Analysis of Dynamic Characteristics of Switched Reluctance Generator

N.B. Kavitha, and B.Vinu Priya

Abstract---This paper presents the Analysis of Dynamic Characteristics of switched reluctance Generator using MATLAB, a widely used simulation tool. Component models are addressed and their incorporation into the MATLAB is provided. The component models are constructed by user-define functions provided in the simulation program. This modeling work is mainly employed to analyse the characteristics of switched reluctance generator.

Keywords---- Dynamic Characteristics**,** Switched Reluctance Generator

I. Introduction

THERE has been significant interest in developing SRMs for numerous variable speed applications. These range from low cost consumer applications to high performance aerospace applications [1-6]. This interest in SRMs is due to the machine's potential for low cost and/or fault tolerance. Most SRM applications addressed in the literature have utilized the SRM as a motor and have addressed its motoring performance [1-6]. The SRM can also be applied as a generator.

The SRM requires power electronics to operate as a generator just as it does to operate as a motor. This means that it is best suited for applications that require variable speed. This makes the SRM a candidate for applications such as aircraft engine starter/generators, automotive starter/generators, and windmill generators. In addition, generating issues arise in applications that regenerate. Examples include washing machines, flywheels, and hybrid and electric cars. To obtain generating action with the SRM, the phase current must be timed relative to the rotor position as shown in Fig. 1 for a 6/4 SRM. In the figure it is assumed that the machine is turning in the positive angular direction so that generating occurs when the phase torque is negative. Thus the phase current is timed to flow for those rotor positions where the torque is negative and to be zero for those rotor positions where the torque is positive. Because the sign of the SRMs phase torque is independent of the sign of the SRM's phase current, motoring or generating action is totally controlled by the rotor positions for which the phase current is nonzero [5].

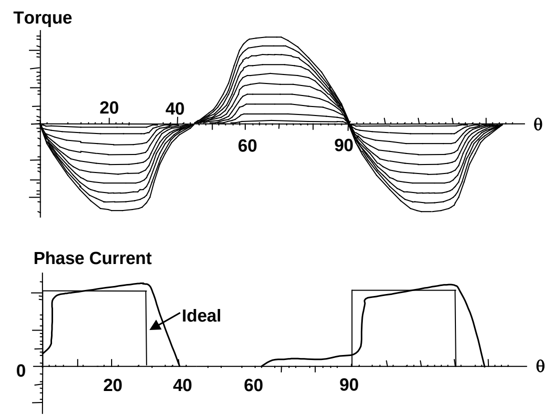

Fig. 1 Static torque and phase current for one phase during generation. Zero and 90 degrees are the aligned position and 45 degrees is the unaligned position.

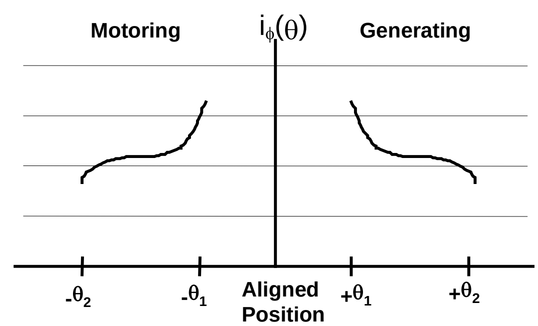

Fig. 2 Phase current during generating is the phase current during motoring mirrored about the aligned position.

The SRM as generator is the dual of the machine as a motor. In fact the machine phase current waveforms during generating are simply the mirror images, around the aligned rotor position, of the phase currents during motoring as illustrated in Fig. 2. This statement can be proven precisely if the machine's winding resistance is zero and it is essentially true for actual machines with reasonable efficiencies.

II. Switched Reluctance Generator Model

A. Switched Reluctance Machine

A commercially available switched reluctance machine Used in experimental study was a 750-W 4-phase 8/6 machine. Fig.3 shows the block diagram of SRG coupled with a DC motor, which functions as a prime mover.

N.B. Kavitha, Non-Student, Power Electronics and Drives Department, RMK Engineering College, Chennai. (email: jbkavitha.me@gmail.com, phone: Mobile: +91-8056109612).

B.Vinu priya, B.E,(EEE), RMD Engineering College, Chennai, India.

