Nonlinear Modeling & Simulation of a Four-phase Switched Reluctance Generator (SRG DS 8/6) Under Matlab/Simulink Environment

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Abstract—This paper presents a **modeling method of switched reluctance generator (SRG) based on the nonlinear inductance model and electromagnetic field finite element analysis (FEA) under Matlab/Simulink environment. The power inverter, excitation source and loads are modeled using Simulink/SimPowerSystem(PSB) in order to analyze both static and dynamic state. The non linear inductance model makes easy the developing of a control strategy that gives high performance controller with a closed loop based on PI controller. Simulation results show the efficiency of the modeling method and validate the applicability of the model and the controller.**

Index Terms-- **Switched Reluctance Generator, Finite element analysis, Proportional Integrator + Current Chopping Control.**

I. INTRODUCTION

Switched reluctance machines (SRM) have been found to offer important advantages over conventional AC machines in generating as well as motoring applications. The phases of the (SRM) are decoupled from each other under normal operation thereby improving reliability. This characteristic offers an advantage over more conventional machines (PM machines primarily) when the machine is used as a generator, since the faulted phase will not conduct current while the remaining phases continue to operate.

Due to their several inherent advantageous features such as simple construction, rug, low cost, fault tolerance and robustness and possible operation in high temperatures or harsh environments, (SRG) are gaining importance in a wide range of applications such as [1]:

- Industries (compressors, ventilators, pumps…)
- Electric household appliances: robots, washing machines, vacuum cleaners…
- Electric traction and aeronautics
- Renewable energies, in particular wind mills.

The SRG is a doubly salient machine. It does not contain any magnets or brushes, and the phases are completely independent. The rotor is made of laminated iron and it does not have any winding. This makes the SRG also mechanically suitable for high speed applications [2].

Unfortunately, SRG is a multivariable, strong-coupling and non linear system, it is very difficult to model and analyze. To do so, lots of modeling methods were studied in literature. The circuit simulation program "SPICE", it has certain limitations [3]. Reference [4] uses object oriented program technique, it is very flexible, but it is difficult to actualize, because it needs the complete mathematical model of the system. Reference [5] introduces some modules and M-file in MATLAB to build the nonlinear mathematical model of the magnetization curves, it is accurate, but the simulation speed is slow.

In this study we propose a nonlinear modeling method based on circuit simulation built by self defining M-functions and basic modules on simulink library. This model is very flexible and visual, its simulation speed is very fast [6].

The control of the (SRM) is more complicated for generator operation than it is for motor. In generator mode, the turn-on and turn-off angles control the peak phase currently jointly and severally.

III. OPERATING PRINCIPLE OF SRG

The structure of SRG is double protruding pole. The SRG in Fig.1 has steel laminations on the rotor and stator. There are no windings or permanent magnets on the rotor, and there are concentrated windings placed around each salient pole on the stator. The coils around the individual poles are connected to form the phase windings.

The SRG has two phases (excitation and generation) in one electrifying period, with generation being the primary phase. When the two switches, S1 and S2, are turned on, the windings on the stator are excited by the outer circuit, and the electrical energy and mechanical energy provided by exterior circuit are converted into magnetic field energy.

When the two switches are turned off and the two diodes, D1 and D2, are turned on, the magnetic field energy and mechanical energy are converted into electricity energy feeding back to the source or supplying power to the load. Because of the characteristics of time-sharing excitation, the control of SRG is very flexible. And there are several parameters for controlling SRG, such as turn-on angle, turn-off angle, and exciting voltage and controlling mode, all these will affect the generation greatly.

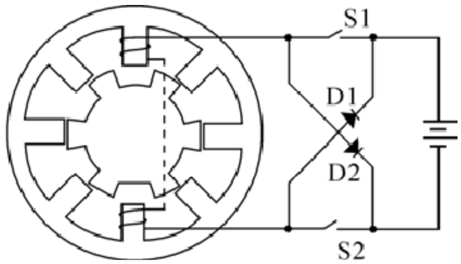

Fig.1. Simplified diagram of the SRG's structure.

A. Basic Equations of SRG

The dynamic mathematical model of SRG includes two basic non linear equations, such as electromagnetic equation and flux linkage equation which are respectively as:

$$\pm V_k = R.i_k + \frac{d\psi(\theta, i_k)}{dt} \tag{1}$$

Where V_k is terminal voltage of the winding, i_k is phase current k (k = a, b, c, d), R is phase resistance, $\psi(\theta, i_k)$ is phase flux linkage, θ is position angle of the rotor.

