International Journal of Advanced Technology & Engineering Research (IJATER)
www.ijater.com

A STUDY ON THE SWITCHED RELUCTANCE MOTOR HIGH EFFICIENCY CONTROL METHOD FOR ISG

Chan-Hee Hong[1] and Ju Lee[1]
[1]Department of Electrical Engineering, Hanyang University, Seoul, Korea

Abstract

Recently, many vehicles have applied electric parts for saving fuel consumption and reducing levels of environmental pollution. ISG (Integrated Starter and Generator) system is one of main electric parts of following these trends and can improve fuel efficiency. If ISG motor and inverter are driven by appropriate switching time, it can be a more efficient system operation than existing ISG operation method. In this paper, we studied Switched Reluctance Motor (SRM) and Switched Reluctance Driver (SRD) for ISG system and then showed the results of comparing the experimental data and simulation. As a result, the SRM for electric vehicles are feasible in practice and has a good prospect.

Introduction

The Switched Reluctance motor (SRM) is a type of a brushless motor and a double salient structure that runs by reluctance torque. But SRM torque has a high pulsation and is not generated continuously because of reluctance torque. So SRM has disadvantage such as noise and vibration. Because of these drawbacks, SRM is difficult to apply on industry. In order to overcome this situation, developing SRM actuation technology for ISG is needed. ISG means that combining generator(power supply) and starter(startup device) in the existing vehicle. In other words, when car is parking or stopping, ISG operates as idle stop & go system. In general mode, ISG operates as motor when car need high starting torque such as start-up or acceleration. And during deceleration or constant-speed driving, ISG operates as generator and to charge a battery. Using these characteristics of the ISG we will try to configure efficient SRM. SRM can not operate without actuation circuit in principle. So to improve operational feature, we consider driving condition when we design SRM. Design parameters of the SRM can divide two parts, one is basic design parameter as the number of poles, turns and conductor diameter and another is detailed parameter like rotor and stator shape, angle of turn-on and turn-off. Detailed design parameters affect torque ripple and torque density of SRM significantly. Especially, turn-on angle and turn-off angle for a high output is not a independent design parameter but design parameter of having a close relationship with motor shape. [1]

Using 2D FEA(Finite Element Analysis), we provide turn-on and turn-off angle at a constant power output. And

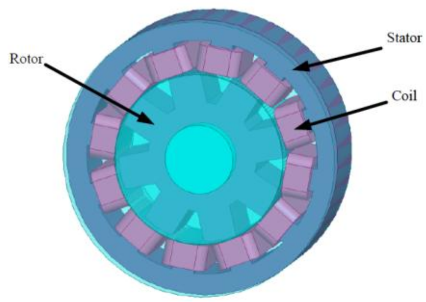

Figure 1. The 3D modelling of Three Phase 12/8 SRM

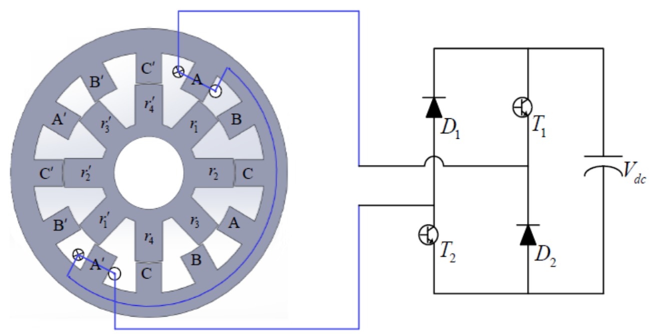

Figure 2. Switched Reluctance Motor and its single phase Drive circuit

on the basis of this angle, we verify through experiments about torque and generated energy at the generating area.

