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Efficiency Analysis of Switched Reluctance Generator According to Current Shape under Rated Speed

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Abstract –This paper introduces the high efficiency operation of switched reluctance generator (SRG). The proposed SRG operates under the rated speed. The high efficiency can be obtained by the optimal current shape which can make the total losses minimum. For this purpose, theoretical analysis of the copper and core loss is done. In addition, a modified angle position control (MAPC) method which can get the optimal current shape over wide speed condition is presented. In order to verity the theory, the experimental platform is set up. The feasibility of the theory is verified by the simulation and experimental results. The proposed method is simple, reliable and easy to achieve.

Keywords: Switched reluctance generator, Current shape, High efficiency

1. Introduction

There are a lot of advantages of the switched reluctance generator (SRG). The rotor construction is very simple, because it consists of only laminated steel. The stator part consists of concentrated phase windings mounted around salient poles [1]. This is good in a commercial sense, as manufacturing cost is low [2]. Besides, the absence of windings and permanent magnets on the rotor encourage high-speed and high temperature operation of the SRG [3]. Furthermore, each phase of SRG is electrically and magnetically independent from others, and it confirms improved system reliability [4, 5]. The merits of using SRG have been proved for some applications like starter/generator for gas turbine of aircrafts [6], windmill generator [7] and as an alternator for automotive applications [8]. The objective of SRG control is normally to track the output power and keep the DC-link voltage at a desired value with high efficiency, low torque ripple, and low acoustic noise. These control objectives can be optimized by appropriately adjusting the turn on/off angles and other parameters of SRG.

At present, there is little relevant literature about improving the system efficiency of SRG, especially the SRG is operated at low and medium speed condition. In [9], for whole operating speeds, all possible turn on and conduction angles have been simulated to get the desired power factor. In other words, the copper losses have been minimized and the efficiency has been improved. In [2], the control of excitation of SRG for maximum efficiency at single pulse mode of operation has been presented. Turn on and turn off angles are defined as control variables, turn on angle is set based on the output power and turn off angle is selected to achieve optimal efficiency at each power level and speed. In [10], a new performance criteria as productivity of generator is described, in this method, instead of two phase commutation steps, which are on and off in single pulse mode, a freewheeling step is added. During this step, the phase is short circuited and the current increases due to back-emf voltage. This method produces more power than the conventional method, for the same conduction period and it reduces current ripple on DC-link bus. Current chopping control and single pulse control are adopted respectively as inner loop to hold on DC-link voltage in [11] and [12]. Moreover, optimal turn on/off angle is chosen by analysis of the system efficiency and torque ripple in [11]. While, in [12], the optimal turn on/off angle is calculated by a ratio of two fluxes. One is the flux at the point where entire-overlapped stator and rotor poles start to detach, and another is the max flux. In [13], the optimal turn on/off angle which corresponding the high system efficiency is selected by measuring and analyzing the system losses of different reference powers and speeds. The control system in this paper is constituted by PI power controller and two-level current hysteresis controller. Based on measured magnetization curve, optimal turn on/off angle can be obtained by analyzing output power and system efficiency under a series of different on/off angle in [14].

In this paper, high efficiency operation of SRG is the

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main objective. The effect of phase current waveform on the system efficiency during the SRG system power generation stage is analyzed. The optimal current waveform which can make the system operate with high efficiency is obtained by the theoretical analysis and simulation of the copper loss and core loss. A modified angle position control (MAPC) method which can get the optimal current shape is presented. The feasibility of the theory are verified by the experiment.

2. Analyze of SRG operation

2.1 Operation principle

There are many configurations for SRG; Fig. 1 illustrates a basic structure of a four phase SRG used in this paper.

