Control of Switched Reluctance Generator for Wind Energy Applications

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ABSTRACT
This paper discusses how the switched reluctance generator (SRG) converts mechanical energy from wind via turbine into electrical energy as directed by an electronic controller. Starting with a review of the electromechanical energy conversion principles, the paper examines the implications of the energy conversion process on how the SRG is controlled. The structure of the SRG controller for speed-control and power-control applications is discussed. The methods for commutation of the SRG are discussed. Concepts are illustrated with a 5-kW SRG designed for wind energy applications where low speed high torque is required.

Keywords- Switched Reluctance Generator (SRG), SRG Control, SRG Converter Circuit, SRG Structure, Turbine, Wind Energy Converter

I. INTRODUCTION

The worldwide increase in the share of electricity generated by wind energy converters (WECs) has in recent times influenced researchers’ motivation to search for the most suitable machines in terms of economy, efficiency, power density and reliability [1]. A variety of principles of Physics are used to create wind turbines that can efficiently capture energy from the wind and turn it to electricity by means of turbine – generator systems. Amongst other electrical machines that could be used for wind energy conversion system, the switched reluctance generator (SRG) stands the chance of achieving better performance because of its mechanical constructional simplicity, extremely low cost, reliability, high torque tolerance, high torque to inertia ratio, wide range of speed variation, high power density and high efficiency. However, the design and control of SRG particularly for wind energy application can be very difficult because of the doubly saliency of the machine poles and the consequent nonlinear magnetic characteristics of the machine [2]. The combined effects of the machine topology and the non-uniform distribution of flux in the airgap result in production of excessive vibration and acoustic noise.

This paper discusses the switched reluctance generator (SRG) and the applicable various control techniques. Even though there are some important differences in control objectives and control implementation of SRG, yet it can be considered for dual as the switched reluctance motor (SRM). The focus of this paper is on the control issues for the SRG and presents the characteristics of typical SRG behavior. In selecting the control strategy and designing the control of SRG important features such as the mechanical topology and converter type must be considered.

The SRG is in developmental stage for variable-speed applications where its inherent characteristics offer it advantage for commercialization. As at now, the SRG has its applications aerospace power systems, starter/alternators for hybrid vehicles [and wind energy converters [3]. While the wind energy application is characterized by low-speed high-torque operation, the aerospace and automotive applications are generally characterized by high-speed operation. The SRG is compatible with demanding applications. The absence of windings and permanent magnets on the rotor allow for both high rotational speeds and high-temperature operation. Further, the absence of windings on the rotor helps to reduces copper loss in the machine and thereby increasing the energy density of the machine [4]. The switched nature of the SRG makes it compatible with any application that requires variable-speed operation. In the case of aerospace and automotive applications, variable-speed operation is needed for compatibility with the engine that drives the SRG. In wind energy applications, variable speed operation is needed to extract additional energy from the wind stream and to lessen the mechanical stresses within the system.

As with motor systems, the proper application of a generator to a system requires an understanding of the characteristics of the prime mover. In the aerospace and automotive applications, the prime mover is able to provide essentially constant power over a wide speed range and in the case of the wind energy application; the shaft power is proportional to the cube of speed,
implying a substantial increase in torque and power as the speed increases [5].

Fig.1. Three-phase 6/4 SRG

The consideration of prime mover torque–speed characteristic is important when determining the electromechanical specifications of the machine. Also essential to consider are the characteristics of the electric power converter into which the SRG provides energy. Section II focuses on the electromechanical energy conversion of the SRG. This includes brief description of torque production and the energy conversion processes with the intention of providing insight into the operation of the SRG control issues. Section III addresses the control strategy and its implementation. This builds on the electromechanical concepts developed in Section II. Many of the concepts discussed in the paper are illustrated through examples with an SRG designed for wind energy conversion system. Section IV is for conclusion. It discusses the results obtained from simulation using 2D and 3D finite element analysis (FEA) of Maxwell, Rmxprt and Simpler software of Ansys in conclusive approach.

II. ELECTROMECHANICAL ENERGY CONVERSION

The wind turbine which extracts energy from the wind through the turbine blades that are attached to rotor shaft of the turbine is mechanically coupled to rotor shaft of the switched reluctance generator. Thus the translational form of mechanical energy of the wind is converted into rotational form of mechanical energy by the turbine. The converter supplies the electrical energy needed by stator coil to produce magnetic flux in the stator core. Both the stator and the rotor of SRG are made of soft iron lamination materials and the both have salient poles. Only the stator poles are wound with copper coils, the rotor poles carry no coil. The figure below shows the doubly salient pole structure of 6/4 SRG.

Fig.2. SRG wind energy conversion system

Fig.3. Doubly salient pole structure of 6/4 SRG

The overall performance of the SRG system depends largely on the efficiency of the wind turbine SR machine the power converter and the control unit. Usually, three blades are attached to the turbine rotor shaft on horizontal axis (as shown in Fig.2 above) but there are those with vertical axis as shown in fig.4 below. For a horizontal axis wind turbine (HAWT), the plane of the rotor turns so that the wind is perpendicular to it and can flow around the blades to make them rotates around the hub as shown fig. 4 below. For vertical axis wind turbine (VAWT) the orientation of the rotor shaft is in vertical position as show in fig. 4. In other words turbine types are determined by the orientation of the rotor shaft. The efficiency of HAWT is found to be higher than that of VAWT of equal capacity.
As a generator, the SRG is designed to convert mechanical energy from the prime mover to electrical energy. The Switched Reluctance Generator drive consists of the machine itself, the converter and also the controller as depicted in Fig. 1. The operation of the machine is based on the principle that the rotor, driven by a prime mover, is free to move to a position of minimum reluctance to the flow of flux in a magnetic circuit. This is achieved by energizing and de-energizing a set of windings on the stator poles. Since an external circuit is required to provide excitation to the stator winding of the machine, it does not allow direct connection to an AC or DC supply.