Basic Structure and Operating Principle of the SRM

A. Basic Mechanism of the SRM

Switched reluctance motor (SRM) , the three phase of 12/8 as shown in Figure 1. The SRM has a doubly salient structure, but there are no windings or permanent magnets on the rotor. The rotor is basically a piece of steel (and laminations) shaped to form salient poles. So it is the only motor type with salient poles in both the rotor and stator.[2]

B. Basic Equation of the SRM

The dynamic process of the Switching Reluctance Motor by the circuit equation, torque equation, and air gap power equation is composed of three parts. [3]

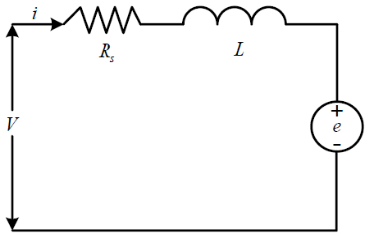

Figure 3. Single-phase equivalent circuit of the SRM

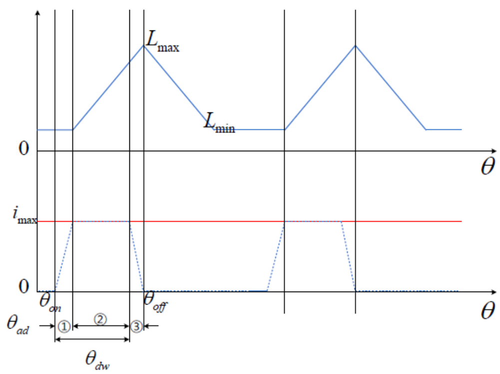

Figure 4. Inductance and current waveforms according the rotation angle when motor operates

According to the energy conservation law and the electro-magnetic induction theory, the applied voltage to each stator winding is equal to the sum of the resistance voltage drop and due to the rate of the flux linkages

$$V = R_s i + \frac{d\lambda(\theta,i)}{dt} \qquad (1)$$

Field ①

$$V_{ph} = R \cdot i_{ph} + \frac{d\lambda_{ph}}{dt} \qquad (2)$$

$$V_{ph} = R \cdot i_{ph} + L_{off}\frac{di_{ph}}{dt} \qquad (3)$$

Field ②

$$V_{ph} = R \cdot i_{ph} + \frac{d\lambda_{ph}}{dt} \qquad (4)$$

$$V_{ph} = R \cdot i_{ph} + L_{(\theta,i)}\frac{di_{ph}}{dt} + \frac{dL_{(\theta,i)}}{d\theta}\omega_{rm} i_{ph} \qquad (5)$$

Field ③ same to field ②

Because of mutual inductance of each phase is very small, mutual inductance is ignored when calculating equations. So flux linkage equation can regard under equation.

$$\lambda = L_{(\theta,i)} i \qquad (6)$$

Electromagnetic torque of the SRM can be achieved by magnetic field energy and co-energy is obtained by the partial derivative of rotor position angle. That is:

$$T_e = \left.\frac{\delta W_f^{'}(i,\theta)}{\delta\theta}\right|_{i=constant} \qquad (7)$$

$W_f^{'}(i,\theta) = \int \lambda(i,\theta)di$ is winding magnetic co-energy.

$$V_{ph} \cdot i_{ph} = R \cdot i_{ph}^2 + \frac{d}{dt}\left(\frac{1}{2}L_{(\theta,i)} i_{ph}^2\right) + \frac{1}{2}\frac{\partial L_{(\theta,i)}}{\partial t} i_{ph}^2 \omega_{rm} \qquad (8)$$

$$T_{ph} = \frac{1}{2}\frac{\partial L_{(\theta,i)}}{\partial t} i_{ph}^2 \qquad (9)$$

$$T_{total} = \sum T_{ph} \qquad (10)$$

SRM output power is expressed as Equation (11).

$$p_i = vi = R_s i^2 + i^2\frac{dL_{(\theta,i)}}{dt} + L_{(\theta,i)} i \frac{di}{dt} \qquad (11)$$

We put the above Eq. (2.4) of deformation:

$$p_i = R_s i^2 + \frac{d}{dt}\left(\frac{1}{2}L_{(\theta,i)} i^2\right) + \frac{1}{2} i^2 \frac{dL_{(\theta,i)}}{dt} \qquad (12)$$

System Control of the SRM Drives

A. Control System Structure

Control system consists of switched reluctance motor, power converter, main controller, a position sensor and a current sensor showed in Figure 5.