The sign before V_k is determined by the operating mode of the system.

Because of the double salient structure of the machine and the magnetic saturation effect, the flux in the stator phases varies according to the rotor position θ and the current of each phase.

$$\psi(\theta, i_k) = L_k(\theta, i_k).i_k \tag{2}$$

$L_k(\theta, i_k)$ is phase inductance, it's depending to the phase current and the rotor position.

B. Nonlinear Model of Inductance

In this paper to study the characteristics of SRG accurately, according to the nonlinear inductance model, a nonlinear SRG model is built based on the electromagnetic field finite-element analysis.

The magnetic circuit of the SRG is saturated and non-linear.

The harmonic component of the inductance can be expressed.

$$L_k(\theta, i_k) = L_0(i) + L_1(i).\cos(N_r.\theta + \pi) \tag{3}$$

$$L_0(i) = \frac{L_{\max}(i) + L_{\min}(i)}{2} \tag{4}$$

$$L_1(i) = \frac{L_{\max}(i) - L_{\min}(i)}{2} \tag{5}$$

Where L_{max} is aligned position inductance, L_{min} is the unaligned position inductance.

Fig.2 shows the relationship between inductance, turn angle of rotor and phase current.

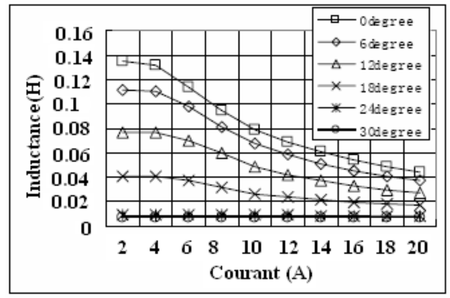

Fig.2. Relationship between inductance, turn angle of rotor and phase current.

L_{max}, L_{min} can be obtained by experiments and electromagnetic field finite element analyzes (FEA). $L_{max}(i)$ can be expressed as a polynomial function with respect to the phase current which can be obtained by curve fitting Fig.3.

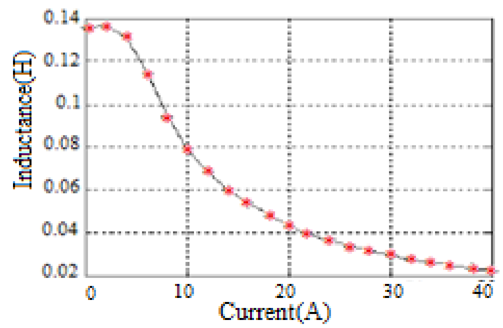

Fig.3.Fitting curve of $L_{max}(i)$.

$$L_{max}(i) = \sum_{n=0}^{4} a_n i^n$$

$$= 0.136 - 0.0045i + 0.0056i^2 - 0.022i^3 + 0.00035i^4 \tag{6}$$

C. Torque Production

The variation of the reluctance between two extreme positions of aligned and unaligned positions will induce a variation of magnetic energy from which a non null average torque will result.

$$T_e = \frac{1}{2} \cdot \frac{dL(\theta, i)}{d\theta} \cdot i^2 \tag{7}$$

The production of the torque does not depend on the sign of current but only on the sign of $\frac{dL}{d\theta}$.

IV. POWER CONVERTER

The most commonly used Switched Reluctance Generator is the classical half-bridge converter which has two power switches and two diodes per phase. Fig.4 shows the structure of a four-phase power inverter, the main advantage of this inverter is that each phase can be controlled independently.

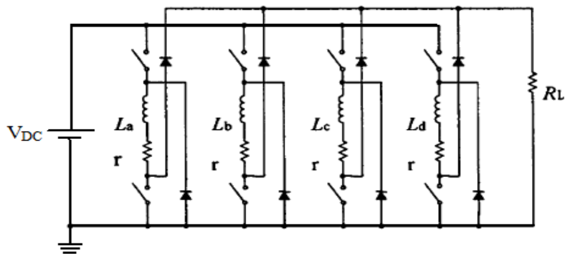

Fig.4. Power Inverter system of a four-phase SRG.

