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FESS용 스위치드 릴럭턴스 전동기/발전기 제어

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Control of Switched Reluctance Motor/Generator for FESS

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Abstract - This paper examines the effect of current slope to the performance of switched reluctance machines (SRMs). The target application is the flywheel energy storage system (FESS) that requires high efficiency in a wide speed range. A previously proposed control method to achieve high efficiency in the generating mode of SRM is applied to the motoring mode in this paper and the result is compared. Simulations were performed to observe the performance of the modified angle control that combines the conventional angle and voltage chopping control.

1. Introduction

Switched reluctance machines (SRMs) are a doubly salient machine that is well known for their simplistic design [1]. The motor has no permanent magnet (PM), making it very ideal for applications in harsh environments [2]. One of the applications that utilize SRM is the flywheel energy storage system (FESS) which is used in power grids to replace batteries [3]. The design of FESS drive demands high efficiency over a wide speed range and robustness, long life-span, and low standby losses. SRMs have low idle loss because of the absence of PM and inherently is operating in a wide speed range, which make it an appropriate candidate for FESS application.

An FESS drive has to perform optimally in both motoring and operating modes. A paper in [4] proposed an excitation method that can increase the efficiency of SRM in generating mode under the rated speed. It is reported that current slope affects the effeciency of the machine and by using the proposed method, the phase current slope can be controlled, and thus the efficiency can be maximized.

In this paper, the proposed method in [4] is analyzed for motoring operation. The results of both generating and motoring modes are also compared according to the current slope. Simulations were performed to observe the performance of the proposed method.

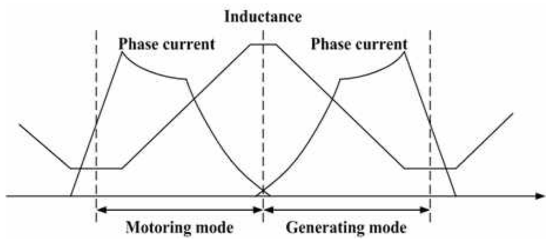
2. Switched Reluctance Motor/Generator

2.1 Motoring/Generating Mode of SRM

Motoring and generating mode of SRM is shown in Fig. 1. An SRM operates in motoring mode, if each phase is excited before aligned position, where the phase inductance increases, and it operates in generating mode if each phase is excited after alignment. The torque is produced by the alignment tendency of poles. The rotor will shift to a position where the reluctance is minimized and thus the inductance of the excited winding is maximized. If magnetic saturation is ignored, the electromagnetic torque T_e can be written as:

$$T_e = \frac{1}{2} i_{ph}^2 \frac{dL}{d\theta} \tag{1}$$

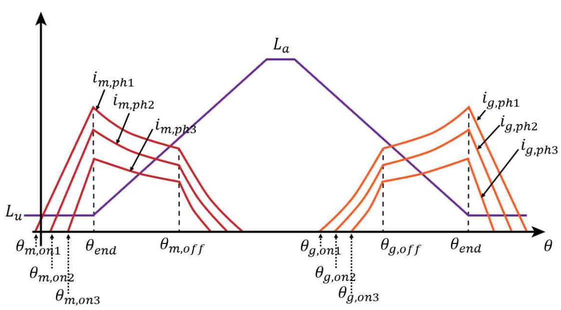
where i_{ph} is the phase current, L is the inductance, and θ is the rotor position.



<Fig. 1> Motoring and generating mode of SRM

2.2 Conventional Angle Position Control

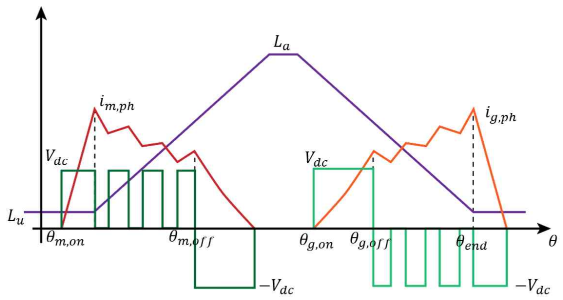
The angle position control (APC) is a method in which the phase current is controlled by adjusting the turn-on angle θ_{on} and turn-off angle θ_{off} when the voltage which is added on the phase winding is constant. The output power can be adjusted by the phase current. The variation of θ_{on} will affect the peak and rms values of the phase current. Fig. 2 illustrates the effect of θ_{on} and θ_{off} on the phase current for both motoring m and generating g operations. L_a and L_u denote the aligned and unaligned inductance level.



<Fig. 2> Conventional angle position control

2.3 Conventional Voltage Chopping Control

The voltage chopping control (VCC) is a method that make the switches operate in pulse width modulation (PWM) mode under the constant θ_{on} and θ_{off}. The VCC method can be divided into two modes. One is adjusting the rms value of the excitation voltage by controlling the duty ratio of the PWM signal in the motoring state. The other one is adjusting the rms value of the generation voltage by controlling the duty ratio of the PWM signal in the generation state. Fig. 3 shows the phase current under the VCC method.



