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Implementation of Control Variables to Exploit Output Power for Switched Reluctance Generators in Single Pulse Mode Operation

T. Yuvaraja, K. Ramya

Department of Electrical and Electronics Engineering, Sri Ram College of Engineering, Bangalore, India

A B S T R A C T

This paper presents an analytical modeling method of optimal control variables to maximize output power for switched reluctance generators (SRGs) in single pulse mode operation. This method extends the basic theory of the Stiebler model and utilizes the flux linkage function to express the inductance model of SRG. In this paper, the optimal phase current shape of SRG for maximum output power is investigated to determine optimal control variables based on phase current model. The expression of phase current in this paper that is in terms of control variables is solved using the basic equation of phase voltage based on inductance model, and then the characteristics of phase current and the energy conversion relations are analyzed to determine optimal shape of phase current. Furthermore, the expressions of phase flux linkage, rms phase current, and phase torque based on the proposed phase current model are presented in this paper to know the trend of main electrical losses. Results from analysis show that the switched reluctance generator with the optimal control variables can produce maximum output power and the shape of phase current in this case is flat top. Simulation and experimental results are presented to verify the proposed method.

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1. INTRODUCTION[1]

Switched reluctance generator (SRG) is the potential candidate in various applications, such as automotive starter/generator [1, 2], engine starter/generator [3, 4] and variable speed wind energy [5] because of its simple structure, low cost, fault tolerant with a rugged structure, easy starting/generating realization, high speed adaptability, and high generation efficiency.

Highly nonlinear nature is main problem of the SRG, therefore the behavior of the SRG cannot be described by mathematical equation using conventional methods for a suitable controller design [6]. The SRG model is used to simulate to find the relationship between output power and control variables since there is no analytical equation for finding the output power based on design parameters and control variables [7]. The dynamic model of SRG using cubic spline technique has been proposed to find the flux linkage, inductance, torque, and output power [8]. The model SRG based on FEM

and power control methods for the small wind power generation system have been proposed in the literature [9]. The SRG model is used to find the output power curve versus shaft speed. This curve is analyzed to determine the optimal switching on-off angle for maximum efficiency of system.

Output power of SRG in single pulse mode can be controlled by adjusting excitation angles, turn-on/off angle is fixed while turn-off/on angle is adjusted, or adjusting both turn-on and turn-off angles. The constant output power control of the SRG has been proposed by controlling the turn-on angle with the fuzzy logic algorithm while the turnoff angle is fixed [10]. The optimal excitation angles for output power control using automatic closed loop control have been proposed that the optimal turn-off angle in terms of power and speed is determined from an analytical fit curve [11], while the optimal turn-on angle is automatically adjusted based on the closed loop power control to regulate the output power. The optimal excitation angles for maximum system efficiency calculated by the ratio of two flux linkages have been proposed [12]. The minimum torque ripple occurs in this case. For two flux

Corresponding Author's Email: yuvarajastr@gmail.com (T. Yuvaraja)

linkages, one is the position which stator and rotor pole corners begin overlap and the other one is the position at maximum value. A modified angle position control (MAPC) method has been proposed to determine the optimal shape of the phase current [13]. The optimal turn-on angle is fixed and the optimal turn-off angle can be determined by the analytical model of SRG for the maximum energy conversion [14, 15].

In mathematical model for analyzing control variables and describing behavior of SRG, the flux linkage versus current characteristics calculation is the essential knowledge. At least, there are two methods to obtain flux linkage versus current characteristics; simulation approach based on Finite Element Method (FEM) and experimental approach based on direct measurement. The flux linkage model based on FEM is well known for its reliability, however it requires intensive computation and many details of the machine geometry and structure [16]. The analytical nonlinear models of flux linkage have been described in some works [17-20] that are accurate and reliable. The model based on machine geometry introduced in the literature [17] is complicated that depends on flux linkage at aligned and unaligned positions, and a position dependent function. The position dependent term has a physical significance that its coefficient needs to be related to the machine geometry. The model proposed by Roux and Morcos [18] is little complex because the flux linkage curve is divided into 2 parts, linear and nonlinear parts. However, it only requires the flux linkage versus current characteristics at the aligned and unaligned positions. The model described by Chi et al. [19] based on Fourier series with limited number of terms is complex since it is necessary to know the flux linkage versus current characteristics at the aligned, unaligned, and midway positions. The coefficients in terms of Fourier series depend on the flux linkage positions at aligned, unaligned, and midway that the flux linkage at aligned and midway positions can be calculated via curve fitting based on an arc-tangent function. The Stiebler model proposed in the literature [20] is simple that is composed of an angular function, aligned and unaligned flux linkage. However, it is proposed in per-unit system.

