Nonlinear Modeling and Simulation of a Four-phase Switched Reluctance Generator for Wind Energy Applications

F. Messai, M. Makhlouf, A. Messai, K. Nabti, and H. Benalla

***Abstract*—Thesubject of this paper is a modeling method of switched reluctance generator (SRG) based on the nonlinear inductance model and electromagnetic field finite element analysis (FEA) to be used in wind energy applications. SRG and its behavior, modeling and Simulations results are presented. It was analyzed the characteristics of the SRG under different conditions. The nonlinear inductance model allows us to develop a control strategy that gives high performance controller with a closed loop was designed on PI controller.**

***Index Terms*—Switched reluctance generator, finite element analysis, proportional integrator + current chopping control, wind applications.**

I. INTRODUCTION

The rapid depletion of fossil fuels has necessitated the need for the utilization of non-conventional energy sources. Among these renewable energies widely used around the world in the last years, wind energy conversion system seems to be very interesting, it is clean energy source suitable for rural areas and the stand alone wind energy conversion system in rural areas must be characterized by economic and maintenance free operation.

Doubly fed induction generator (DFIG) suffers from limited rotor converter rating and has problems with over currents during voltage dips and the multistage gearbox that the DFIG must incorporate is unreliable and expensive. The direct coupled variable speed generators for these systems obviate the need for gear box which is the most unreliable and maintenance intensive component in the system. Permanent Magnet Synchronous Generator or Field Wound Synchronous Generator in standalone wind energy conversion systems eliminate the unreliability associated with gear box drive trains through direct coupled variable speed operation and even though permanent magnet machines will have a better torque density than the field wound version, the presence of permanent magnets will make assembly more difficult [1]. In the Field Wound Synchronous Generator, the brushes required to excite the field winding demand maintenance at regular intervals. The variable speed direct drive synchronous generator shortfalls from cost, size, weight, energy yield and requirement of a converter.

Although Permanent magnet generators exhibit low losses, lower weight, better torque density and perhaps low cost with the disadvantage that the excitation cannot be controlled while axial flux permanent magnet generators are heavier and more expensive than radial flux counterparts.

To overcome the beyond mentioned obstacles Switched Reluctance Generator (SRG) is being considered as the generator of choice in standalone wind energy conversion systems.

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 nonlinear 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.

II. 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

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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.

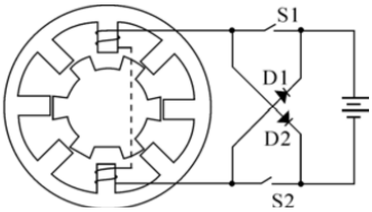

Fig. 1. Simplified diagram of the SRG's structure.

A. Basic Equations of SRG

The dynamic mathematical model of SRG includes two basic nonlinear 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

According to the nonlinearinductance model used in this paper an 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.

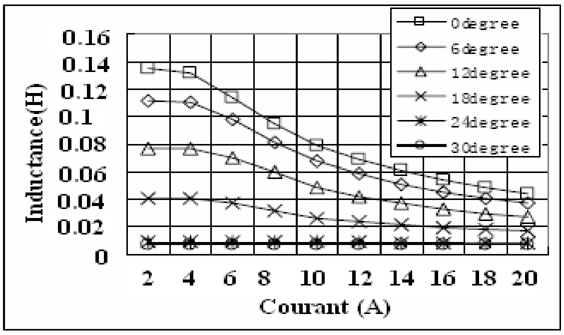

Fig. 2. Relationship between inductance, turn angle of rotor and phase current.

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.

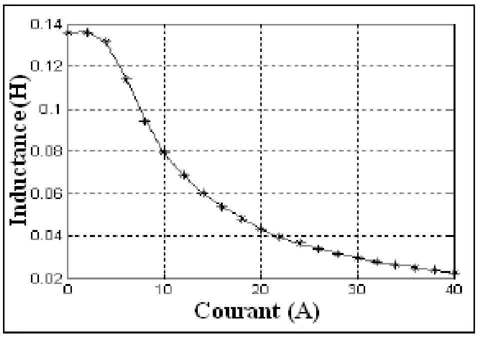

Fig. 3. Fitting curve of $L_{max}(i)$.

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

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

C. Torque

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

The torque can be expressed by:

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

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

III. Power Converter

The principle type converter used in the 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.

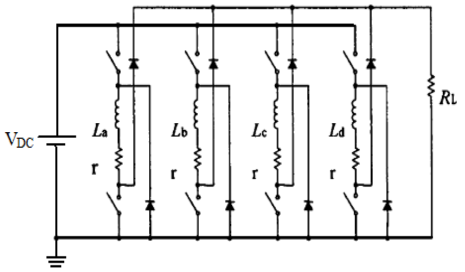

Fig. 4. Power Inverter system of a four-phase SRG.