B. Energy Conversion

A switched reluctance machine can generate electrical power by proper synchronizing each phase current with rotor position (after alignment).

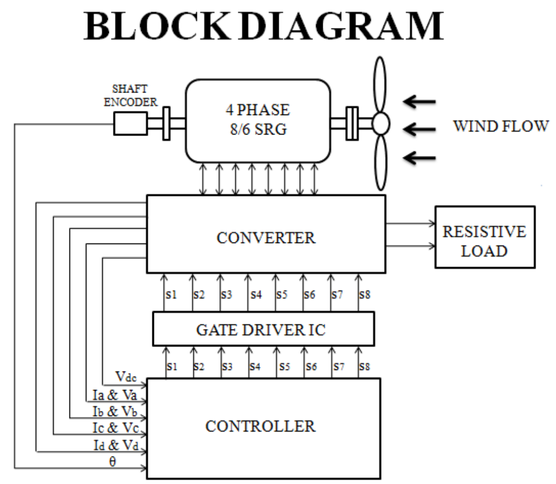

Fig. 3 Block Diagram of SRG

To achieve this, each phase current must be on during the period of negative slope of its flux linkage versus rotor position. In this generating mode, the SRG creates negative torque which is trying to oppose the rotor motion. Therefore, mechanical energy is extracted from the prime mover, converted to electrical energy by returning the energy to the DC bus.

C. Operating Modes

SRG is analogous to switched reluctance motor (SRM). The controller of the SRG maintains the average DC-link voltage constant in much the same way as the controller of SRM maintains a constant average torque. At low speed, the DC-link voltage can be controlled by varying the reference current, thus the chopping mode is used**.** However, at high speed the SRG is operated in single-pulse mode by varying the commutation angles.

D. Asymmetric Half-Bridge Converter

The power electronic converter used in this SRG control is an asymmetric half-bridge converter, as shown in Fig.4. This converter circuit is the standard topology for switched reluctance machine drives, as it provides the most control flexibility and fault tolerance. Each phase of the converter uses the same DC-bus for excitation through two controllable switches and for generation (demagnetization) through two diodes. Thus, each winding can be supplied with positive and negative DC-bus voltage, as well as zero voltage if only one switch is on after excitation (freewheeling state). This is an ideal feature for current control in chopping mode. This circuit can also operate single-pulse mode by turning on and ,off both switches at variable commutation angles. The fact that the two switches are series-connected with phase winding makes this circuit inherently free from shoot-through fault. Another reason that makes this converter so reliable during fault conditions is the electrical independence among phases.

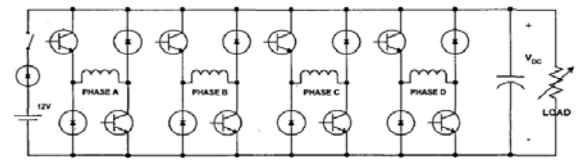

Fig. 4 Circuit Diagram of 4-phase asymmetric half bridge Converter for SRG drive

E. Dynamics of SRG

For better understanding of the excitation and generation of the SRG, it is crucial to look into the dynamics of each phase winding.
Consider the dynamic equation of phase voltage:

$$v = R \cdot i + \frac{d\lambda(i,\theta)}{dt} \qquad (1)$$

The flux linkage is a function of current and rotor position, therefore the voltage equation can be rewritten as:

$$v = R \cdot i + \frac{\partial \lambda}{\partial i} \cdot \frac{di}{dt} + \frac{\partial \lambda}{\partial \theta} \cdot \frac{d\theta}{dt}, \qquad (2)$$

or

$$v = R \cdot i + L \cdot \frac{di}{dt} + \frac{\partial \lambda}{\partial \theta} \cdot \omega\,. \qquad (3)$$

The last term of (3) is the negative back EMF (e):

$$e = \frac{\partial \lambda}{\partial \theta}\omega = \frac{\partial L}{\partial \theta} i\omega\,. \qquad (4)$$

Now consider one phase of the converter in Fig. 4 for generation mode. During magnetization (excitation) period both switches connect the DC bus to the Winding, thus the phase current increases.