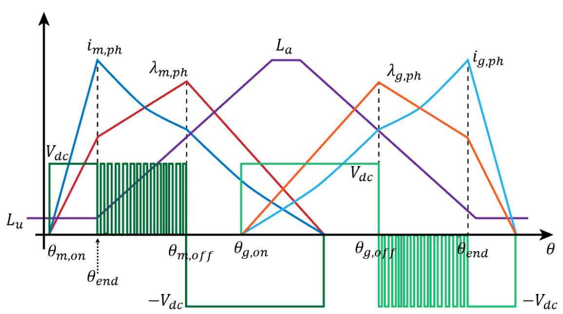
<Fig. 3> Conventional voltage chopping control

3. Modified Angle Position Control

3.1 Concept of MAPC

According to the analysis of the commonly-used control methods of the SRM, it can be known that the substance of SRM control is to control the phase current. When SRM is operated under the rated speed condition, the three kinds of typical current shapes can be obtained by adjusting the turn-on/off angle and the voltage added on the phase winding during the generation stage. The top of the current can be have positive, negative, and zero slope. Considering the influence of θ_{on} and θ_{off} on the phase current and power conversion, fixing the optimal θ_{off} and adjusting the θ_{on} is used to optimize the phase current.

The modified angle position control (MAPC) is the combination of APC method and VCC method. So it has the characteristics of APC and VCC, and it can be used in variable-speed systems for SRM, especially in FESS applications. The concept waveform of the MAPC method is shown in Fig. 4. The essence of the MAPC method is to change the rms value of the phase winding voltage. MAPC can be used to improve the system efficiency by adjusting the current slope value by the means of varying the turn-on angle.



<Fig. 4> Modified angle position control

3.2 Simulation Results

In this paper, the 8/6 pole SRM is used, and the main parameters are shown in Table 1.

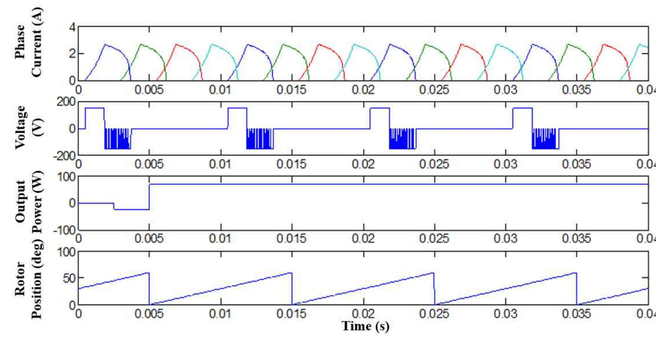
<Table 1> Parameters of the 4-phase 8/6 SRM

Parameters	Value
Rated voltage [V]	310
Rated speed [RPM]	2000
Rated power [kW]	1.67
Stator pole arc [deg]	22.4
Rotor pole arc [deg]	24.2

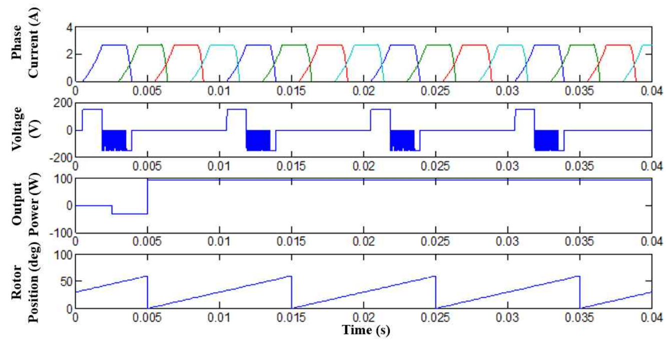
The simulation condition is DC-link voltage is $150\,V$, speed is $1000\,rpm$. The θ_{end} can be calculated by

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

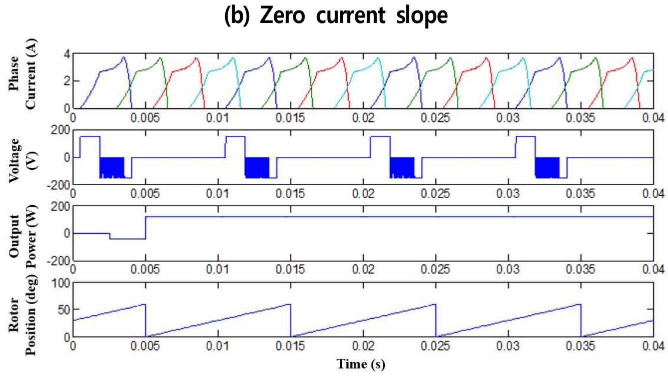
where θ_{rrp} is the rotor pole pitch, β_s and β_r is the stator and rotor pole arcs, respectively. Fig. 5 below shows the result for the generating mode. When current slope is negative, the output power is the least than the others. Moreover, the rms current is biggest with positive slope, but it may lead to an increased copper loss. By changing the turn on angle, the ratio between θ_{off} and θ_{end} changes accordingly, and as this ratio changes, the value of current rms varies as well.



