Operating stability study of SRM drive system based on variable excitation period single-pulse control for independent-wheel electric vehicle

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Abstract. In this paper, a switched reluctance motor (SRM) drive system using variable excitation period single-pulse control for independent-wheel electric vehicle (EV) is presented. A novel single-pulse control oriented maximum efficiency and fast adaptation using excitation mode shift according to load is examined for operating stability analysis of this system under the conditions of different speed references. In addition, comparison experiments of the proposed control and a voltage PWM control are described to confirm the operating performance of experimental miniature EV system in actual operational environment.

1. Introduction

With the number of vehicles increasing, the massive use of fossil fuels has caused a tremendous damage to human living environment and a waste to natural resources. The future solution for scarcity of fossil fuels, as well as the environmental problems associated with their wide usage, will most likely involve using electric vehicle (EV) extensively. Switched Reluctance Motor (SRM) is suitable to be used as an EV driving source because of following main features like fast dynamic response, good robustness and simple structure, having the advantage of brushless DC motor as well as asynchronous motor [1]. Moreover, it can be used competently in severe condition since no permanent magnet in constituent elements of SRM.

The control method of SRM determines whether motor can have a good performance and operate efficiently. It can be classified by the controllable quantity loaded on the windings of motor. One representative control method for SRM drive is single-pulse control, controlling the current and torque to achieve speed regulation by changing the turn-on and commutation angle of excitation period [2].

The effect of different excitation angles sets in single-pulse control method on efficiency was examined in [3]. Authors [4] presented a compute and analysis of core loss in single-pulse control to discuss the turn-on and commutation angle effects on efficiency of SRM operating. In order to optimize the excitation angle timings, a general self-tuning control method based on rotor position detection and speed feedback was proposed in [5]. Compared with the self-tuning control, a novel single-pulse control method using excitation mode shift oriented maximum efficiency for all speed region and fast adaptation was examined in [6]. The effectiveness of this method was confirmed by Simulink simulation and experiment [7, 8].

This paper presents a miniature independent-wheel electric vehicle using variable excitation period
single-pulse control. The structure details of experimental EV is given in section 2. Section 3 explains how magnetization modes of proposed control method is shifted, and presents a SRM drive system adapted to this method. In order to confirm the performance and operating stability of this EV in actual operational environment, tests under conditions including no-load operating, aboveground comprehensive operating and steep-ascent operating are described. Finally, the results in classical PWM control and in variable excitation period single-pulse control are presented and compared.

2. Experimental EV
A one-person miniature experimental EV with independent-wheel structure is shown in figures 1 and 2. This structure is also regarded as the final drive form of EV drive, as it has compact structural arrangement, high transfer efficiency, and fast response [9].

![Figure 1. Independent-wheel experimental EV compositions.](image1)

![Figure 2. One-person miniature experimental EV.](image2)

Two rear independent-wheels are connected with two identical parameters SRM separately, but are controlled respectively by one drive system. Transmission is not used in this vehicle, the connection is only constituted by a reduction gear of 1/2 gear ratio. Through the inverters, DC power converts into three-phase current as power supply for motors. An accelerator is used to adjust rotating speed.

3. Control method and SRM drive system

3.1. Principle of torque generation
Unlike in traditional motor, the energy conversion in SRM occurs for magnetic pull by the trend of minimum reluctance through interaction of one stator and one rotor pole pair. A double salient structure can meet this need for a model of the 6/4 SRM as shown in figure 3. With a desired sequence and interval of current switching in the three-phase windings, due to the induction electromotive force for aligning the rotor and the stator, the rotor could rotate continuously [10].

Figure 4 shows a typical self-inductance change of stator winding as a function of rotor position, while it also defines the corresponding rotor position. The origin coordinate of abscissa is 0°, where the central axis of the stator salient is coincident with the central axis of the rotor groove, and the inductance value is minimum. The rotor starts to rotate to the position coinciding with the stator at θ1. In this process, the value of inductance begins to rise and reaches the maximum value at θ2, where the central axis of the stator and rotor is aligned. After that, as the rotor salient pole gradually deviates from the stator coverage, the self-inductance drops back to its minimum value at θ4 [11].