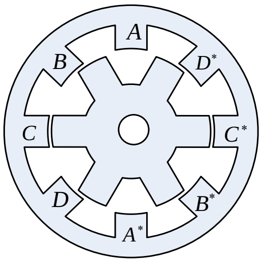


Fig. 1. Cross section of a four phase SRG

Voltage equation for each phase of SRG is given by

$$u_{ph} = R_{ph} i_{ph} + L(i_{ph}, \theta) \frac{di_{ph}}{dt} + e_{ph} \quad (1)$$

where, subscript ph is one of these phases, R_{ph} is the phase resistance, the phase inductance L is the function of the rotor position θ and the phase current i_{ph}, and $e_{ph} = i_{ph}\omega\, \partial L(i_{ph}, \theta)/\partial\theta$ is back-emf .

A switched reluctance machine operates in generating mode, if each phase is excited after aligned position, where the phase inductance decreases, $\partial L/\partial\theta < 0$. From (1), it can be known that, the behavior of the phase current depends on the relationship between back-emf and source voltage. Since the amplitude of back-emf varies with rotor speed, the current waveform depends on the rotor speed.

2.2 Calculation of main electrical losses

The main electrical losses of a SRG are copper loss and core loss. The copper loss depends on the root-mean-square (rms) phase current and is given by

$$P_{Cu} = m I_{rms}^2 R_{ph} \quad (2)$$

where, m is the number of phase, and the I_{rms} is calculated in (3) by Fig. 3. $\theta_{rrp} = 2\pi/N_r$ is rotor pole pitch, and N_r is the number of rotor poles. θ_q is rotor angle at which phase current extinguishes.

$$I_{rms} = \sqrt{\frac{1}{\theta_{rrp}} \int_{\theta_{on}}^{\theta_q} i_{ph}^2 d\theta} \quad (3)$$

The core loss is proportional to the excitation magnetic motive force (mmf) and the stroke frequency. Since the flux waveform is non-sinusoidal and flux harmonic spectra differ in various parts of the magnetic circuit, core loss is not uniformly distribute in the core. In this paper, the core loss is calculated by an approximate formulae based on the actual flux waveforms for every part of SRG. In addition, Fourier analysis is used to obtain the frequency and the amplitude of the fundamental and the harmonic components. The approximate equation is shown in (4).

$$P_{Fe} = K_h f (B_m)^2 + K_c (f B_m)^2 \quad (4)$$

where, f is the stroke frequency, K_h and K_c is the hysteresis and eddy-current loss coefficient, respectively, and B_m is the amplitude of flux density for sinusoidal variation.

2.3 Calculation of system efficiency

The system efficiency which is an important criterion for SRG performance is defined as

$$\eta = \frac{P_G}{P_M} \quad (5)$$

where, P_G is the electrical output power of SRG, and P_M is the mechanical input power of prime mover. The input power can be calculated by

$$P_M = T_L \cdot \omega \quad (6)$$

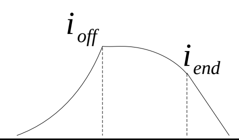
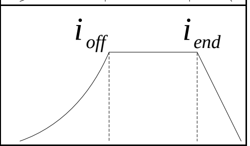
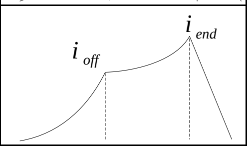
where, T_L and ω is the electromagnetic torque of the prime mover and angle velocity, respectively.

From (5) and (6), it is concluded that in order to calculate the system efficiency, the measurements of P_{out}, T_e and ω are required.

3. Analysis of the effect of current shape on the system

Fig. 2 is the phase currents and flux linkages with different current waveforms at the same output power. Under the rated speed, it can be obtained three kinds of typical current shapes by adjusting the turn-on/off angles and the voltage added on the phase during the generation stage. The three kinds of current shapes can be expressed using current slope factor CSF. The relationship between the CSF and the current shape is illustrated in Table 1. In the table, the i_{off} and i_{end} is the current value at rotor position θ_{off} and θ_{end}, respectively. The θ_{off} and θ_{end} is the turn-off angle and the rotor position at which the stator and rotor pole corners complete overlap. From (1), it can be known that the absolute value of phase voltage is smallest as CSF is "+", and the condition is opposite when CSF is "−". So at the same output power, the rms phase current is biggest when CSF is "+", and as the result, the copper loss is maximum. On the contrary, the copper loss is minimum as CSF is "−". In addition, from Fig. 2, it can be known that the peak value of flux linkage occurs on the θ_{off}. So the core loss is minimum when CSF is "+", Inversely, the peak value of flux linkage and the core loss is maximum as CSF is "−".