In this paper, chopped current control and angular position control are mainly used. Chopped current control can be used in two ways, one is ΔI type which is based on current limit, another ΔT type based on switch turn-off time. These control methods key-point are the control of the main switch turn-on angle and turn-off angle. Normally these method use at high speed area and adjusts only turn-on angle. At this time, Role of rotor position sensor is important. Because position sensor senses present angle states and send a signal to the controller as feedback. Using this method, we can reach a purpose to control the SRM electromagnetic torque.

B. Converter for the SRM Drives

This paper adopts the double switch structure, also called Asymmetric Bridge Converter, the concrete structure as shown in Figure 6. This type of converter has a characteristic that each phase is completely independent.

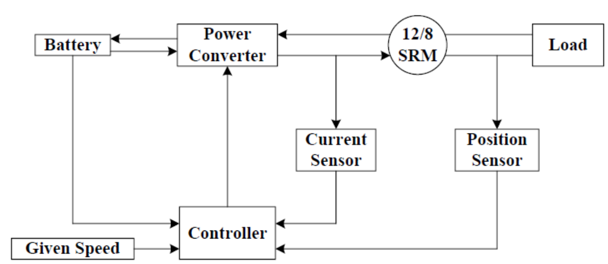

Figure 5. Control System Structure Diagram

C. Controller Design (DSP Selection)

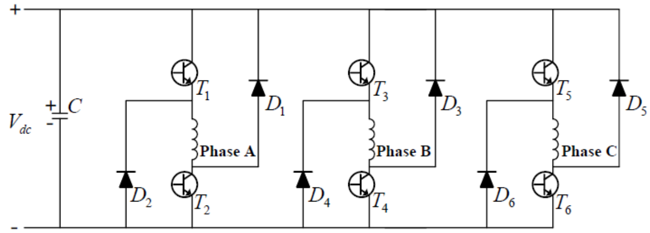

Figure 6. Asymmetric Bridge Converter

In the system, we use the DSP TMS320F28335 chip which has a high degree of integration it can provide the entire system, at the same time, reduce the cost of the system, high efficiency and economy.

DSP is operated as shown in Figure 7. block diagram.

(1) Starting state subroutine

Starting state mainly use chopped current control (CCC) mode. Current comparing with chopping current limit and current chopping Δt delay realize by external comparison circuit.

(2) Electric state subroutine

Electric state mainly uses the angle position control (APC) and chopped current control (CCC) combination method.

(3) Generating state subroutine

When SRM works in the generating state, the motor is the battery charging power and load power supply at the same time. Generating state subprogram of flow chart as shown in Figure 7.

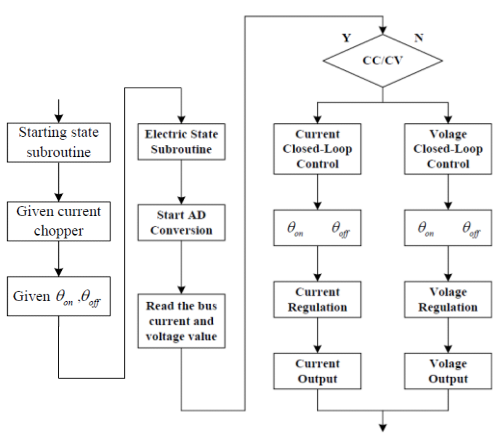

Figure 7. Generating state subprogram of Flow Chart

D. Rotor Position Signal Detection

We can detect the position of SRM using direct or indirect method. In this paper, we detect absolute position of motor shaft by the resolver. At Electric vehicle normally use the resolver because it has a strong heat-resistant and durability.[3]

Simulation and Structural Analysis

Through the FEA(Finite Elements Analysis), we got parameters of SRM and the simulation configuration follows the SRM parameters of Table 1.

