Output Voltage Control Method of Switched Reluctance Generator using the Turn-off Angle Control

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Abstract- SRG (Switched Reluctance Generator) have many advantages such as high efficiency, low cost, high-speed capability and robustness compared with characteristics of other machines. However, the control methods that have been adopted for SRGs are complicated. This paper proposes a simple control method using PID controller that only controls turn-off angles while keeping turn-on angles of SRG constant. The linear characteristics between the generated current and the turn-off angle can be used to control the turn-off angle for load variations. Since the reference current for generation can be produced from an error between the reference and the real voltage, it can be controlled to keep the output voltage constant. The proposed control method enhances the robustness of this system and simplifies the hardware and software by using only the voltage and speed sensors. The proposed method is verified by experimental results.

I. INTRODUCTION

Switched Reluctance Machines are the subject of researches because of their ruggedness, low cost and high efficiency. Nowadays, their application fields in the industry are more enlarged than ever before because of the development of the switching technique and the motor design.

In order to generate voltage with SRG, they must be needed to supply excitation current to the stator windings. Fig. 1 helps the explanation of the generating sequence for a phase of SRG. Each inductance profile for a phase can be divided to two areas, one is the excitation area and the other is generating area. When the switches, T_1 and T_2, are turned-on from θ_{on} to θ_{off}, V$_{DC}$ is applied as the phase voltage. The induced flux of the phase would be made e.m.f voltage across the stator winding even if both switches are turned-off. This voltage can charge the DC-Link capacitor via D_1 and D_2.

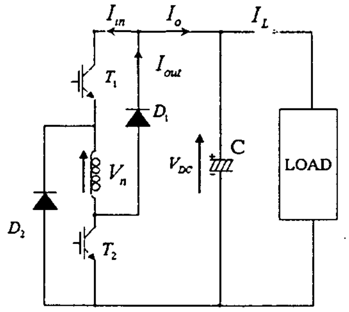
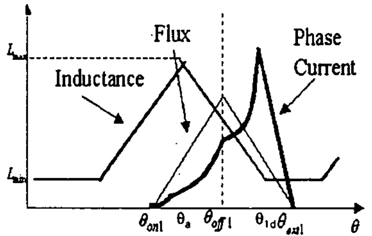
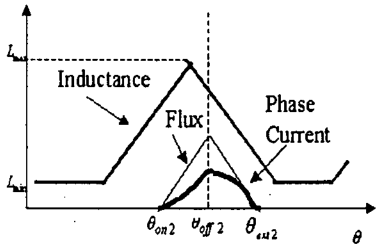


Fig. 1. A phase leg of SRG with a load circuit



(a) Sufficient excitation and its result



(b) Insufficient excitation and its result

Fig. 2. Relationship between the turn-on duration and the generated current

Fig. 2 illustrates the relationship between the generated current and On/Off angle. In case (a), the excitation current is sufficiently impressed during the inductance profile so that the generated current of the phase is greater than the excitation current. When the excitation current is not enough during the entire inductance profile, the produced current is smaller than the impressed one. To acquire the stability of the output voltage, the turn-on and turn-off angle must be controlled according to the load variation [1].

Several methods to control the output voltage of the SRG are suggested. Error voltage of the DC-Link is used to make the current reference and this is also rendered to decide the turn-on angle [2]. The current reference obtained from the voltage error is used at the inverse model of SRG. And then

Inverse model decide that the turn-on and turn-off angle [3]. Different approach was attempted to control the output voltage. The turn-on and turn-off angle is fixed at a value and the excitation current is PWM controlled according to the load variation [4]. However, those methods take a long time so that high-speed application of the SRG is very difficult.

In this paper, we propose the turn-off angle control method observed from that the output voltage is proportional to the turn-off angle. The voltage error is produced to decide the current reference. And then turn-off angle is calculated with simple linear equation including the current reference.

The validity of the proposed algorithm is verified by experimental results.