In this paper, an analytical modeling method of optimal control variables to maximize output power for SRG in single pulse mode is presented. This method extends the basic theory of the Stiebler model and utilizes the flux linkage function to express the inductance model in real system. The expression of phase current in terms of control variables proposed in this paper is solved from the basic equation of phase voltage based on inductance model. The control variables comprise a DC bus voltage, a shaft speed or angular velocity, and excitation angles. The optimal shape of phase current is analyzed to determine the optimal control variables based on the phase current

model. Furthermore, the equations of the flux linkage, rms phase current, and torque based on the current model are proposed to know the trend of the main electric losses. The 8/6 SRG experimental setup is used to verify the proposed method

2. PRINCIPLE OF SRG IN SINGLE PULSE MODE OPERATION

A 4-phase 8/6 SRG is used in this paper which is driven by a 4-phase asymmetrical bridge converter as shown in Figure 1. When S_A and $S_{A'}$ are both on, the phase A voltage is $_U$. When S_A and $S_{A'}$ are both off, the phase A voltage is $_U$.

The mutual inductance between individual phases of the SRG is usually neglected. Therefore, the equation of voltage for each phase of SRG is expressed as the voltage equation at constant speed which is given by:

$$U = Ri + \frac{d\lambda(i,\theta)}{dt} \tag{1}$$

The voltage equation at constant speed is given by:

$$U = Ri + L(\theta)\frac{di}{dt} + e \tag{2}$$

where u represents the DC bus voltage, i is the phase current, R and L are the phase of resistance and inductance, respectively, ω is the angular velocity, and the back emf is defined as:

$$e = i\omega\frac{\partial L(i,\theta)}{\partial \theta} \tag{3}$$

The energy converted is the area enclosed by the loci which is expressed as:

$$\omega = \oint \lambda di = \oint i d\lambda \tag{4}$$

The SRG requires an excitation source in order to generate electrical energy. The SRG (phase A) is excited by the asymmetrical bridge converter as shown in Figure 2. This of the SRG through two switches as shown in Figure 2 (bottom) and demagnetizing the same phase through two diodes as shown in Figure 2 (top). In Figure 2, the current builds in the SRG phase winding when the controllable switches are closed. In this duration, no energy is supplied to the load. When the controllable switches are opened, the store field energy is supplied to the load through the two diodes.
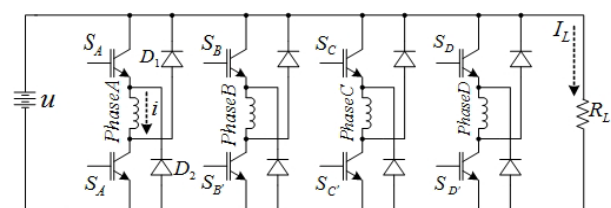

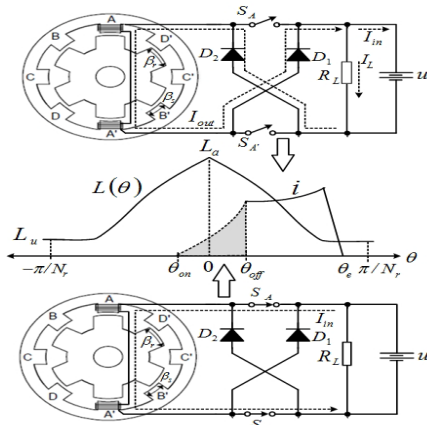**Figure 1.** 4-phase asymmetrical bridge converter

Figure 2. Power generation process for the SRG in single pulse mode

The average load current can be defined as:

$$I_L = \frac{1}{2\pi/N_r}\left(\int_{\theta_{off}}^{\theta_e} id\theta - \int_{\theta_{on}}^{\theta_{off}} id\theta \right) \tag{5}$$

where turn- θ_{on} and turn- θ_{off} angles represent the controllable switches which are closed and opened, respectively, θ_e is angle at which phase current is depleted and it is given as $2\theta_{off} - \theta_{on}$, θ is the rotor position and N_r is the number of rotor poles. The average electric power of the SRG is the summation of output power of each phase in one revolution which is given by:

$$P_L = I_{L*}U \tag{6}$$

The main electrical losses of a SRG are copper loss and iron loss. The copper loss P_{cu} depends on the rms phase current I_{rms} in the range $\theta_{off} \le \theta \le \theta_e$ [21] which is expressed as:

$$P_{cu} = N_{ph}I_{rms}^2 R \tag{7}$$

$$I_{rms}^2 = \frac{1}{2\pi/N_r}\int_{\theta_{off}}^{\theta_e} i^2 d\theta \tag{8}$$