Table 1. Parameter of SRM

Rated Output Power	5.027[kW]	Rated Voltage	270[V]
Rated Speed	2000[rpm]	Friction Loss	0[W]

A. Motoring Mode Simulation

Switched reluctance motor speed is more than 800rpm, when the electric vehicle is in the accelerating state, main control method is the angle position control (APC) and chopped current control (CCC) combination method.

(1) Turn-on θ_{on} Optimization($\theta_{off}=15^\circ$)

We change the size of the opening angle $[-7.5^\circ, 0^\circ]$ and measuring the output torque and efficiency under different speed then we find optimal opening angle.

As the table shows that efficiency of advanced opening angle -7.5° is partially low than others but torque is relatively higher than others. So advanced opening angle -7.5° is proper opening angle.

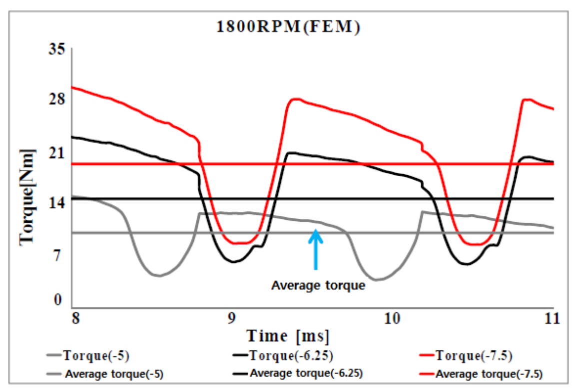

Figure 8. 1800 RPM (FEM) Torque Diagram($\theta_{off}=15^\circ$)

Table 2. $\theta_{off}=15^\circ$ Corresponding the output torque value and efficiency value

θ_{on}	-5°		-6.25°		-7.5°	
	T	η	T	η	T	η
1000	68.79	79.2895	68.80	78.6256	68.84	78.2565
1200	55.94	80.6549	60.24	80.3456	62.67	80.2598
1500	28.53	78.3356	39.65	78.3412	47.73	80.8223

1800	12.66	77.3363	20.76	78.9826	28.02	80.4389

(2) Turn-off θ_{off} Optimization($\theta_{on} = -7.5^{\circ}$)

Opening angle is fixed at -7.5°, turn-off angle from 15 degrees to 22.5 degrees, we can get a data as following table.

Table 3. $\theta_{off} = -7.5^{\circ}$ Corresponding the output torque value and efficiency value

θ_{on}	20°		21.25°		22.5°	
	T	η	T	η	T	η
1000	55.17	80.1632	68.05	78.3321	68.83	77.5142
1200	50.28	81.3305	54.22	78.6591	59.32	77.3697
1500	47.43	80.5621	46.51	78.5541	48.48	77.8404
1800	21.52	76.6664	21.61	74.1282	21.96	73.2401

From the data in the table we can see that when opening angle is the same, 20° turnoff angle generated the largest torque and efficiency is also higher than other one.

B. Generating Mode Simulation

Power analog controller will use to optimize turn-on angle in [0°, 30°]. The simulations are performed in the 5000 *rpm* ~ 7000 *rpm* speed range.

Turn-on angle and conduction angle of the conversion method:

$$\theta_{on} = 15^{\circ} - \frac{\theta_{ad}}{8} \tag{13}$$

$$Pw = \frac{\theta_{dw}}{8} \tag{14}$$

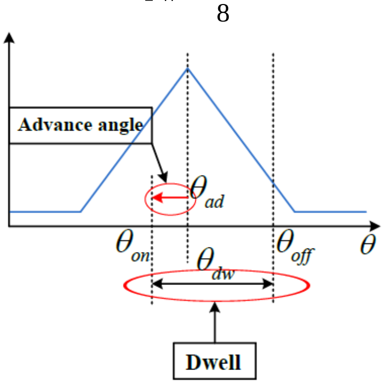

Figure 9. Schematic Diagram of Angle Control

Table 4. In under different speed torque value

Rpm	Advanced	Dwell	Torque
5000	65°	155°	13.6186
6000	80°	178°	10.3312
7000	85°	188°	7.7244