II. Modeling of SRG

The total current generated from SRG can be calculated from the difference between the impressed and generated current. In Eq. (1), $I_{o,total}$ is the average value of the total generated current during one cycle. In a cycle, all other phase currents are generated separately.

$$\begin{aligned} I_{o,total} &= \frac{N_s}{2}\cdot\frac{1}{T}\int_0^T i_n dt \\ &= \frac{N_s}{2}\cdot\frac{1}{2\pi/N_r}\int_0^{2\pi/N_r} i_n dt \\ &= \frac{N_s\cdot N_r}{4\pi}\cdot I_o \qquad (1) \end{aligned}$$

where, $I_o = I_{out} - I_{in}$, N_r : pole number of rotor

N_s : pole number of stator, i_n : phase current

When the generator connected to a load, the relationship between the load current(I_L) and generated current(I_o) is shown in Eq. (2).

$$\begin{aligned} V_{dc}(t) &= V_{dc}(t_0) + \frac{1}{C}\int_{t_0}^{t} i_n dt \\ &= V_{dc}(t_0) + \frac{1}{C}\int_{t_0}^{t}[\frac{N_r\cdot N_s}{4\pi}\cdot I_o - I_L]dt \qquad (2) \end{aligned}$$

where, V_{dc} : DC-Link voltage

Generally, the voltage equation of SRG can be written as Eq. (3) and (4).

$$V_{dc} = R_n i_n + \frac{d\lambda}{dt} = R_n i_n + \omega L\frac{di_n}{d\theta} + \omega\, i_n\frac{dL}{d\theta} \qquad (3)$$

$$(R_n i_n - V_{dc})d\theta + \omega\, L di_n + \omega\, i_n dL = 0 \qquad (4)$$

where, R_n : resistor of stator winding

λ : stator flux

L : inductance

ω : rotor speed

In order to get an equation about generated current(I_o) and turn-off angle (θ_{off}), the generated current can be divided two equation as follows.

$$I_{in} = \int_{\theta_{on}}^{\theta_{off}} i_n d\theta = \int_{\theta_{on}}^{\theta_a} i_n d\theta + \int_{\theta_a}^{\theta_{off}} i_n d\theta \qquad (5)$$

$$I_{out} = \int_{\theta_{off}}^{\theta_{ext}} i_n d\theta = \int_{\theta_{on}}^{\theta_{1d}} i_n d\theta + \int_{\theta_{1d}}^{\theta_{ext}} i_n d\theta \qquad (6)$$

If it is assumed that the current would not conduct in motoring region and Eq. (5) and (6) are simplified with Euler's equation, I_o can be written as 4th order equation of θ_{off}.

$$\begin{aligned} I_o = I_{out} - I_{in} &= \int_{\theta_{off}}^{\theta_{ext}} i_n d\theta - \int_{\theta_{on}}^{\theta_{ext}} i_n d\theta \qquad (7) \\ &= G\theta_{off}^4 + H\theta_{off}^3 + J\theta_{off}^2 + K\theta_{off} + M \end{aligned}$$

where,

$$G = \frac{R_n^2(V_{dc} - R_n i_a)}{\omega^3 L_{1d} L_{offa} L_{offd}} \qquad (8)$$

$$\begin{aligned} H = &\frac{R_n A}{\omega L_{1d}} - \frac{R_n(V_{dc} - R_n i_a)}{2\omega^2 L_{offd} L_{offa}} \qquad (9) \\ &- \frac{R_n^2(\theta_{on} + \theta_{1d})}{\omega^3 L_{1d} L_{offa} L_{offd}}(V_{dc} - R_n i_a) \end{aligned}$$