The iron loss is proportion to the excitation magnetic motive force and the stroke frequency. It is not uniformly distributed in the core since flux shape is non-sinusoidal and a flux harmonic spectrum differs in various parts of the magnetic. The iron loss [22] can be approximately calculated as:

$$P_c = K_h f B_m^{a+bB_m} + K_e f^2 B_m^2 \tag{9}$$

where F is the stroke frequency, K_n and K_e are the hysteresis and eddy-current loss coefficients, respectively, a and b are the constant of exponent, and B_m is the amplitude of flux density for sinusoidal variation. The control variables of the SRG are the DC bus voltage u, the angular velocity ω, the phase current i, and

turn on/off angle θ_{on}/θ_{off}. The Angle Position Control (APC) method can control the phase current shape by adjusting the θ_{on} and θ_{off} while u and ω are constant. The output power can be adjusted by the phase current. The advantages of the APC method [13] can be described as follows: the optimal θ_{on} and θ_{off} can improve efficiency, the multiple phases can be conducted at the same time, and the torque adjustment range is wide.

3. PHASE CURRENT SCHEME

The effect of θ_{on} and θ_{off} on the phase current shape using the APC method is illustrated in Figure 3. The θ_{on} is fixed and θ_{off} is adjusted as shown in Figure 3(a). The θ_{off} is fixed and θ_{on} is adjusted as shown in Figure 3(b). The resistance of the phase windings, the voltage drop of the main switches and diodes are neglected, the voltage in Equation (2) can be expressed as:

$$U = \omega L(\theta)\frac{di}{d\theta} + \omega i \frac{\partial L(i,\theta)}{\partial \theta} \tag{10}$$

The maximum value of the phase current in Figure 4 is in the range $\theta_{off} \le \theta \le \theta_p$. The θ_p equals to $((\beta_r + \beta_s)/2)$ where β_r is rotor pole arc and β_s is stator pole arc. Consider that in Equation (10), if the back emf is smaller than the DC bus voltage, then $\frac{di}{d\theta} < 0$. Phase current shape in this case is shown in Figure 4 (a). If the back emf is equal to the DC bus voltage, then $\frac{di}{d\theta} = 0$. In this case, phase current shape is shown in Figure 4(b). If the back emf is bigger than the DC bus voltage, then $\frac{di}{d\theta} > 0$ and phase current shape is shown in Figure 4(c).
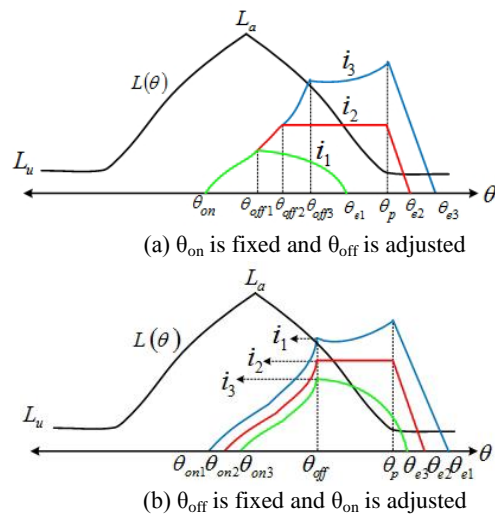

(a) θ_{on} is fixed and θ_{off} is adjusted

(b) θ_{off} is fixed and θ_{on} is adjusted

Figure 3. Phase current shapes using the angle position control method

From Equation (9), the iron loss depends on the maximum of flux linkage. The maximum value of flux linkage in Figure 4 can be known that occurs on the θ_{off}. The copper loss depends on rms phase current that can be known by calculating in Equation (7).

The energy conversion loops for 3 kinds of i and λ by the loci are shown in Figure 5. The maximum output power can be produced when the phase current is controlled in shape of the flat top (Figure 4(b)). This result has been confirmed the validity by Yu et al. [23].