Table 5. (FEM) Power and Maximum Efficiency value

θ_{on}	9.875°		5°		4.375°	
θ_{off}	29.25°		27.25°		27.875°	
rpm	Power [kW]	Max Efficiency	Power [kW]	Max Efficiency	Power [kW]	Max Efficiency
1000	68.79	65.24	68.80	65.56	68.84	65.64
5000	5.60	95.10	5.40	91.70	5.34	90.68
6000	5.12	93.92	5.25	96.30	5.21	95.57
7000	5.63	85.71	5.41	82.36	5.82	88.60

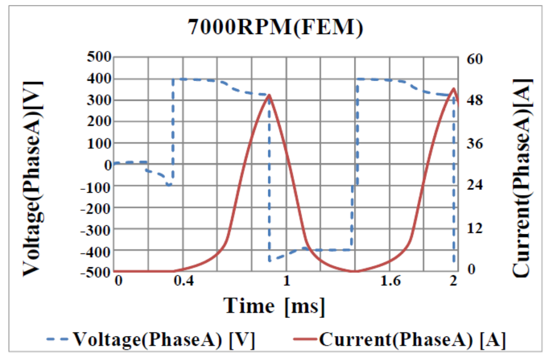

Figure 10. A-phase of 7000 RPM (FEM)

According to the simulated data and the following calculation formula, we can quickly calculate power generation power and efficiency.

$$P_{generating} = \frac{\omega \cdot T}{60} \cdot 2\pi \tag{15}$$

$$P_{3-phase} = V_a \cdot I_a + V_b \cdot I_b + V_c \cdot I_c \tag{16}$$

$$\eta_{generating} = \frac{P_{3-phase}}{P_{generating}} \tag{17}$$

Experimental Results and Analysis

A. Motoring Mode Test

Switched reluctance motor speed is more than 800 rpm, when the electric vehicle is in the accelerating states, control main way is using the angle position control (APC) and chopped current control (CCC) combination method.

Figure 11 illustrates test environment for this experiment.

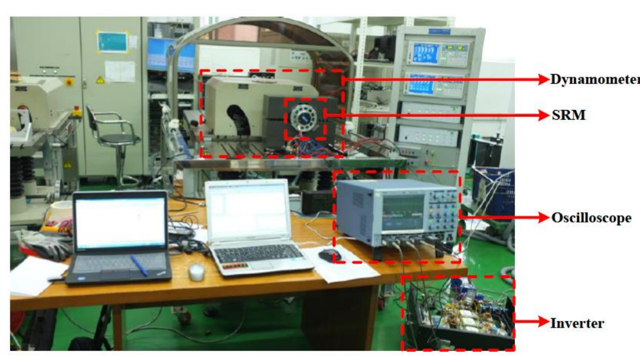

Figure 11. Experimental Platform

Table 6. $\theta_{off} = 15^{\circ}$ **Corresponding the output torque value**

θ_{on}	-5°		-6.25°		-7.5°	
	Torque[Nm]		Torque[Nm]		Torque[Nm]	
rpm	FEM	Test	FEM	Test	FEM	Test
1000	68.79	65.24	68.80	65.56	68.84	65.64
1200	55.94	52.24	60.24	54.23	62.67	55.13
1500	28.53	28.12	39.65	36.66	47.73	45.71
1800	12.66	12.10	20.76	16.56	28.02	18.31

(1) Switching-On Angle Optimization

Turning-on angle on θ_{on} has a greater effect to the torque. We can find optimal opening angle. Method is fixed turn-off angle θ_{off}. We change the size of the opening angle $[-7.5^{\circ}, 0^{\circ}]$, and measuring the output torque and efficiency under different speed.

We compare with the experimental data and simulation data, we found that the data values are close, and indicating that the driver design is feasible.

(2) Switching-Off Angle Optimization

Opening angle is fixed at -6.25°, turn-off angle from 15 degrees to 22.5 degrees.

From the data in the table we can see that when opening angle is the same, 20° turnoff angle generated the largest torque and efficiency is also higher than other one.