$$\begin{aligned} J = &\frac{-R_n\theta_{1d}}{2\omega L_{offd}} - \frac{1}{2\omega}\{\frac{V_{dc}}{L_{offd}} - \frac{2V_{dc}}{L_{1d}} + \frac{(V_{dc} - R_n i_a)}{L_{offa}}\} \qquad (10) \\ &+ \frac{R_n F}{\omega L_{1d}} + (\frac{R_n\theta_{1d}}{\omega L_{offd}} - \frac{dL_d}{L_{offd}})\frac{(V_{dc} - R_n i_a)}{\omega L_{offa}} \\ &- \frac{R_n(\theta_{on} + \theta_{1d})A}{\omega L_{1d}} + \frac{R_n^2(\theta_{on} + \theta_{1d})^2}{4\omega^3 L_{1d0} L_{offa} L_{offd}}(V_{dc} - R_n i_a) \end{aligned}$$

$$\begin{aligned} K = &(\frac{R_n\theta_{1d}}{\omega L_{offd}} - \frac{dL_d}{L_{offd}})E - \frac{R_n(\theta_{on} + \theta_{1d})F}{\omega L_{1d}} + B \qquad (11) \\ &- (\frac{R_n\theta_{1d}^2}{2\omega L_{offd}} - \frac{dL_d}{L_{offd}}\theta_{1d})\frac{(V_{dc} - R_n i_a)}{\omega L_{offa}} \\ &+ \frac{R_n(\theta_{on} + \theta_{1d})^2}{4\omega L_{1d}}A \end{aligned}$$

$$M = (\frac{dL_d\theta_{1d}}{L_{offd}} - \frac{R_n\theta_{1d}^2}{2\omega L_{offd}})E + \frac{R_n(\theta_{on} + \theta_{1d})^2}{4\omega L_{1d}} - D \qquad (12)$$

$$\begin{aligned} A = &\frac{-R_n}{\omega^2 L_{offa} L_{offd}}(V_{dc} - R_n i_a)\theta_a \qquad (13) \\ &+ \frac{R_n}{\omega L_{offd}}(\frac{dL_a}{L_{offa}} + 1)i_a + \frac{V_{dc}}{\omega L_{offd}} \\ &- (\frac{R_n}{\omega L_{offd}}\theta_{1d} - \frac{dL_d}{L_{offd}} - 1)\frac{(V_{dc} - R_n i_a)}{\omega L_{offa}} \end{aligned}$$

$$B = \frac{V_{dc}\theta_{1d}}{\omega L_{offd}} - \frac{V_{dc}(\theta_{on} + \theta_{1d})}{\omega L_{1d}} + \frac{(V_{dc} - R_n i_a)\theta_a}{\omega L_{offa}} - \frac{dL_a i_a}{L_{offa}} \qquad (14)$$

$$D=\frac{V_{dc}\theta_{1d}^2}{2\omega L_{offd}}-\frac{V_{dc}(\theta_{on}+\theta_{1d})^2}{4\omega L_{1d}}-\frac{dL_a}{L_{offa}}i_a\theta_a+\frac{(V_{dc}-R_n i_a)}{2\omega L_{offa}}\theta_a^2+\frac{V_{dc}}{\omega L_a}(\theta_a-\theta_{on})^2 \tag{15}$$

$$E=-\frac{(V_{dc}-R_n i_a)}{\omega L_{offa}}\theta_a+(\frac{dL_a}{L_{offa}}+1)i_a \tag{16}$$

$$F=-(\frac{R_n\theta_{1d}}{\omega L_{offd}}-\frac{dL_d}{L_{offd}}-1)E-\frac{V_{dc}\theta_{1d}}{\omega L_{offd}} \tag{17}$$

When the turn-on angle of SRG is fixed to a value, we can achieve that the generated current is proportional to the turn-off angle because of the relation described in Eq. (7). Fig. 3 shows a simulation result that the generated current of SRG can be linearly controlled by the turn-off angle. We assume the zero point of the turn-off angle as the maximum value of inductance profile because the turn-off angle is generally appeared after this point. In this simulation, the turn-on angle is fixed at -3° and the minimum turn-off angle is restricted to 12°. The generated current of SRG is proportionally increased during the region between 12° and 19°. The bold straight line in the Fig. 3 can be simplified to a linear equation as following Eq. (18).