$$V_{DC} = R \cdot i_{exc} + L\frac{di_{exc}}{dt} - |e| \qquad (5)$$

During freewheeling state one switch and one diode are in conduction mode, so the winding experiences zero voltage. The phase current, however, continues to rise up due to the influence of the negative back EMF.

$$0 = R \cdot i_{fre} + L\frac{di_{fre}}{dt} - |e| \qquad (6)$$

During demagnetization (generation) period both switches are off, then the DC bus is connected in reverse polarity through the diodes. Consequently, the phase current flows back to the DC bus and return the generated power to it.

$$-V_{DC} = R \cdot i_{gen} + L\frac{di_{gen}}{dt} - |e| \qquad (7)$$

At low speed, the absolute value of the back EMF is lower than that of the DC-bus voltage. Hence the phase current can be controlled by appropriately coordinate the above three switching states. This can be done in both hard-chopping (+Vdc and -Vdc) and soft-chopping (0 and -Vdc) modes.

F. Analysis of Switched Reluctance Generator

A study is made on the smoothening of torque profile of Switched reluctance motor by 2-D finite element approach,

http://dx.doi.org/10.15242/IIE.E0314211

Pole geometric modifications and stator pole shoe introduction. An analysis of SRG feeding an isolated load, In this the generator performance has been investigated by a software development kit based on object oriented program technique. An analysis of the SRG's faults and excitation requirements is essential to utilize the fault tolerance capability of this machine in aerospace starter / generator and in various automotive applications. One such research has been undertaken in [40] to identify, analyze and simulate various fault modes of SRG and investigation about SRG's excitation requirements with and without faults has been carried out. Another study on fault –tolerant operation of multi-pole single-phase 8/8 structure of SRG has been carried out,where open and short-circuit coils are studied through linear analysis, finite element analysis and static torque measurement. In the quality analysis of SRG based on piece-wise approximation has been presented. In this two SRG constructions, one with strong magnetic saturation is compared with the one with the linear characteristics and it is shown that the former has larger power output than the later.

G. Controllers for Switched Reluctance Generator

There are four control issues of SRG such as

1) angle position control ;
2) chopping-current control ;
3) PWM control ; and
4) direct extinction voltage control .

These main control variables are due to the threshold of the exciting current indirectly. Excitation process can be controlled through regulating turn-on and turn-off angles. At low and medium speed operation the SRG phase current is regulated using PWM control of magnetizing voltage and for high speeds it is controlled using a single pulse mode. Constant power output control with the constant output voltage of SRG is implemented with the following control strategies.

1) fixed conducting angle PWM control strategy
2) variable conducting angle control strategy

The structure of SRG controller for speed –control and power control applications and the details for commutation of SRG are discussed. In the topology and control methods of SRG drive are compared with the topology & control of conventional AC drives and the control of SRG for flywheel energy storage system for the application in UPS is discussed.

A closed loop control of power output of SRG to drive a wind energy conversion system to the point of maximum aerodynamic efficiency is presented. A maximum power point tracking control and constant resistance control methods for SRG are proposed. A control system for the grid side inverter is presented in and a control technique of a SR starter/generator system has been patented. There are two voltage control schemes namely voltage feedback control and commutation shift control scheme. In lower driving speed and heavier load conditions, the voltage feedback regulation control ability under chopping switching mode will be failed and under such circumstances dynamic commutation shift controller is suggested in and tested on an experimental prototype model of SRG.

The range of design parameters and control variables that generate maximum output power are investigated. The speed feedback control method for the SRG system described, to make the wind turbine work at an optimal speed. The variable speed control has the potential to increase the energy capture.

III. Simulations Results

The SRG used for simulation is based on parameters from a 4 phase 8/6 machine. The maximum and minimum phase inductances are 60mH and 8mH. Currently the simulation is tested by fixing both the firing angles with constant speed, the single pulse cur-rent increases slowly during the increasing inductance region and as switches are turned off the current gradually decreases and reduced to zero. The waveform pro-duced by simulation is similar to waveform shown in Figure 1. According to simulation, the firing angles must vary to accommodate the change in speed. Overall from the simulations performed, it can be seen that the amount of power generation depends on placement of firing angles. A good control strategy which synchronizes the phase current with rotor position would provide more efficient SRG system. If we use advanced turn on angle it gives sample time for current to build up. However the disadvantage of advancing too far is that it will be in the positive torque region which reduces the efficiency. The firing angles must vary to accommodate changes in speed to maximize the output power. The simulation model needs to be enhanced to cater for varia-tion in the above parameters.