The slope of the self-inductance K is expressed as follows:

$$K = \frac{L_{max} - L_{min}}{\theta_2 - \theta_1}$$  (1)
Figure 3. Schematic diagram of three-phase S6R4SRM.

Figure 4. Typical self-inductance change of stator winding.

The analytical formulas of the winding inductance are:

\[
L(\theta) = \begin{cases} 
L_{\text{min}} & 0^\circ \leq \theta \leq \theta_1 \\
K(\theta - \theta_1) + L_{\text{max}} & \theta_1 \leq \theta \leq \theta_2 \\
L_{\text{max}} & \theta_2 \leq \theta \leq \theta_3 \\
L_{\text{min}} - K(\theta - \theta_3) & \theta_3 \leq \theta \leq \theta_4 
\end{cases} 
\]  

(2)

By considering the linear magnetic circuit and the independent inductance of the phase winding, with a current value \(i\), the electromagnetic torque in one phase is:

\[
T_e = \frac{dW(\theta, i)}{d\theta} = \frac{1}{2} i^2 \frac{dL(\theta)}{d\theta} 
\]  

(3)

It can be seen that the direction of SRM torque has no relation with direction of the current, only relates to the inductance for angle change. Energizing winding at the area of inductance rising, a positive electromagnetic torque will be produced and the magnitude of torque is proportional to square of the winding current value.

3.2. Control method

As the equation (3), the phase current does not contribute any torque during flat inductance profile, and that it increases copper and iron losses [12]. Thus, there are some different magnetization modes of single-pulse control shown in figure 5 to figure 7 to provide an optimal scheme for the balance between copper loss and efficiency.

Figure 5. Magnetization mode 1.
In magnetization mode 1, phase current flows only into the positive torque region by controlling commutation angle $\theta^*_{c}$. It is the most efficient mode in medium speed region, when the instruction turn-on angle $\theta^*_o$ is fixed as where the rotor starts to rotate to the position coinciding with the stator, called overlap angle $\theta_{olp}$. And the instruction commutation angle $\theta^*_c$ is regulated by conduction angle.

When the objective in mode 1 torque is insufficient, mode will shift to the magnetization mode 2. The $\theta^*_c$ in mode 2 is fixed as optimal commutation angle $\theta^*_{c, opt}$. And $\theta^*_o$ is regulated according to the reference torque from the overlap angle to $0^\circ$. Compared with mode 1, the efficiency of mode 2 decreases since the current starts from invalidity torque region. And for this reason, current of high average value can flow into positive torque region to provide larger torque.

If the objective torque in mode 2 is still insufficient, the mode will shift to magnetization mode 3. The $\theta^*_o$ in mode 3 is fixed as 0. And $\theta^*_c$ is adjusted from the optimal commutation angle to the commutation angle of maximum torque. Mode 3 is the most inefficient mode since part of current flows into reverse torque region. However, lagging commutation angle can enlarge the average current flowed into positive torque region, so the largest torque is provided in mode 3.

3.3. SRM drive system
The SRM drive system is shown in figure 8. The instruction turn-on angle $\theta^*_o$ and instruction commutation angle $\theta^*_c$ are calculated from phase current, position information of rotor and optimal conduction angle $\theta^*_{con}$. Position information (three-phase ABZ signal) is the key-information of SRM excitation judgment, which is generated by the rotary encoder on shaft.

The mode shift is determined by turn-on angle and phase current in aligned position of rotor. In modes 1 and 3, state switching depends on whether phase current is 0. In mode 2, state will shift to mode 1 if turn-on angle is fixed as $\theta_{olp}$, and it shifts to the magnetization mode 3 when turn-on angle is $0^\circ$. The initial state value is the magnetization mode 3, since at start-up timing a large torque is required.
4. Experiment and result

4.1. Parameters of tested SRM

The model and parameters of SRM used in this project are shown in figure 9 and table 1 respectively. The motor is designed with 12/8 poles structure, and rated power is 3.5 kW. The maximum efficiency could reach to about 87% in theory, and it can be used as a good electric vehicle power output unit.