$$\theta_{off}=\theta_{offo}+K\cdot I_o \tag{18}$$

where, θ_{offo} : minimum turn-off angle for generating

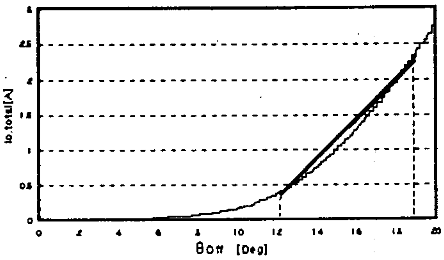


Fig. 3 Generated current according to variation of the turn-off angle

III. Control Scheme of SRG

DC-link voltage equation as shown in Eq. (2) can be modified as follows

$$V_{dc}(t)=V_{dc}(t_o)+\frac{1}{C}\int(QI_o-I_L)dt \tag{19}.$$

where, $Q=\dfrac{N_r\cdot N_s}{4\pi}$

When the above equation is arranged to I_o and transferred to Laplace Transform, we can get a simple reference current.

$$\begin{aligned} I_o&=\frac{C}{Q}\frac{dV_{dc}}{dt}+\frac{I_L}{Q}=\frac{C}{Q}\frac{dV_{dc}}{dt}+\frac{V_{dc}}{R_L Q} \\ &=K_d\frac{dV_{dc}}{dt}+K_p\cdot V_{dc} \\ &=(K_d s+K_p)\cdot V_{dc} \end{aligned} \tag{20}$$

where, $I_L=\dfrac{V_{dc}}{R_L}$, R_L : Load Resistance ,

K_p, K_d :constant

If the voltage error is defined as $V_{err}=V_{ref}-V_{dc}$, the current reference is obtained from a PD controller.

$$\Delta I_{o.ref}=(K_d s+K_p)\cdot V_{err} \tag{21}$$

This controller may have steady state error so that the integration control gain must be considered in the controller design.

IV. Experimental Results and Discussions

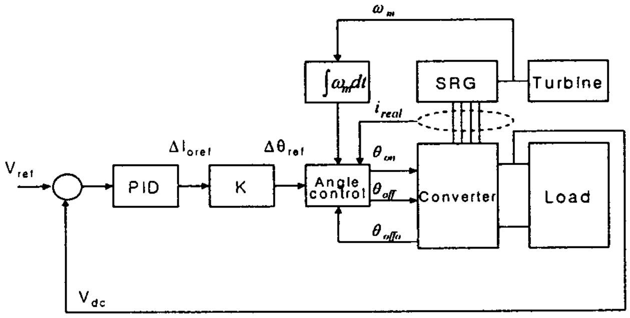


Fig. 4. Block diagram of proposed control method for SRG

Table 1. Specification of SRG

Number of stator poles	8
Number of rotor poles	6
Rated output power	1Hp
Maximum RMS Current	8A
Rated current	5A
Rated voltage	DC 240V
Maximum Rotor Speed	4000rpm
Phase Resistance	1.5Ω

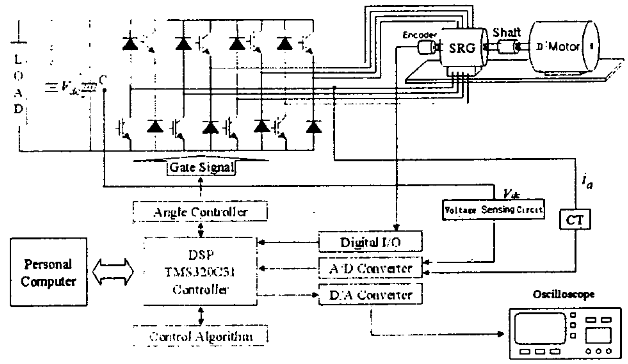


Fig. 5. System configuration for SRG

Fig. 4 shows a block diagram of the proposed control method that is realized with a simple PID controller.