(a) Back emf is smaller than DC bus voltage

(b) Back emf is equal to DC bus voltage

(c) Back emf is bigger than DC bus voltage
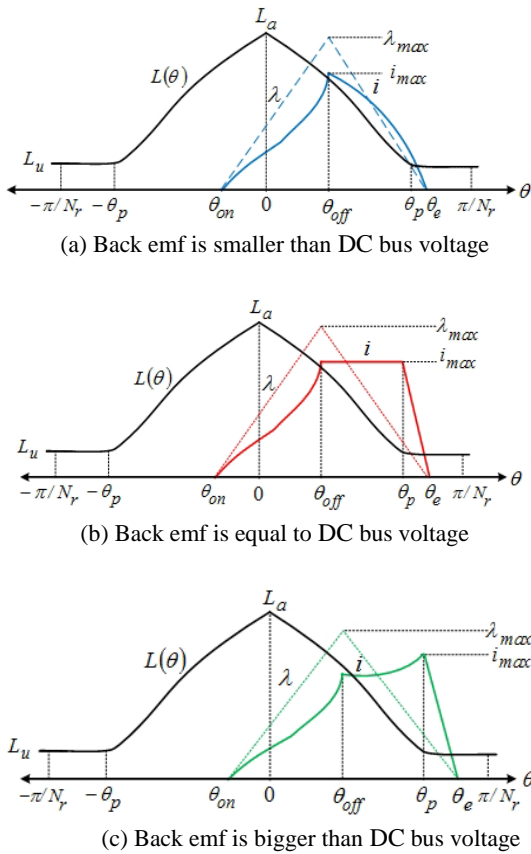
Figure 4. 3 kinds of phase current and flux linkage at different turn-on and turn-off angles with the same maximum value of the phase current

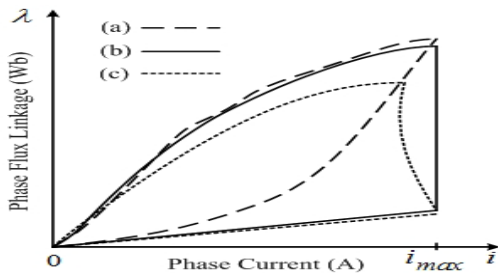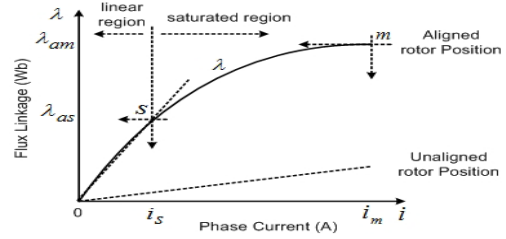**Figure 5.** Energy conversion loops by the loci with the same maximum value of the phase current

Figure 6. Magnetization curve of a SRG

4. ANALYSIS OF OPTIMAL CONTROL VARIABLES

The optimal shape of the phase current in single pulse mode operation for maximum output power is the key to determine the optimal control variables. From Equation (10), the phase inductance model is a significant factor to find the phase current equation. The flux linkage function in per unit system proposed by Stiebler is developed as the inductance model in real system. The proposed model of the inductance in this paper is the real system which requires the geometrical parameters of a SRG at aligned and unaligned rotor positions. These parameters are easy to know using the experiment or the FEM. The parameters are inductance at positions of aligned La and unaligned Lu, and flux linkage at points s and m as shown in Figure 6.

In Figure 6, the flux linkage function at aligned rotor position is given as Equation (11) that is developed from the Stiebler model. This flux linkage is composed of linear and saturated regions. The saturated region begins at point s and finishes at point m. The flux linkage of the saturated region can be known by a Froelich function $\lambda = \dfrac{i}{a+bi}$ where a and b are constant as a slop and intercept [24]. The constants of a and b can be determined by substituting the λ_{us}, i_s of the point s λ_{am} i_m of the point m into a Froelich function.

$$\lambda(i,\theta) = L_u i + (L_a - L_u)\frac{i}{a+bi}f(\theta) \qquad (11)$$

where k is the effective overlap position of stator and rotor poles, and the angular function can be given as:

$$f(\theta) = \begin{cases} 0.5 + 0.5\cos\left(\theta\dfrac{\pi}{\theta_k}\right), & -\theta_k \le \theta \le \theta_k \\ 0 \end{cases} \qquad (12)$$

To verify the proposed method, an 8/6 SRG is used to analyze to find its geometrical parameters using FEM that its specifications are shown in Table 1.