Table 1. Relationship between CSF and current shape

CSF	Current equation	Current shape
−	$i_{off} > i_{end}$	
0	$i_{off} = i_{end}$	
+	$i_{off} < i_{end}$	

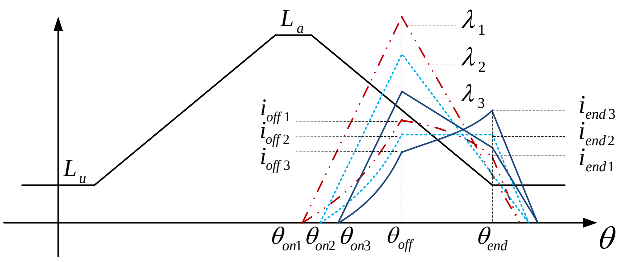


Fig. 2. Phase current and flux linkage with different current shapes at same output power

From the above it is concluded that the optimal current waveform which can make the total losses minimize is existed and the value CSF can determine the current shape.

In order to obtain the optimal current shape, the modified angle position control (MAPC) method is proposed. This method is made up of angle position control method and voltage chopping control method. So it includes the merit of these two kinds of control method.

Fig. 3 is the concept waveform of MAPC method. Where, L_a and L_u is the inductance value at aligned and unaligned position, respectively. θ_{on} and θ_{off} is turn-on and turn-off rotor position, respectively. θ_q is the rotor position at which phase current extinguishes. V_{dc} and i_{ph} is the DC-link voltage and phase current, respectively. λ_{ph} is the phase flux linkage. In addition, the θ_{end} can be calculated by (7). From (7), it can be known that, for the specific motor, value of θ_{end} is constant. According the used SRG parameters, the θ_{end} is 53.3°.

$$\theta_{end} = \frac{\theta_{rrp}-(\beta_s+\beta_r)}{2} \tag{7}$$

where, θ_{rrp} is the rotor pole pitch. β_s and β_r is stator and rotor pole arcs, respectively.

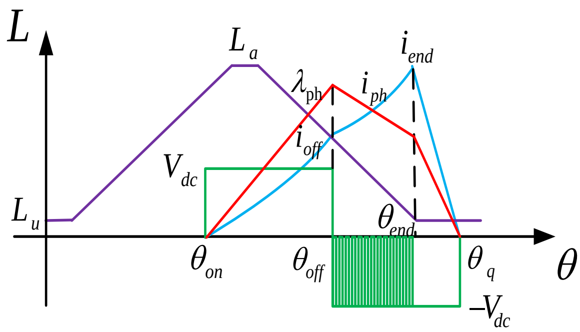


Fig. 3. Concept waveform of MAPC method

4. Simulation and experimental results

The control structure of the system is shown in Fig. 4, which consists of SRG, AC servo motor, power converter, angle position controller, duty calculator and position sensor. The AC servo motor serves as the prime mover in the system. The SRG as the core of the entire system plays a part that absorbs the mechanical energy from the prime mover and delivers the electrical energy to the load. In the figure, P^* and P_{out} is the command power and output power of SRG, respectively. θ_c is the dwell angle, and it is determined by the PI controller. $\theta_{on} = \theta_{off} - \theta_c$ is turn-on angle. It is worth noting that, the duty calculator is determined by the *S1* and CSF. The *S1* is the speed error single ($\Delta\omega = \omega^* - \omega$). It includes two values, 0 and 1, corresponds to the under rated speed operation and over speed operation, respectively.