VI. NONLINEAR SIMULATION MODEL OF SRG

In order to simplify the simulation process, in this paper four assumptions are introduced as follows:

- Parameters of each phase in SRG are symmetrical.
- Ignore mutual inductance and leak inductance.
- Ignore hysteric's and eddy effect.
- Switches in power converter are ideal device and the exciting source is constant.

A. Model of Each Phase

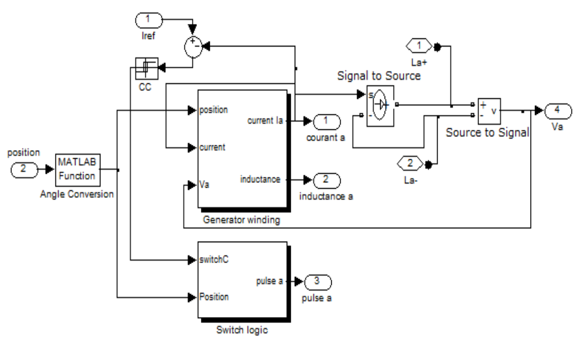

Fig.5.The simulation model of Phase (a).

We presents the model of windings, it is built according to (1)-(7). The parameters of each phase are symmetrical, take phase (a) example, its simulation model shows the detailed structure of the nonlinear machine modeling is created by Embedded Block in Fig. 6.

The three other phases are identical but different just on the level from the value of the angular shift where we take 0° for the phase (a), θ_s for the phase (b), $2\theta_s$ for the phase (c), and $3\theta_s$ for the phase (d), θ_s is defined as:

$$\theta_S = 2\Pi\ (1/N_r - 1/Ns) \quad (9)$$

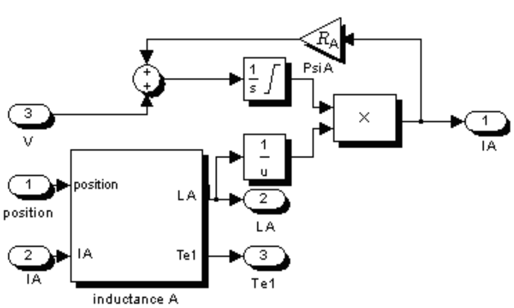

Fig.6. Inductance and current Calculator.

In this block, we can also calculate the inductance and the torque of a one phase by applying the formulas (3) to (7), with L_{min} = 0.01H.

B. Design of the Controllers

The objective of the controller system is to create a high performance control commands to maintain the output voltage of the system. The performance controller seriously affects the dynamic and static characteristics of the system. For SRG, there are lots of controllable parameters. Turn-off angle θ_{off}, turn on angle θ_{on}, turn-off peak current I_c and so on.

As a result, there are three typical control strategies. Angle position Control (APC), Current Chopping Controller (CCC) and Pulse Width Modulation (PWM).

Because the performance of system is very sensitive to the turn-off angle, the implement of APC has certain difficulties. In this paper, a high-performance control strategies named PI+CCC control (PCC) is proposed. The controller has two closed loops: outer voltage closed-loop (VC) and inner current closed-loop (CC).

VC shown in Fig.7 is based on PI controller. Firstly it obtains the D-value between the output voltage of the system and the given voltage signal (270V), and then creates the reference current I_{ref} through PI controller.

CC is based on current chopping control; it is implemented by the Relay module in Simulink library as shown in Fig.5.By the way, turn-on and turn-off angle in this controller is optimized and fixed.

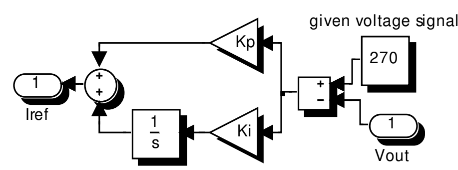

Fig.7. the simulation model of outer voltage controller.

C. Model of Prime Motor

Prime motor is imitated by position sensor as shown in Fig.8. The speed of the rotor is integrated to obtain the mechanical angle of the rotor. Original angle supplies the original angle of the rotor as the system is started up.

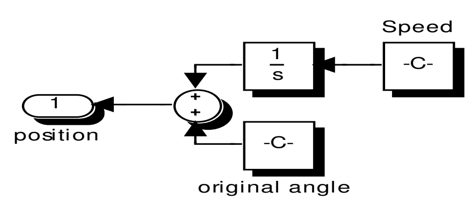

Fig.8. the simulation model of position sensor.