The operation cycle of the machine can be classified as excitation stage and generation stage. An essential component of the machine to perform switching sequence, exciting the stator phase in synchronism with the rotor position is the power converter. In generating operation, the machine is controlled in such a way that it operates along the decreasing inductance profile.

The electromagnetic torque in the SRG, as in the SRM, is developed naturally as the rotor pole moves from the region of high reluctance to the region of low reluctance. If the phase is excited before the rotor poles come into alignment with the stator poles, the rotor experiences torque in the direction of rotation consistent with operation as a motor. If the phase is excited as the rotor poles move through the aligned position, the rotor experiences torque opposing rotation consistent with generator operation. The inductance is at maximum...
when the rotor pole aligned completely with the excited stator pole and at minimum when it completely unaligned. For any value of excitation current, the inductance varies with the relative position of the rotor [6]. The torque is independent of the direction of the current in the stator coil but a function of the magnitude of the current and the relative angular position of the rotor. At base speed the phase back electromotive force (EMF) balances the source voltage and resistive drop in the coil.

In general, the inductance-current characteristic of SRG has both spatial and magnetic nonlinearity parts which must be taken into consideration in the design process. The magnetic nonlinearity is evident particularly near the aligned position; there is no evidence nonlinearity in the unaligned position.

Machines having the same number of turns, current density in the winding and stator dimensions, the inductance profile of the higher rotor poles is narrow as compared to the machine with lower number of rotor poles. Therefore, a higher number of rotor poles machine will require more excitation than the one with lower number of poles. Nevertheless, it gives better torque profile than the machine with lower number of poles.

The torque equation \( T \) relating the excitation current \( i \), inductance \( L \) and the rotor position \( \theta \) I given by equation (1) below.

\[
T = \frac{1}{2} i^2 \frac{dL}{d\theta}
\]

For multiphase SRM the instantaneous torque equation becomes the summation of individual torque value for each phase and is expressed as:

\[
T(\theta, i_1, i_2, ..., i_k) = \sum_{n=1}^{k} T_n(\theta, i_n)
\]

or

\[
T = \sum_{n=1}^{k} T_n
\]

where \( n \) is the phase number and \( k \) is the total number of phases.

The exponential function

\[
\psi = a_0 i + a_1 (1 - e^{-\alpha_1 i}) + a_2 (1 - e^{-\alpha_2 i}) + a_3 (1 - e^{-\alpha_3 i})
\]

can be used to represent the magnetisation curve of SRM because of its natural fitness to typical magnetization curve. This function consists of three exponential terms and a linear term.

where \( a, a_1, a_2, a_3 \) are coefficients and \( \alpha_1, \alpha_2, \alpha_3 \) are constants.

A nonlinear least square analysis is used to calculate the coefficients and the constants are obtained from \( \psi/I \) curve.

Fig. 6. Phase flux linkage as a function of current and rotor position for the SRG of Fig. 1.
III. CONTROL STRATEGY

Similar control strategies of SRM can be adopted for SRG with different control objectives and implementations. In motoring mode, the excitation of the phase windings is made in the period of minimum inductance profile. At this time, a high rise of current is expected hence at low speed current chopping mode is employed for overcurrent protection. In contrast to the generating operation, the excitation is made during maximum or increasing inductance profile. The phase current will be low at starting and will slowly increase as the rotor moves away from the stator pole, decreasing the inductance value. Once the signal reaches the turn off angle, the increase in phase current can no longer be controlled. Therefore, the current chopping mode is not suitable for generating operation especially at low speed and under heavy load conditions.

The electronic control unit is responsible for switching operation of the electronic switches. By the switching action the coil is excited or de-energized [7]. The electronic control unit is the heart of the SRG as it controls every unit the SRG system. It controls the magnitude of the current and voltage needed for excitation. It also gets information of the rotor pole from the position sensor and selects the phase to energise at a particular time. The firing angle depends on the information available to the controller.

Figure 7. Basic control model for SRG

Figure 6 above describes the control links between the different segments in the entire SRG system. The difference lies in the control strategies applied. Unlike in motoring single pulse mode is used for high speed whereas pulse width modulation (PWM) is used for low speed. SRG control strategy based on the determination of the firing angles could be classified into three groups. These groups are:

- fixing both the turn on and turn off angles
- one of the angles may be fixed whilst varying the other
- vary both turn on and turn off angles

As there will be variation in wind velocity, the best strategy is to vary both the turn on and turn off angles in order to achieve optimum performance.

Four control techniques available for SRG are
1) angle position control;
2) chopping-current control;
3) PWM control; and
4) direct extinction voltage control.

These main control variables depend indirectly on the threshold of the exciting current [8]-[10]. Excitation process may be controlled through regulating turn-on and turn-off angles. At low and medium speed operations the SRG phase current is regulated using PWM control method of magnetizing voltage and for high speeds it is controlled using a single pulse mode.

IV. CONCLUSION

Switched reluctance generator is a good potential candidate for wind energy conversion systems. Its ruggedness, low cost and wide range of speed variation makes it suitable for wind energy application since wind speed changes from time to time. With the right choice of converter topology and control strategy, SRG can be made to operate with very high efficiency thereby minimizing losses and overall cost of electricity generation. As there will be variation in wind velocity, the best strategy is to vary both the turn on and turn off angles in order to achieve optimum performance. At low and medium speed operations of SRG, as in the case of wind energy application, phase current is regulated using PWM control method.

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