IV. NONLINEAR SIMULATION MODEL OF SRG

Four assumptions are introduced In order to simplify the simulation process, 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*

We present 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. 5.

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:

$$\theta_S = 2\Pi\,(1/N_r - 1/Ns) \tag{8}$$

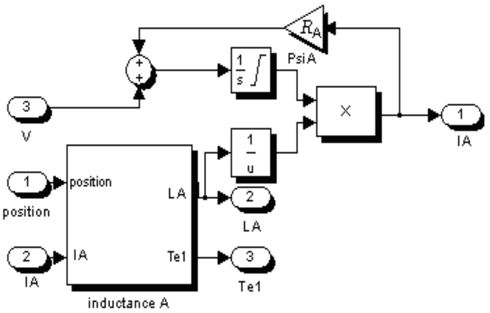

Fig. 5. Inductance and current Calculator.

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. *Controllers of SRG*

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 θoff, turn on angle θon, turn-off peak current Icand 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. 6 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 Iref through PI controller.

CC is based on current chopping control; it is implemented by the Relay module in Simulink library as shown in Fig. 7. By the way, turn-on and turn-off angle in this controller is optimized and fixed.

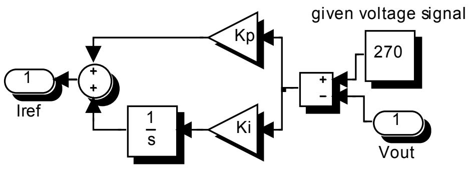

Fig. 6. the simulation model of outer voltage controller.

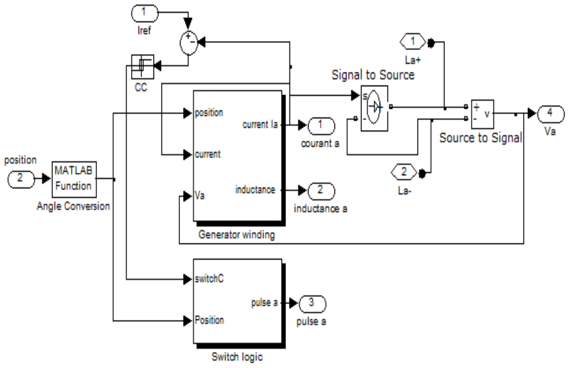

Fig. 7. The simulation model of Phase (a).

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.

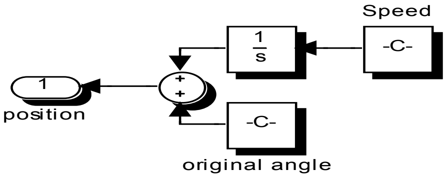

Fig. 8. the simulation model of position sensor.

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}.

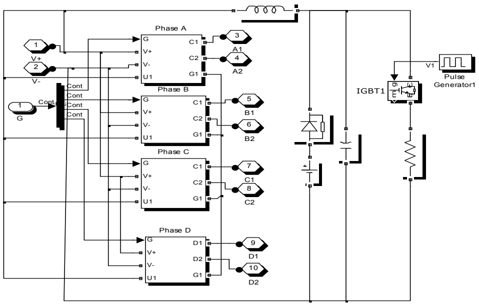

Fig. 9. PSB simulation model of exciting source and loads.

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.

The exciting circuit and the load are simulated using the model shown in Fig. 9.

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.

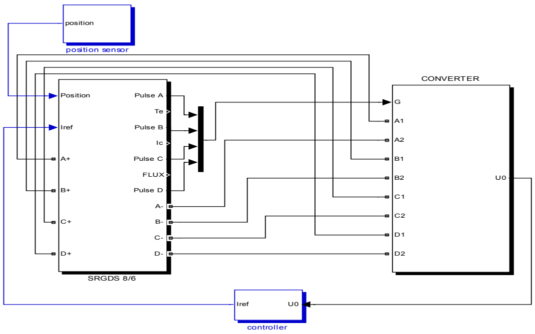

Fig. 10. Simulation Model of SRG System.

V. NONLINEAR SIMULATION RESULTS

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

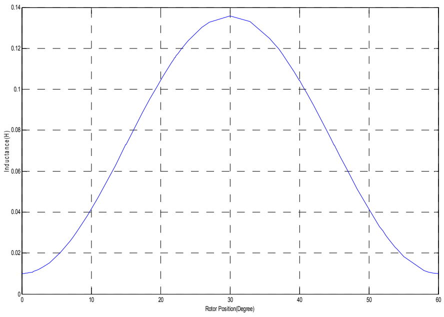

Fig. 11. Nonlinear inductance (H).