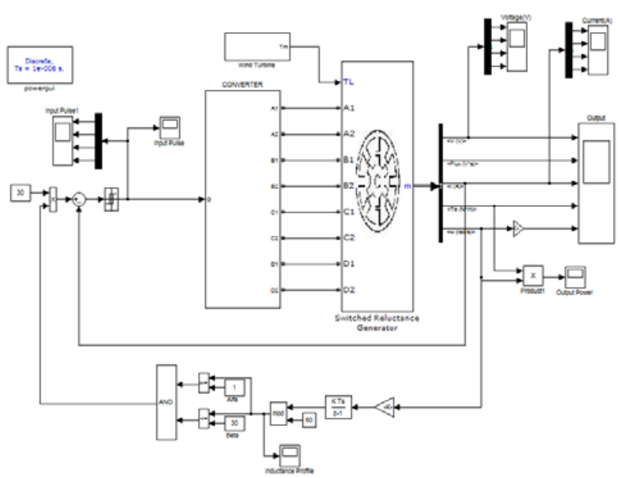

Fig. 5 Simulation diagram of 4 Phase SRG

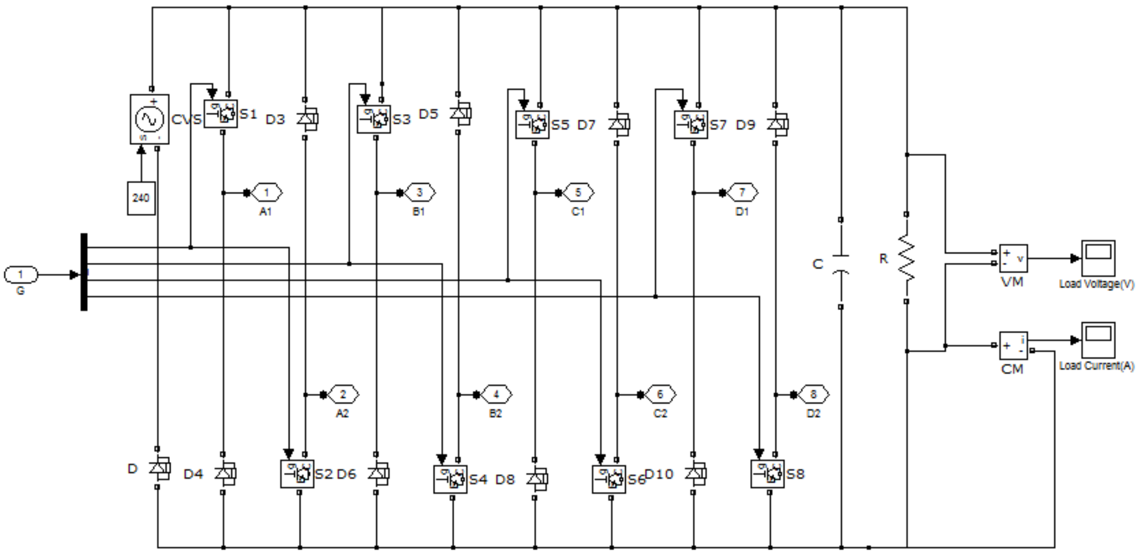

Fig. 6 Simulation model of an asymmetric half bridge converter

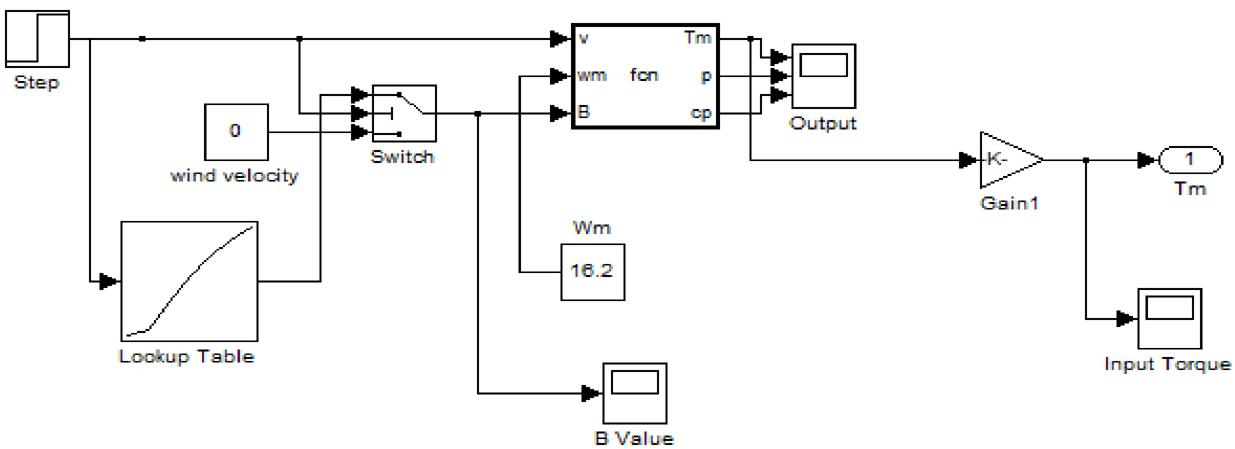

Fig.7 Simulation model of Wind Turbine

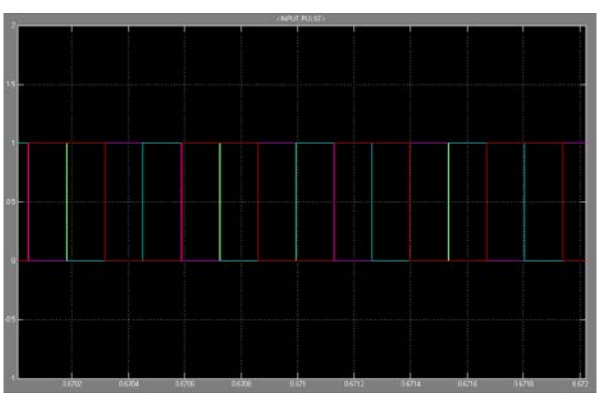

Fig. 8 Input pulse waveform

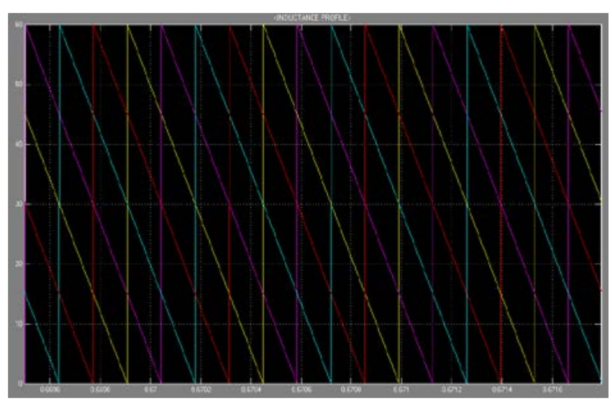

Fig. 9 Inductance profile

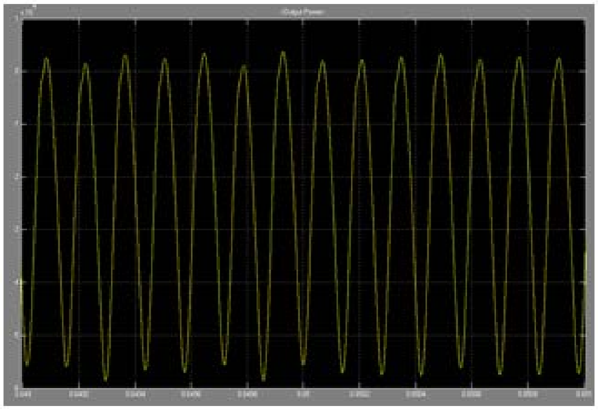

Fig. 10 Output Power

IV. CONCLUSIONS

The Analysis of Dynamic Characteristics of switched reluctance Generator has been done using MATLAB, a widely used simulation tool. The component models have been constructed by user-define functions provided in the simulation program. The results present the dynamic characteristics of SRG, moreover the same procedure can be used to optimize the design and control of any other SRG for maximum output power.