D. Exciting Circuit and Loads

The direct current exciting source V_{DC} supplies the original exciting current to the windings. The Diode module over V_{DC} is used to prevent the current of SRG from returning to V_{DC}.

The switching device over load it use to imitate sudden load-on and load-off, it is composed of an IGBT module and a step-function signal module.

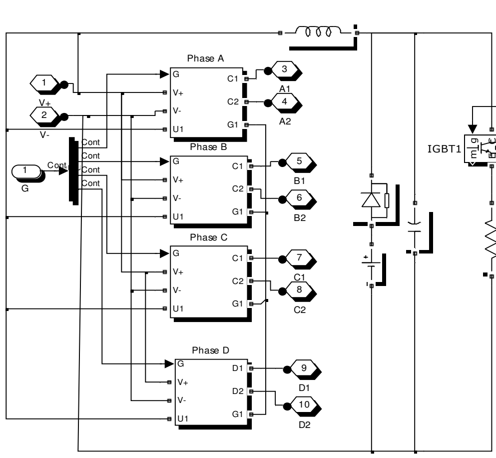

Fig.9. PSB simulation model of exciting source and loads.

To test the proposed model feasibility a four phase 8/6 SRG system is built and simulated as shown in Fig.10. The rated parameters of the SRG are 3000r.p.m, 250 volt. The SRG was simulated under different conditions.

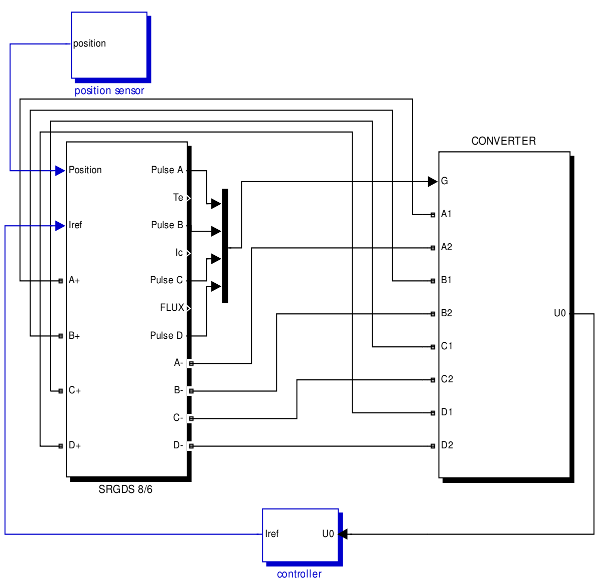

Fig.10. Simulation Model of SRG System.

VI. NONLINEAR SIMULATION RESULTS

Fig.11 shows the nonlinear inductance phase and its variation when the rotor position changed.

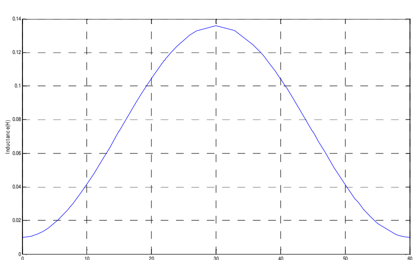

Fig.11. Nonlinear inductance (H)

When speed is increased, the phase current is reduced and the generating capacity of SRG is degraded.

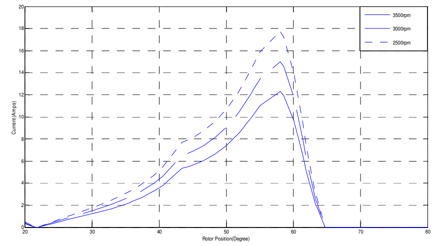

Fig.12. phase current Waveforms with different speeds

The exciting process can be controlled by regulating the turn-on and turn-off angles. Advance of θ_{on} or delay of θ_{off} may all increase exciting current; and we can see their effects in Fig.13 and Fig.14 from these two figures, it appears that the exciting current is extreme sensitive to θ_{off}. Generally, in this controller, θ_{off} is optimized and fixed with rotor speed, and output energy of SRG is regulated by changing turn-on angle.