The performance of the SRG drive is highly affected by the performance and characteristics of the converter. The power converter used in this paper is share switch type, and it can save two power switched and two diodes, so it can reduce the system cost. The structure of the converter is shown in Fig. 5. Fig. 6 takes phase A as the example to describe the operation mode of the converter. From Fig. 5 and 6, it can be known that, the phase winding voltage depends on the state of the power switches, and the value includes U_S, 0, and $-U_S$.

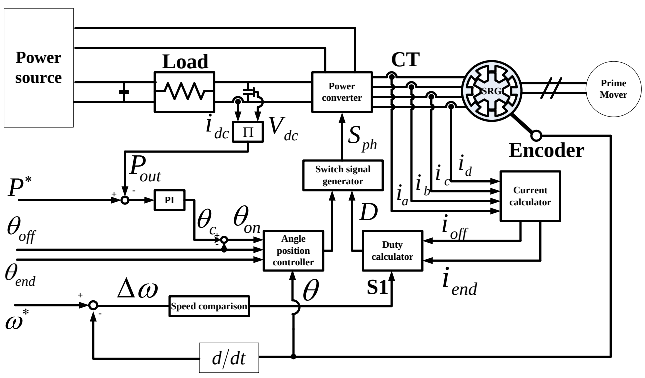


Fig. 4. Block diagram of 8/6 SRG control system

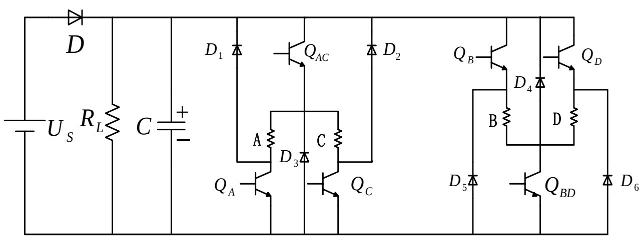
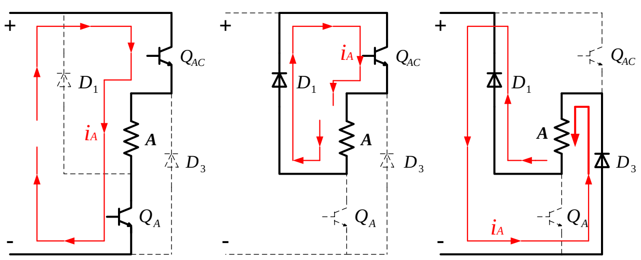


Fig. 5. Power converter of 8/6 SRG



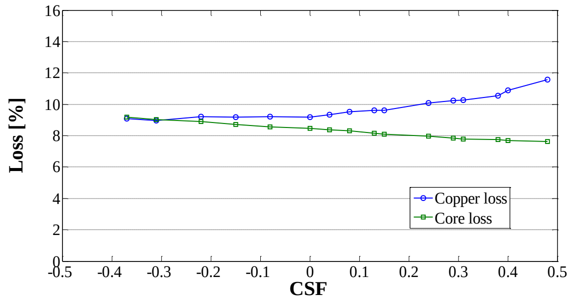
(a) (b) (c)

Fig. 6. Operation mode of the converter (a) magnetization mode (b) freewheeling mode (c) demagnetization mode

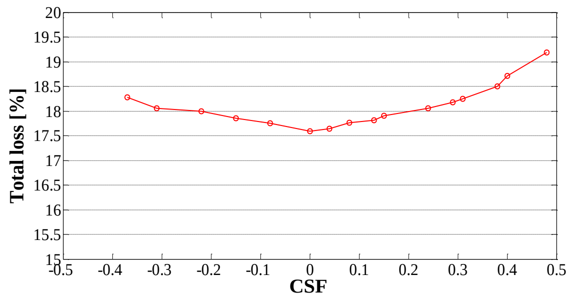
4.1 Simulation results

Fig. 7 shows the relationship between CSF and the loss. From the figure, it can be known that the copper loss will increase when the CSF value increases. However, the core loss will decrease when CSF value increases. When the CSF is "0", the total loss is minimum at the same output power condition. This result matches the theoretical analysis.