The relationship between the flux linkage and current at rotor position 0º, 15º, 30º obtained by FEM are shown in Table 2. The parameters obtained from FEM for calculation in this paper consist of L_a = 480 μH, L_u = 44 μH, θ_k = 30º, a = 0.95 b = 0.186. Figure 7 shows the result of magnetization curve at rotor position

0º, 15º,30º obtained from the analytical model (11) compared with the FEM which demonstrates the validity of the proposed model.

TABLE 1. Specifications of the candidate SRG

Parameter	Value
Outer diameter of stator	145 mm
Inner diameter of stator	63 mm
Stack length	63 mm
Number of phases	4
Pole Arc	24 degree
Number of stator/Rotor poles	6/4
Voltage	46 V
Power	2.2 kW
Speed	5500 rpm

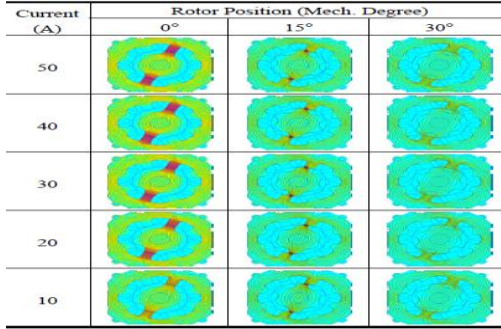**TABLE 2.** The analysis results obtained by FEM
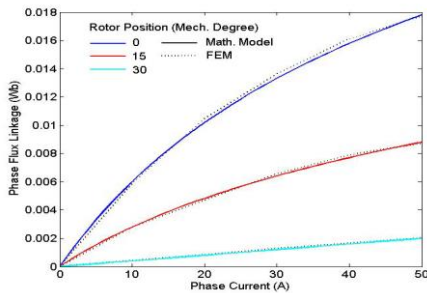
Figure 7. Magnetization curve of the candidate SRG at rotor position 0º, 15º, 30º obtained by the analytical model and FEM

$$L(i,\theta) = \begin{cases} L_u \\ L_u + \left(\dfrac{L_a - L_u}{a + bi} \right) f(\theta) \\ L_u \end{cases} \tag{13}$$

$$i = \begin{cases} \dfrac{u(\theta - \theta_{on})}{\omega \left[L_u + \left(\dfrac{L_a - L_u}{a + bi} \right) f(\theta) \right]} \\ \dfrac{u(\theta_e - \theta)}{\omega \left[L_u + \left(\dfrac{L_a - L_u}{a + bi} \right) f(\theta) \right]} \end{cases} \tag{14}$$

Based on Equations (13) and (14), the phase flux linkage can be known by:

$$\lambda(i,\theta) = L(i,\theta) \tag{15}$$

The phase inductance is much more, comparing with the mutual inductance, therefore the mutual inductance is neglected [25, 26]. The phase inductance model is proposed in this paper which is divided into three regions based on Equation (11) depending on phase current and rotor position which can be expressed in Figure 8.

Figure 8 depicts phase inductance of the candidate SRG obtained by the proposed analytical model (Equation (13)) and FEM that the characteristics of the phase inductance versus current and rotor position closely match each other. The phase current model can be known by solving Equation (10) based on Equation (13) which can be expressed as:

$$T(i,\theta) = \frac{1}{2} i^2 \frac{\partial L(i,\theta)}{\partial \theta} = (L_a - L_u) \left[\frac{(a+bi)f'(\theta) + bf(\theta)(L_a - L_u)f(\theta)i + \frac{u}{\omega}b + c}{(2bL_u + b)(a + bi)^2} \right] \tag{16}$$

In Figure 4, the maximum value of the phase current occurs on θ which is in range $\theta_{off} \le \theta \le \theta_e$. So, the maximum value of the phase current can be given as:

$$i_{max} = \frac{u(\theta_e - \theta)}{i_{max} \left(L_u + \left(\dfrac{L_a - L_u}{a + bi_{max}} \right) f(\theta) \right)} \tag{17}$$
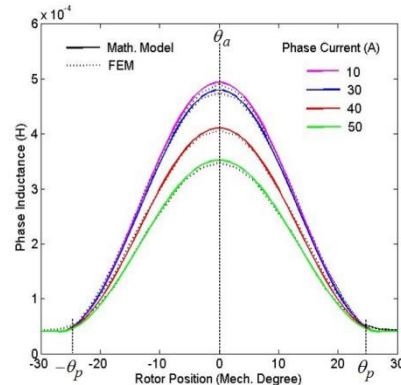