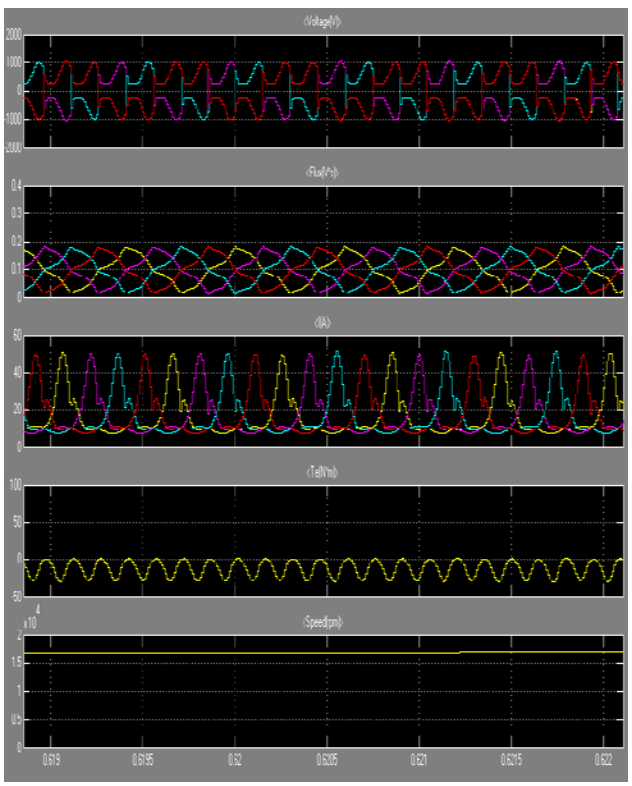

Fig.11 Output Waveforms (Voltage,Flux,Current,Torque,Speed)

The use of power converter for switching allows it to operate at variable speed operation. By proper placement/excitation of firing angles the output power can be maximized. Future work will look into enhancing the model to cater for various parameters such as the control methods in order to vary the firing angles, varying speed and also include load. The final model will allow user to study the characteristic of the machine and choose the optimum design based on its parameters.

REFERENCES

[1] T.J.E. Miller, *"Switched Reluctance Motors and Their Control"*, Clarendon Press, Oxford, 1993.

[2] R. Krishnan, *"Switched Reluctance Motor Drives"*, CRC Press, 2001.
http://dx.doi.org/10.1201/9781420041644

[3] D.A. Torrey, X.M. Niu, E.J. Unkauf, *"Analytical modelling of variable-reluctance machine magnetization characteristics,"*IEE Proceedings, Electrical Power Applications, Vol. 142, No. 1, January 1995, pp. 14-22.
http://dx.doi.org/10.1049/ip-epa:19951567

[4] R. Cardenas, W.F. Ray, G.M. Asher, *"Switched reluctance generators for wind energy applications,"* in PESC '95 IEEE Power Electronics Specialists Conference Record, Volume 1, June 1995, pp. 559-564.

[5] D.A. Torrey, *"Switched reluctance generators and their control,"* IEEE Transactions on Industrial Electronics, Volume 49, No. 1, Feb. 2002, pp.3-14.
http://dx.doi.org/10.1109/41.982243

[6] R. Cardenas, R. Pena, M. Perez, J. Clare, G. Asher, P. Wheeler, *"Control of a switched reluctance generator for variable-speed wind energy applications,"* IEEE Transactions on Energy Conversion, Volume 20, No. 4, Dec. 2005, pp. 781-791.
http://dx.doi.org/10.1109/TEC.2005.853733

[7] C. Mademlis, I. Kioskeridis, *"Optimizing Performance in Current-Controlled Switched Reluctance Generators,"* IEEE Transactions on Energy Conversion, Volume 20, No. 3, Sept. 2005, pp. 556-565.
http://dx.doi.org/10.1109/TEC.2005.852960

[8] E. Mese, Y. Sozer, J.M. Kokernak, D.A. Torrey, *"Optimal excitation of a high speed switched reluctance generator,"* in Proceedings of APEC 2000 IEEE Applied Power Electronics Conference and Exposition, Vol. 1, Feb. 2000, pp.*362-368.*