| Element            | Style     |
|--------------------|-----------|
| Stator outer diameter | 182 [mm] |
| Translator outer diameter | 96.33 [mm] |
| Air gap            | 0.3 [mm]  |
| Rated output       | 3.5 [kW]  |

4.2. System structure of experimental SRM drive system

Figure 10 shows system structure of proposed experimental EV. The hardware part of the system include: SRM, FPGA, inverter, A/D (D/A) converter, rotary encoder of 3600 PPR and overcurrent protection circuit. Through asymmetric half-bridge inverter, 100V DC supply flows into windings of SRM as a three-phase excitation voltage. The FPGA is used to calculate position information of rotor and also determine the switching timings for inverters. The real time current, voltage and rotor position information can be observed by an oscilloscope.
4.3. No-load single-wheel rotation experiment

In order to evaluate the stationary characteristic of the SRM drive system based on proposed control, series experiments are described based on the left-wheel in floating situation. The gate voltage and phase current of phase U and V shown in figure 11 are obtained in operation points at 2000 rpm, 4000 rpm, and 6000 rpm. Since in a no-load condition, magnetization modes of these operation points are both in the mode 1.

As rotation speed increases sequentially from 2000 rpm to 6000 rpm, the number of excitation per 10ms is also increasing. Since the excitation periods are shortened in high speed region, obviously, it can be seen that the peak value of phase current is decreasing with speed increasing.

Figure 10. Actual SRM control system structure.

Figure 11. Waveforms from phase U and V in no-load condition.
4.4. Aboveground comprehensive operating experiment
Figure 12 shows an aboveground comprehensive operating experiment setup. The results shown in figure 13 are obtained from U phase of left-wheel at 1000 rpm and 2000 rpm. It verifies that excitation mode 1 is set at speed of 1000 rpm, because the turn-on angle is fixed as the overlap angle, and the demagnetization angle is smaller than the align position, and the conduction angle is instant. Similarly, in the speed of 2000 rpm, the excitation mode is changed to mode 2 because the turn-on angle is smaller than overlap angle and the degaussing angle became to overlap the align position.

![Figure 12](image_url)

**Figure 12.** Aboveground comprehensive operating experiment.

![Waveforms from one phase in comprehensive driving experiment](image_url)

(a) 1000 rpm

![Waveforms for convenient PWM control methods at 1000 rpm](image_url)

(b) 2000 rpm

**Figure 13.** Waveforms from one phase in comprehensive driving experiment.

**Figure 14.** Waveforms for convenient PWM control methods at 1000 rpm.

Figure 14 shows the waveforms from phase U for convenient PWM control method in proposed
drive system at 1000 rpm. Compared with in variable excitation period single-pulse method, the current flows into invalidity torque region, but no occurs in the single-pulse method. And the current peak is approximately 100 A. as double value of voltage PWM control.

4.5. Steep-ascent operating experiment
To further verify the operating stability of the proposed SRM drive system, the steep-ascent operating shown in figure 15 is experimented. This slope is about 7° and about 50 meters in total length. The phase voltage and current waveforms at 1000 rpm for each control is shown in figure 16.

![Figure 15. Steep-ascent operating experiment](image)

![Figure 16. Waveforms for different control methods in steep-ascent operating.](image)

The steep-ascent experiment results is accordant with the results of comprehensive driving experiment, only the current in PWM control flows into invalidity torque region to impact on the system efficiency. In variable excitation period single-pulse control, the turn-on angle is fixed as overlap angle, and demagnetization angle is smaller than the align position, since the Overcurrent protector of SRM drive system, excitation mode 1 is set at that operating point. And the phase current does no rise steeply as the result observed before.

5. Conclusion
This paper has analyzed the operation performances of a SRM drive system using variable excitation period single-pulse control for miniature independent-wheel EV. Through no-load rotation experiment, comprehensive operating experiment and steep-ascent operating experiment, it shows different magnetization modes of proposed control can be shifted reliably by rotation speed and load. Based on the compare of experimental results in proposed control and classical PWM control by this drive
system, it can be confirmed almost no current flows into invalidity torque region and current crest of proposed control is much steeper. It provides a better performance than PWM control in corresponding operating points.

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