Figure 8. Phase inductance of the candidate SRG obtained by the mathematical model and FEM

Then, the maximum angular speed is given by:

$$\omega_{max} = \frac{u(\theta_e - \theta)}{i_{max}\left[L_u + \left(\dfrac{L_a - L_u}{a + bi_{max}}\right)f(\theta)\right]} \quad (18)$$

In order to obtain the optimal control variables, the phase current shape in Figure 4(b) is used to analyze. The phase current shape in this case is a flat top that the maximum value exists in the interval θ_{off} to θ_p. If $\theta = \theta_{off}$, the maximum value of phase current based on Equation (14) is:

$$i_{max1} = \frac{u(\theta_{off} - \theta_{on})}{\omega\left[L_u + \left(\dfrac{L_a - L_u}{a + bi_{max1}}\right)\left(\dfrac{1}{2} + \dfrac{1}{2}\cos\left(\theta_{off}\dfrac{\pi}{\theta_k}\right)\right)\right]} \quad (19)$$

If $\theta = \theta_p$, the maximum value of phase current based on Equation (14) is:

$$i_{max2} = \frac{u(2\theta_{off} - \theta_{on} - \theta_p)}{\omega\left[L_u + \left(\dfrac{L_a - L_u}{a + bi_{max2}}\right)\left(\dfrac{1}{2} + \dfrac{1}{2}\cos\left(\theta_p\dfrac{\pi}{\theta_k}\right)\right)\right]} \quad (20)$$

Since i_{max1} is equal to i_{max2}, the optimal turn-on angle can be calculated by substituting i_{max1} into i_{max}.

$$q = \frac{L_a - L_u}{a + bi_{max}} \quad (21)$$

$$f_1(\theta) = 0.6 + 0.6\cos\left(\theta_{off}\frac{\pi}{\theta_k}\right)$$
$$f_2(\theta) = 0.61 + 0.6\cos\left(\theta_p\frac{\pi}{\theta_k}\right) \quad (22)$$

$$\pi(L_a - L_u)\sin\left(\theta\frac{\pi}{\theta_k}\right) = z\left(\frac{u}{\omega}\right)\theta_k(a + bi_{max})$$

$$\theta_{off} = \frac{\theta_k}{\pi}\sin^{-1}\left(\frac{2u\theta_k}{\omega\pi(L_a - L_u)}(a + bi_{max})\right) \quad (23)$$
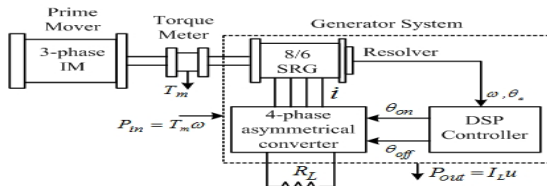

Figure 9. Schematic layout of the experimental setup

Figure 10. Experimental setup

5. SIMULATION AND EXPERIMENTAL RESULTS

To verify the proposed method, the 8/6 SRG system is used. A 3-phase induction motor is used as the prime mover that its speed is controlled by an inverter. Parameters of the SRG are shown in Table 1. A battery rated 12V 120A amount 4 pieces is used as the constant DC bus voltage u. The results indicate that the actual output power can be good for tracking variations in the command power, and that the dwell angle will be stabilized eventually. The control system is shown to have good dynamic performance. The average torque T_m of the prime mover is measured by a rotational torque transducer which is connected between the prime mover and the SRG. Shaft speed or angular velocity ω and aligned position are detected by a resolver mounted on the SRG. The SRG is driven by a 4-phase asymmetrical bridge converter that excitation angles are created by a TMS320F28027.

Load resistance, equal to 1.25Ω, is used as the resistive load. Figure 9 shows the schematic layout of the experimental setup that the mechanical input power can be calculated by:

$$P_{in} = T_m\omega \quad (24)$$

The efficiency of the system is defined as:

$$\eta = \frac{P_{out}}{P_{in}} \quad (25)$$

where output power is the electrical output power and input power is the mechanical input power.

In this paper, parameters used to analyze comprise $L_u = 44$ µH, $L_a = 480$ µH, $\beta_s = 25°$, $\beta_r = 24°$, a = 0.70, b = 0.186.