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

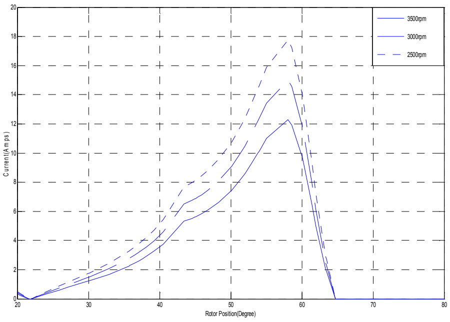

Fig. 12. phase current Waveforms with different speeds.

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

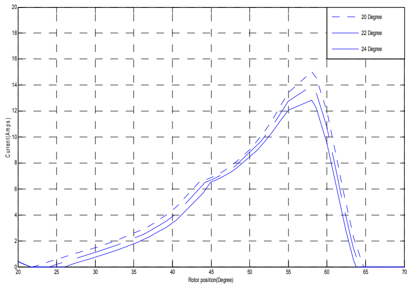

Fig. 13. Current phase with θ_{off}= 45° and different θon,(speed=3000 rpm).

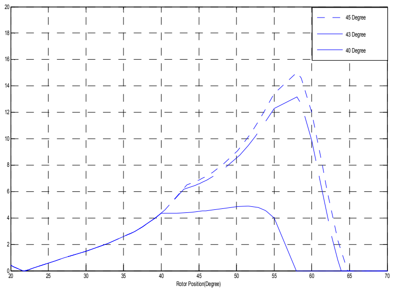

Fig. 14. Current phase with θ_{on} = 22° and different θoff,(speed=3000 rpm).

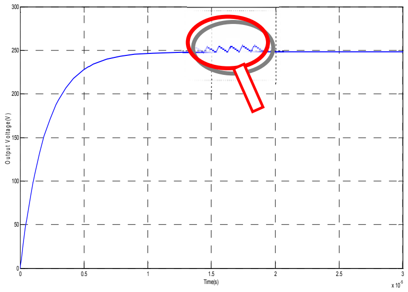

Fig. 15. Output voltage (V) Vs time (ms) capacitor (across).

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.

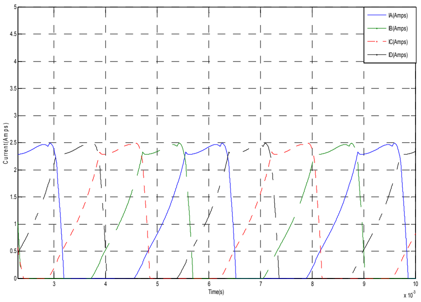

Fig. 16. Phase current (A).

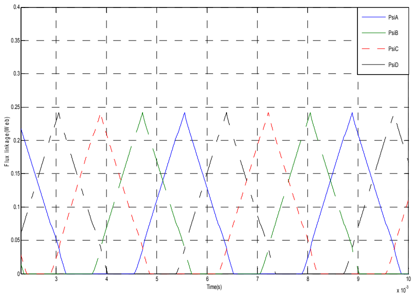

Fig. 17. Waveform of flux linkage (Web).

Fig. 18 shows the output voltage of one phase of the SRG converter.

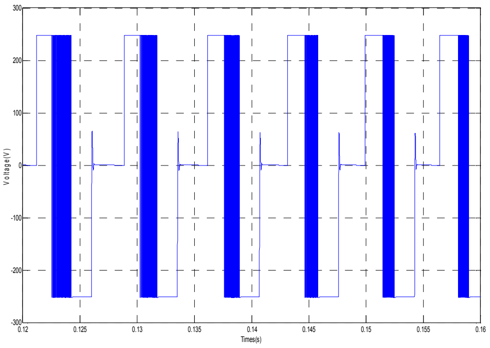

Fig. 18. Output voltage of one phase (V).

The electromagnetic torque produced by the SRG is represented in Fig. 19.

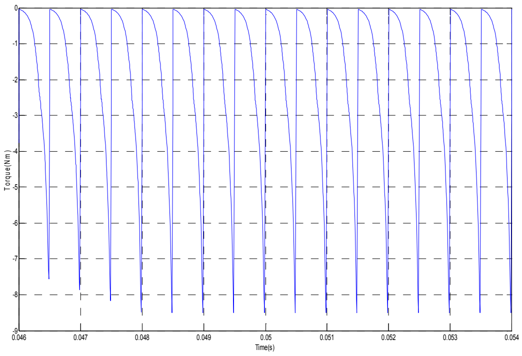

Fig. 19. Waveform of the torque (Nm).

VI. 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.

The prototype built and the results obtained confirmthat the application of the Switched Reluctance Generatorfor wind power plants is suitable

APPENDIX

Values of parameters used in modeling and simulation.

R=25Ω, N_r=4, L_{min}=0.01H, $V_{exciting}$=250V, R_L=100Ω, $\theta_{original}$=10°, K_p=10, K_i=5.

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