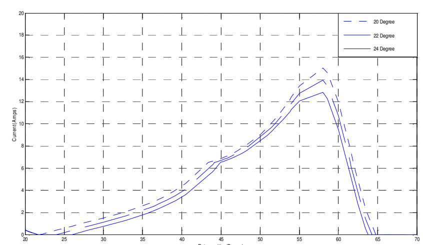

Fig.13. Current phase with θ_{off}= 45° and different θ_{on},(speed=3000 rpm)

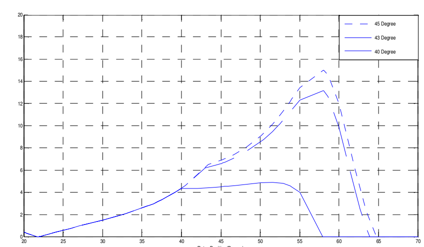

Fig.14. Current phase with θ_{on} = 22° and different θ_{off},(speed=3000 rpm)

Fig.15 shows the output voltage response of SRG with no load.

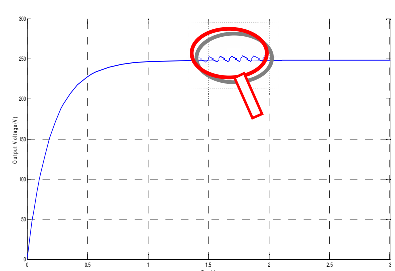

Fig.15. Output Voltage (V) Vs Time (ms) Capacitor (across)

The voltage will stabilize after a short time. The ripples of the voltage are very small.

Fig.16 and Fig.17 presents the current and flux waveforms of three phases respectively.

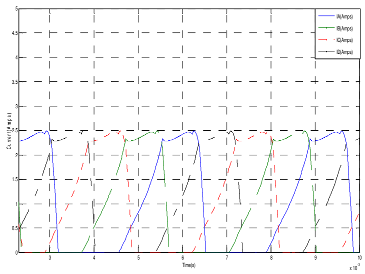

Fig. 16. Phase Current (A)

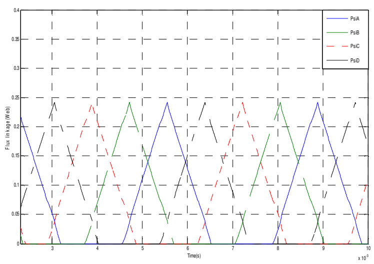

Fig.17.Waveform of flux linkage (Web)

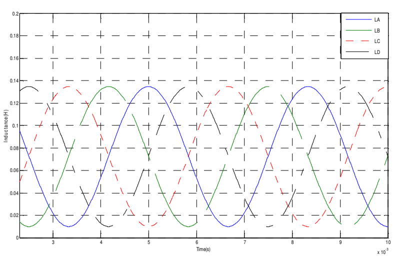

Fig.18.Inductance of three phase (H)

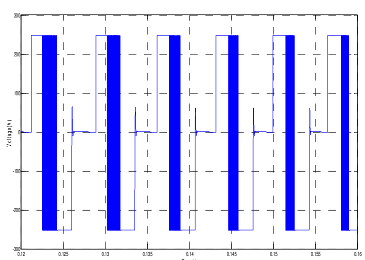

Fig.19.Output voltage of one phase (V)

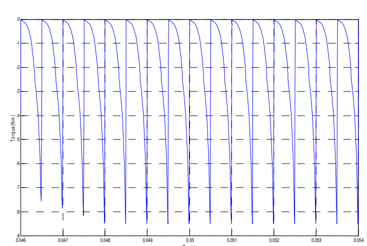

Fig.20. Waveform of the torque (Nm)

VII. CONCLUSION

There are lots of nonlinear characteristics in the SRG system. When the operation conditions and loads are changed, the characteristics of some components in SRG system will be changed. So it is difficult and complex to build the model by a simply use of a mathematical model and nonlinear inductance model, this paper built a complete nonlinear simulation model of SRG system based on Matlab/Simulink.

This proposed SRG minimized the ripple, and constant steady state output voltage is stabilized. The simulation results really report the work status of the generator system and validate the applicability of the model and proposed controller.

The obtained results in this paper show that the control simulink model provides an efficient SRG controller that is easy to implement.

According to the above, it is obvious that the SRG system has better dynamic and static performances with PI+CC controller.

Through the results obtained in this paper we deduce that the use of PI+CC controller gives high performance comparing to PWM controller.

APPENDIX

Values of parameters used in modeling and simulation. $R=25\Omega$, $N_r=4$, $L_{min}=0.01H$, $V_{exciting}=250V$, $R_L=100\Omega$, $\theta_{original}=10°$, $K_p=10$, $K_i=5$.

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