In the control scheme, the strategy consists of optimizing *off* q, and adjusting *on* q when the SRG is operated at a high speed. Figure 11 gives the relationship between the efficiency and *off* q. In the simulation, the source voltage is 150V, and the speed is 3000 rpm. Taking the selection range of *on* q in the practical application consideration, *off* q is selected at 46°. Figure 12 gives the experimental results of the relationship between the efficiency and the current shape. In the experiment, the source voltage is 150V, and *off* q and *end* q are fixed at 42° and 53.3°, respectively. From Figure 14, it can be easily seen that, the system efficiency is at its maximum when *off end i = i*. In other words, at the same output power, the flat-top wave of the current corresponds to the maximum system efficiency when the SRG is operated under the rated speed. In addition, comparing the results of Figures 12 and 13, it is not difficult to see that the results of Figure 12 are larger than that of Figure 13 even though the conditions are the same. The reason is that only the copper and core losses are considered in the simulation. However, in the experiment, the switching loss and mechanical loss are also included.
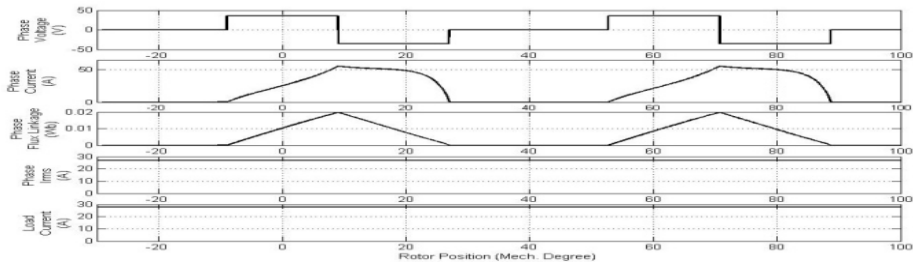
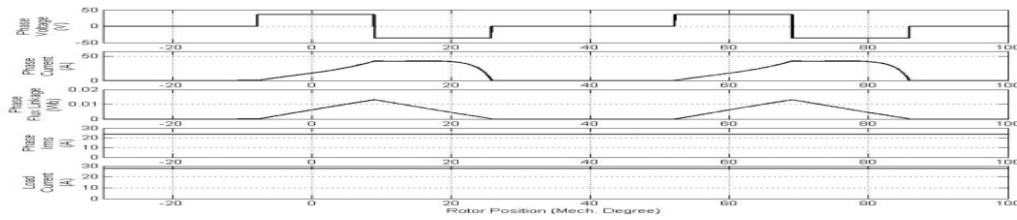**Figure 11.** Case 1: the θ_{on} and θ_{off} are -9.2 and 9

Figure 12. Case 2: the θ_{on} and θ_{off} are -7.8 and 9
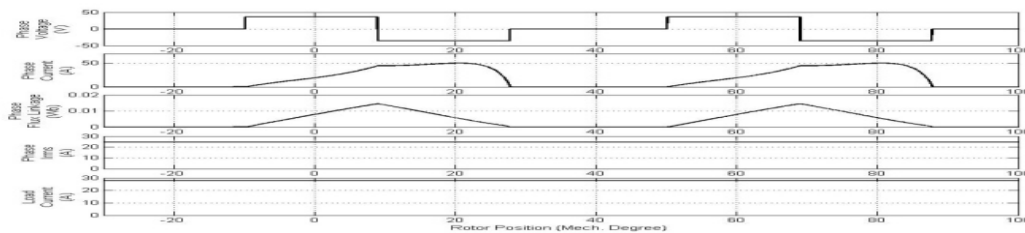
Figure 13. Case 3: the θ_{on} and θ_{off} are -8.15 and 9
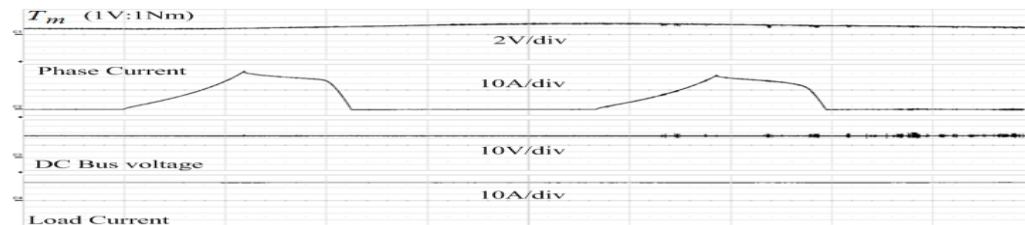
Figure 14. Case 1: the θ_{on} and θ_{off} are -9.2 and 9