(a) Negative current slope



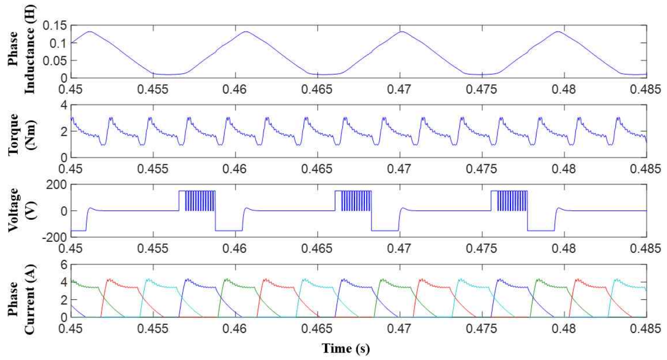
(b) Zero current slope



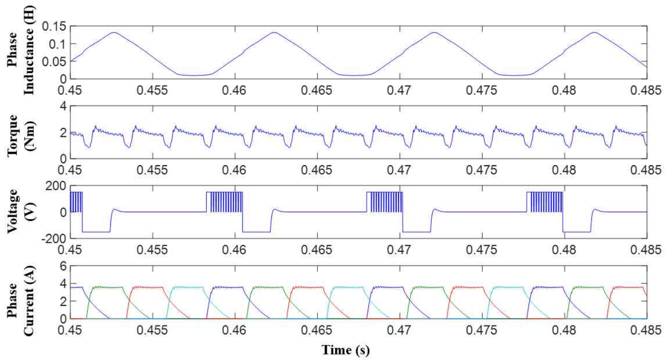
(c) Positive current slope

<Fig. 5> Simulation results of the generating mode

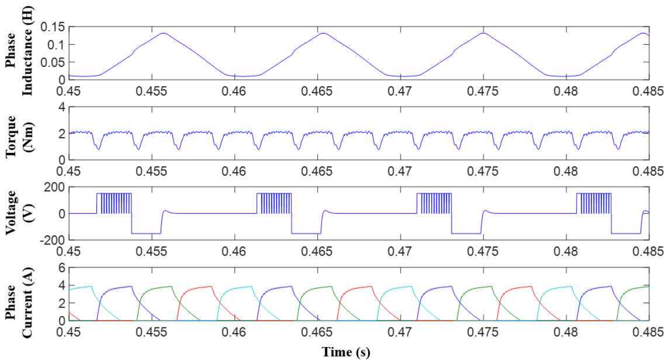
Fig. 6 shows the result for the motoring mode. The rms current is the biggest when the current slope is negative and the peak is maximized as well. However, as the rms current decreases with the slope, the voltage rms is increases which in turn can lead to less copper loss. In motoring mode, when the phase is turned on too late, the current cannot increase to satisfy the required torque and thus the PWM duty cycle in MAPC for the VCC mode will have to increase. If the value becomes 100%, then MAPC will no longer work since only APC is available and current is controlled by the angle.



(a) Negative current slope



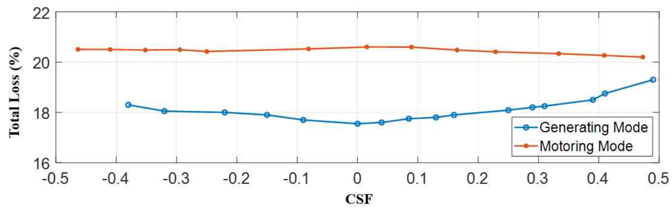
(b) Zero current slope



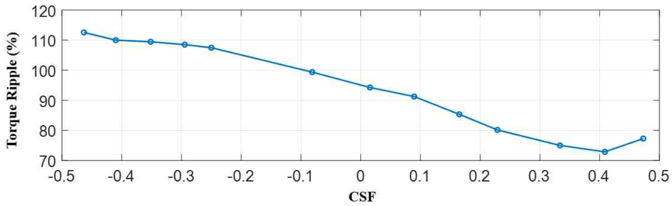
(c) Positive current slope

<Fig. 6> Simulation results of the motoring mode

Finally, the loss comparison is presented in Fig. 7(a). CSF denotes the current slope factor going from negative to positive. The loss considered here is only copper and core loss that are mainly affected by the rms current. The optimum value of the current slope for the generating mode is zero since it produce the least loss. However, changing the current slope does not seem to affect the motoring operation much. Therefore, another observation is performed with the torque ripple, which is also an important factor in SR motors. For the same output power, changing the turn on to affect current slope affects the torque ripple. Contrary to the result in the generating mode, a positive current slope is preferred to reduce the torque ripple while still maintaining efficiency.



(a) Total loss



(b) Torque ripple (motoring only)

<Fig. 7> Relationship between performance and current slope

4. Conclusion

In this paper, the effect of current slope in SRM is observed. MAPC method is used and it is a combination of angle and voltage current control which is useful in a wide-speed range applications. Simulations were performed to analyze the effects. For generating mode, the zero current slope is preferred to obtain the optimum efficiency. For motoring mode, the slope does not affect the performance much and thus the positive slope is preferred to reduce the torque ripple.

[Acknowledgements]

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