Fig. 8 shows the relationship between the CSF and the efficiency. It is worth mentioning that, only the copper and core loss are considered in the simulation. The simulation condition is that source voltage is 150V, speed is 1000 rpm, and θ_{off} and θ_{end} is fixed at 41° and 53.3°, respectively. From the results, it can be seen that the efficiency is maximum when CSF is "0".



(a)



(b)

Fig. 7. Relationship between CSF and loss
(a) copper and core loss (b) total loss

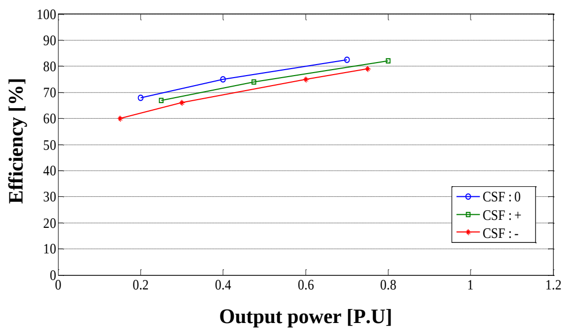


Fig. 8. Relationship between CSF and efficiency (simulation)

4.2 Experimental results

In order to verify the theory and simulation results, the AC servo motor and SRG system is set up. The AC servo motor is controlled by speed closed-loop method to maintain a constant speed. In experiment, the main parameters of SRG are 150V, 200W, 1500rpm, the TMS320F28335 DSP-150MHz produced by Texas Instruments is used. In addition, the precision power analyzer PPA2530 produced by Newtons4th Ltd and bipolar DC power supply BP4610 produced by NF corporation are used in the experiment. The experiment set-up of the SRG system is shown in Fig. 9.

Fig. 10 shows the relationship between CSF and system efficiency at 1000rpm and 1500rpm. In the experiment, DC-link voltage is 150V, θ_{off} and θ_{end} is fixed at 41° and 53.3°, respectively, and the θ_{on} is a variable. In addition, the system efficiency is calculated by (5), and the T_e and P_{out} can be obtained by the AC servo motor controller and power analyzer respectively. At this time, with the decreasing of the turn-on, the output power of the SRG will increase, and the phase voltage during the generation stage which maintain the needed current waveform will increase. As shown in Fig. 10 (b), when CSF is "−", the reason why the output power less than the rated power is that if the output power continues to increase, the given current shape is not able to maintain. From Fig. 10, it can be seen obviously, the system efficiency is maximum when CSF is "0". The results match the simulation results and the theoretical analysis.

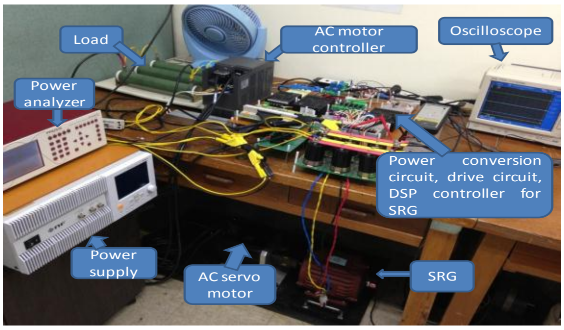


Fig. 9. Experimental platform

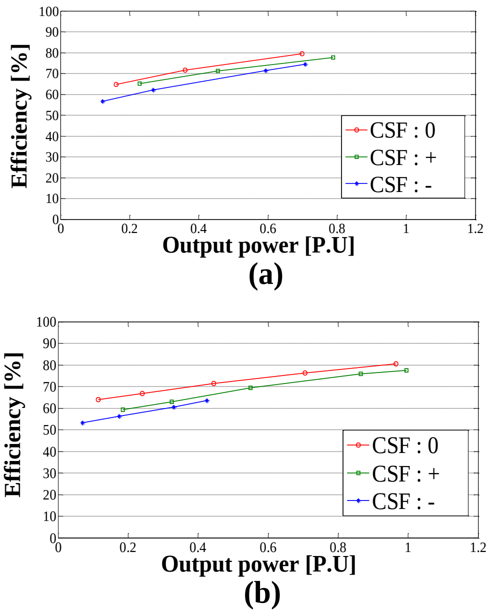


Fig. 10. Relationship between CSF and system efficiency
(a) 1000 rpm (b) 1500 rpm