Figure 15. Case 2: the θ_{on} and θ_{off} are -7.8 and 9
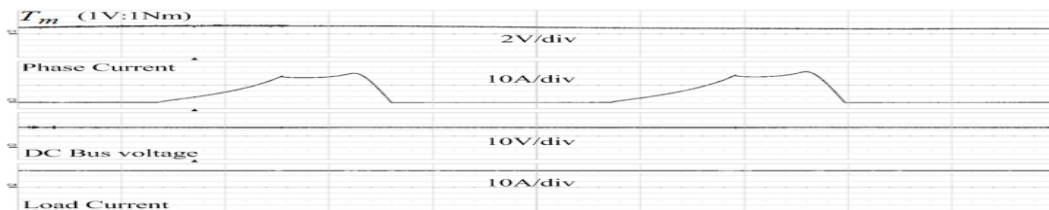

Figure 16. Case 3: the θ_{on} and θ_{off} are -8.15 and 9

6. CONCLUSION

In this paper, an analytical modeling method of optimal control variables to maximize output power for SRG in single pulse mode is proposed. This method extends the basic theory of the Stiebler model and utilizes the flux linkage function to express the inductance model in real system using a Froelich function. The expression of phase current in terms of control variables is proposed in this paper that is solved using the basic equation of phase voltage based on inductance model. The 3 kinds of phase current shape in single pulse mode are investigated that the optimal shape of phase current is flat top. The optimal phase current shape is used to determine the optimal control variables. In this paper, the optimal control variables can be known by calculation from the proposed analytical model in Equations (21)-(23). Furthermore, the equations of the flux linkage, rms phase current, and torque based on the phase current model are proposed to know the trend of the main electric losses. The results indicate that the flat-top current shape corresponds to the maximum efficiency when the output power is the same. The proposed control scheme has a good dynamic response, can be used over a wide speed range and is easy to accomplish. The 8/6 SRG experimental setup is used to verify the proposed method. Based on the experimental results, the SRG can generate the maximum output power and the phase current shape is flat top all cases when the SRG is controlled with the optimal control variables. The output power obtained from the measurement and analytical model is different with an average of 3.49%. This result demonstrates the accuracy and reliability of the proposed method.

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Implementation of Control Variables to Exploit Output Power for Switched Reluctance Generators in Single Pulse Mode Operation

T. Yuvaraja, K. Ramya

Department of Electrical and Electronics Engineering, Sri Ram College of Engineering, Bangalore, India

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چکیده

در این مقاله یک روش مدلسازی تحلیلی از متغیرهای کنترل بهینه برای به حداکثر رساندن قدرت خروجی در ژنراتور مقاومت مغناطیسی در حالت کار تک پالس ارائه شده است. این روش نظریه اساسی مدل استیبلر و بهره گیری از تابع شار برای بیان مدل اندوکتانسSRG را توسعه می‌دهد. در این مقاله، فاز بهینه شکل رایج SRG برای حداکثر قدرت خروجی برای تعیین متغیرهای کنترل بهینه و بر اساس مدل فعلی فاز بررسی شده است. در این مقاله جریان فاز برحسب متغیر های کنترل با استفاده از معادله عمومی ولتاژ فاز و بر اساس مدل اندوکتانس حل شده و سپس ویژگی های حالت و روابط تبدیل انرژی برای تعیین شکل مطلوب جریانهای فاز مورد تجزیه و تحلیل قرار گرفتند. علاوه بر این، عبارت شار فاز پیوندی، جریان rms فاز، و گشتاور فاز بر اساس مدل جریانهای فاز ارائه شده است تا به شناخت روند اصلی اتلاف الکتریکی بیانجامد. نتایج حاصل از تجزیه و تحلیل نشان می دهد که ژنراتور مقاومت مغناطیسی با متغیرهای کنترل بهینه شده می‌تواند حداکثر قدرت خروجی و شکل جریانهای فاز تولید کرده و جریان در این حالت در این مورد بالا مسطح است. شبیه سازی و نتایج عملی به منظور تائید روش پیشنهادی ارائه شده‌اند.

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