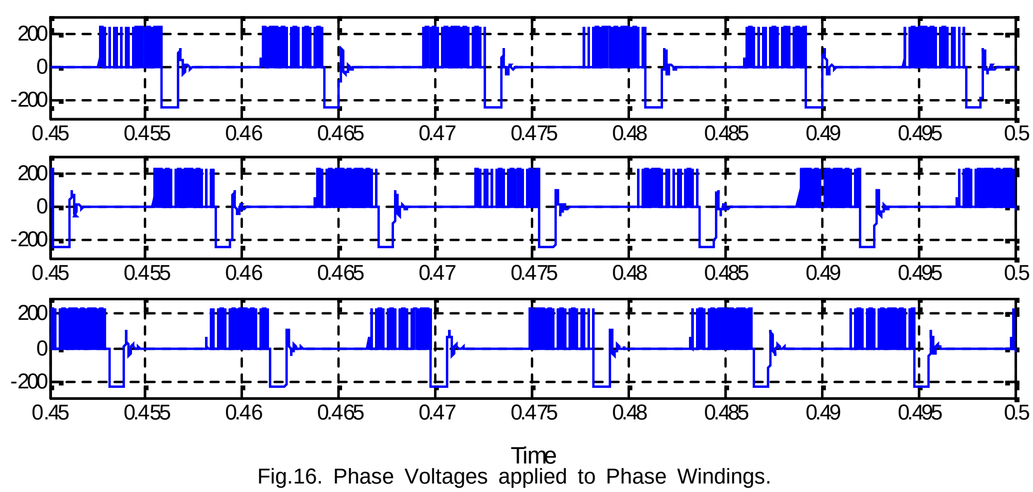

Fig.16. Phase Voltages applied to Phase Windings.

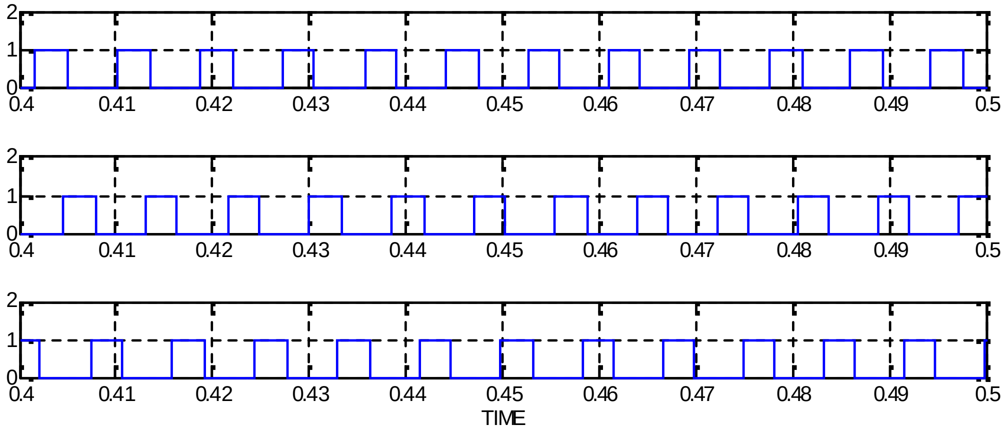

Fig.17. Driving Pulses for three Phases.

VI. CONCLUSION

In this paper, a computer-based matlab-simulink modelling was presented and the feasibility of Field Programmable Gate Array (FPGA) usage in Switched Reluctance Motor controller design is investigated. The modelling allows learners to see the results of analysis and the possible remedial action. The program provides a better understanding of the SRM's dynamic behaviour and remedial action without the need to perform time consuming hardware experiments, which are also expensive to set-up. The Swicthed Reluctance Motor whose controller is embedded into a Xilinx Spartan-3 Field Programmable Gate Array (FPGA) by means of the Xilinx System Generator Toolbox, is simulated via a complete system modeled in Matlab Simulink environment. The sub modules required for the completion of the controller designed are introduced and realized by means of digital blocks provided by Xilinx System Generator in Matlab/Simulink environment.After the completion of the design stage of the controller, the whole system including the motor, the power converter and the controller is modeled using Matlab/Simulink environment. The whole model is then simulated to see the effect of the controller in the control of the system. The Simulink measurement tools are used to observe and follow-up the output signals of each sub-block of the design and these signals are analyzed and evaluated until obtaining the proper operation.

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