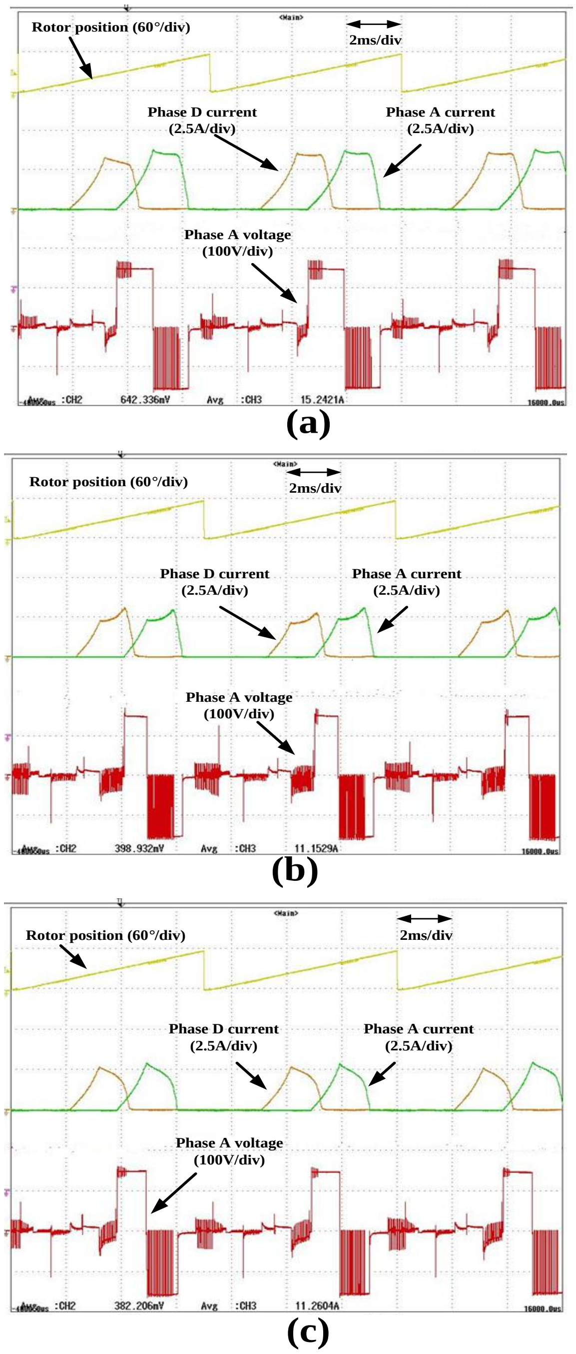


Fig. 11. Experimental waveforms at 1500 rpm
(a) CSF is "0" (b) CSF is "+" (c) CSF is "−"

Fig. 11 gives the rotor position, phase current, and phase voltage of the three kinds of current shape at 1500rpm.

5. Conclusion

In this paper, the effect of current shape on the system efficiency is investigated when the SRG is operated under rated speed. The current slope factor CSF is proposed to express the current shape. The effect of current shape on the main electrical loss is analyzed in detail. A MAPC method which can be used over a wide speed range is presented. Using the method the optimal current shape can be obtained. The experimental system is set up. According to the simulation and experimental results, when CSF is “0”, the system efficiency is maximum at the same output power condition. In other words, the flat-top current shape is better for SRG when it is operated under rated speed. The control method proposed in this paper is simple, reliable and easy to achieve.

Acknowledgements

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