Table 7. $\theta_{on} = -7.5^{\circ}$ **Corresponding the output torque value**

θ_{off}	20°		21.25°		22.5°	
	Torque[Nm]		Torque[Nm]		Torque[Nm]	
rpm	FEM	Test	FEM	Test	FEM	Test
1000	55.17	53.17	68.05	66.06	68.83	67.09
1200	50.28	49.20	54.22	53.22	59.32	58.36
1500	47.43	46.51	47.75	46.96	48.48	47.41
1800	21.52	18.11	21.61	18.36	21.96	18.80

B. Generating Mode Test

In order to test results, we performed several tests, and we put the data collection.

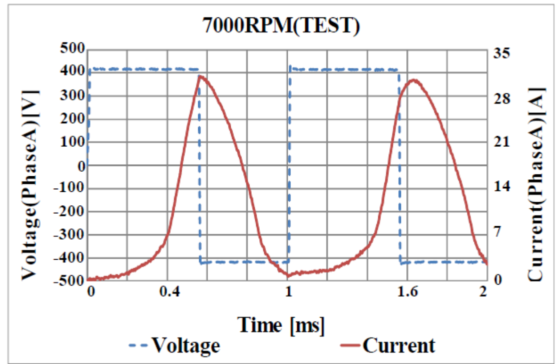

Figure 12. One periodic Voltage and Current Graph (7000 rpm, $\theta_{ad} = 85^{\circ}$**)**

Table 8. Generating of all experiment [Electricity Generation]

RPM	Power[kW]		Maximum Efficiency	
	FEM	Test	FEM	Test
5000	5.60	5.12	95.1%	87.0%
6000	5.52	5.13	96.3%	89.5%
7000	5.82	5.13	88.6%	78.1%

Conclusion

In this paper, we compared and analyzed using the results of simulation and experiment for turn-on angles that can affect the maximum output power generation of SRM. Using the selected turn-on angle, we can obtain results nearly close to standard current and torque.

Also we were verified the validity and accuracy of the theoretical analysis of the simulation based on the results of the experiment.

References

[1] Wen Ding, Deliang Liang, "A Fast Analytical Model for an Integrated Switched Reluctance Starter/Generator", *IEEE Trans. on EC*. Vol.25, no.4, Aug. 2010, pp.948-956.

[2] Jin-Woo Ahn, Ph.D "Switched Relutance Motor" Kyungsung University, 2011.

[3] J. David Irwin, "Switched Reluctance Motor Drives Modeling, Simulation, Analysis, Design, and Applications" Auburn University, 2001.

[4] Staff of University of Paderborn, "E-learning Resources in Microelectronics-Resolver", University of Paderborn

[5] Hee Jo, and Kyeong-Hwa Kim, "A Study on the Design and Speed Control of the Switched Reluctance Motor for Railway Traction Application", *JOURNAL OF THE KOREAN SOCIETY FOR RAILWAY*, Vol.15, No.3, Jun. 2012, pp.237-243.

[6] F. Soares, and P.J. Costa Branco, "Simulation of a 6/4 switched reluctance motor based on Matlab/Simulink

environment", *IEEE Trans. on AES,* Vol.37, No.3, Jul. 2001, pp.989-1009.

[7] Sahoo S.K., Panda S.K., and Xu J.X, "Indirect torque control of switched reluctance motors using iterative learning control", *IEEE Trans. on PE*, Vol.20, No.1, Jan. 2005, pp.200-208.

[8] Sozer Y., and Torrey D.A, "Optimal turn-off angle control in the face of automatic turn-on angle control for switched-reluctance motors", *IET EPA*, Vol.1, No.3, May 2007, pp.395-401.

[9] Russa, K., Husain, I., and Elbuluk, M., "A self-tuning controller for switched reluctance motors", *IEEE Trans. on PE*, Vol.15, No.3, May. 2000, pp. 545–552

[10] Xu Y. Z., Zhong R., Chen L., and Lu S. L., "Analytical method to optimise turn-on angle and turn-off angle for switched reluctance motor drives", *IET PA*, Vol.6, No.9, Nov. 2012, pp.593-603.