The specification of the SRG is described in Table 1. Fig. 5 shows a system configuration that is realized by IGBT converter, DSP controller and 1HP SRG (stator pole number :

8, rotor pole number : 6). The load consists of pure resistive load and the rotation speed fed from a BLDC motor is 3000rpm. All the experiments are done with a sampling time of 100μs.

Fig. 6 is the result of the transient response of DC-link voltage that reference voltage set as 200V. We start the SRG with pre-charged initial voltage of 2V. According to the proposed method, the voltage error is used to make the current reference($\Delta I_{o,ref}$) and then the current reference is also used to decide the turn-off angle as denoted in Eq. (18). The result shows a slight overshoot but it is suppressed within one second.

When the load is varied from 148[W] to 450[W], Fig. 7 shows the step response of the proposed controller. The maximum voltage ripple remains within ±8V and the ripple factor during the transient time is also sustained at about 5[%]. The ripple factor in the steady state is merely 1[%]. Fig. 8 shows the experimental result when the load is lightened from 450[W] to 148[w]. The upper waveform is DC-link voltage and the lower is a phase current. The proposed method can keep the reference voltage response even though the load was changed.

V. CONCLUSION

In this paper, we proposed a turn-off angle control method while the turn-on angle is fixed at a value. A simple relationship between the generate current and the turn-off angle of the SRG is derived by the mathematical way and the simulation. The experimental results show the validity of the proposed method.

(1) The proposed control method of the turn-off angle for the switched reluctance generator can generate output voltage without voltage variation under the any load condition.
(2) The proposed controller also can minimize the voltage ripple during the transient time.
(3) This method is apt to be applied to high speed application of SRG because of its simplicity.

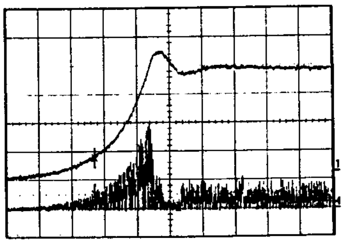
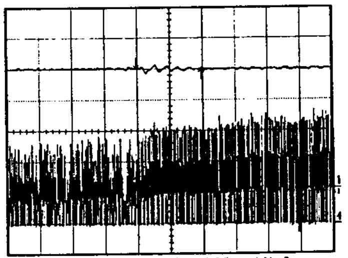
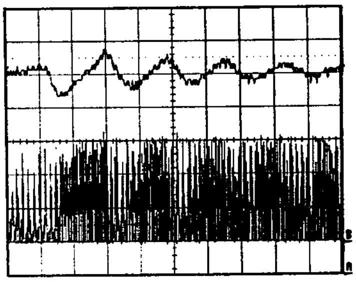

50[V/div], 2[A/div], 500[ms/div]

Fig. 6. Transient characteristics of the proposed system (upper : DC-link voltage, lower : a phase current)

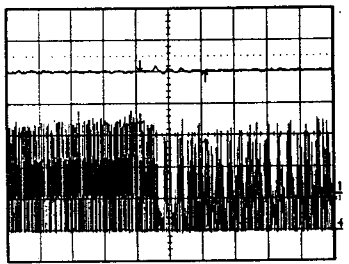

50[V/div], 2[A/div], 500[ms/div]

(a) DC output voltage and a phase current

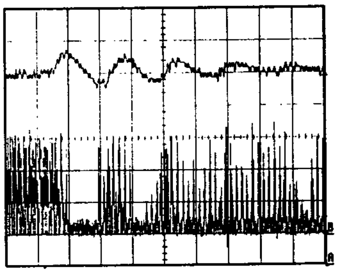

10[V/div], 2[A/div], 500[ms/div]

(b) Enlarged Scale of (a)

Fig. 7. Step response when the load is increased from 148[w] to 450[W] (upper : DC-link voltage, lower : a phase current)


50[V/div], 2[A/div], 500[ms/div]

(a) DC output voltage and a phase current


10[V/div], 2[A/div], 100[ms/div]

(b) Enlarged Scale of (a)

Fig. 8. Step response when the load is decreased from 450[w] to 148[W] (upper : DC-link voltage, lower : a phase current)

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