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A Performance Comparison of Excitation Strategies For a Low Noise SRM Drive

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ABSTRACT

A simple construction, low cost, and a fault tolerant power electronic drive have made the switched reluctance drive a strong contender for many applications. But the switched reluctance drive exhibits higher levels of vibration and acoustic noise than most competing drives. The main source of vibration in the switched reluctance drive is generated by the rapid change of radial magnetic force when the phase current is extinguished during commutation. In this paper, some excitation methods are proposed to reduce the vibration and acoustic noise of the switched reluctance drive. The excitation strategies considered in this research are 1-phase, 2-phase and hybrid excitation methods. The 1-phase method is the conventional approach, while in the 2-phase method, the two phases are excited simultaneously. The hybrid excitation has 2-phase excitation using a long dwell angle as well as conventional 1-phase excitation. The vibration and acoustic noise are compared and tested. The suggested 2-phase and hybrid strategies reduce acoustic noise because the schemes reduce the abrupt change in excitation level by using distributed and balanced excitation.

Keywords: Switched Reluctance Motor (SRM), 1-phase excitation, 2-phase excitation, Hybrid excitation, Low vibration, Low acoustic noise

1. Introduction

The Switched Reluctance Motor(SRM) has considerable potential for industrial and electric vehicle applications because of its high reliability resulting from the absence of rotor windings. In addition, most of the losses are confined to the stator, and they are more easily removed. Therefore, an SRM has good cooling characteristics, high efficiency, and a robust structure. One of the main problems with the SRM is its higher vibration and acoustic noise compared to an induction motor of the same size.

There are many possible sources of vibration and acoustic noise in an SRM. In addition to magnetic and mechanical origins of the problem, the control algorithm and inverter system are also considered. The inherent vibration and acoustic noise are derived from the torque production mechanism, in which the force between the excited stator teeth and the rotor. It contains a significant radial force component in addition to the required tangential component. Some authors[1,2] have used time domain analysis to conclude that a stator vibration was initiated each time a phase winding was commutated.

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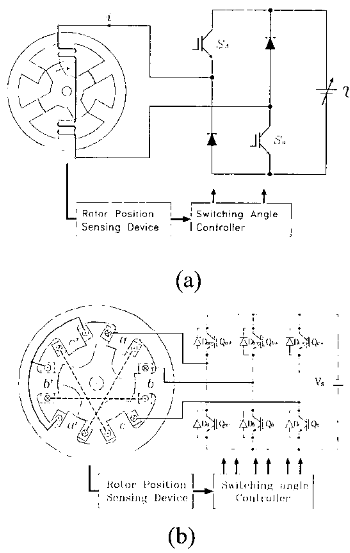
Some suggestions have been introduced to reduce vibration and acoustic noise. A multilevel switching technique has been used to reduce the radial attraction [2,3]. Design optimization of the magnetic structure was also used to reduce resonance in the motor operation range [4]. Winding topology and phase excitation methods were also considered [5,6]. The full-pitched winding, which was used to utilize mutual torque, however, reduces drive efficiency [5]. The symmetrical excitation technique in a conventional winding also reduces the torque [6].

This paper compares excitation methods used to reduce acoustic noise and torque ripple.

2. Excitation method for noise reduction

The generation of acoustic noise is an inherent characteristic of all electric motors but is particularly severe in an SRM. Due to the rapid change of mmf during commutation, radial vibration of the stator is the dominant source of acoustic noise in an SRM. These mechanical vibrations are primarily increased when a large harmonic component of the radial force with resonant force which tries to reduce the gap separation between stator and rotor poles, especially when both poles approach alignment.



(b)

Fig. 1 SRM excitation (a) 1-phase excitation (b) 2-phase excitation

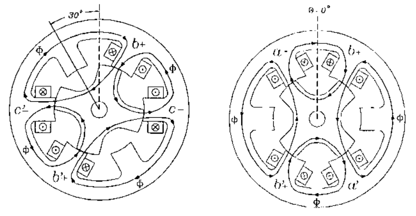
This tendency, while exciting for all positions of the rotor during the excitation of a phase, is particularly prevalent at the aligned position, where the reluctance is lowest and the flux is highest.

2.1 2-phase excitation method

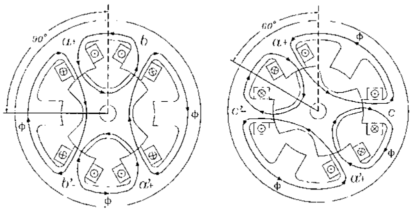
A rapid change of current particularly associated with a declined range of inductance induces a vibration. The magnitude of the vibration is directly proportional to the gradient and the magnitude of the exciting current. In addition, vibrations increase as an approaching rotor pole aligns with a stator pole for a given current magnitude.

The winding connection of a 6/4 SRM with 2-phase excitation is shown in Fig. 1(b). The phase winding is wound in the reverse direction to the opposite side pole, and Y-connected.

The two phases are excited in opposite directions, which utilizes the self- and mutual inductance of the motor. The principle of torque production is explained in Fig. 2 and 3.



(a) phase *a*(+), phase *b*(-) (b) phase *c*(+), phase *b*(-)



(c) phase *c*(+), phase *a*(-) (d) phase *b*(+), phase a(-)

Fig. 2 Flux distribution by 2-phase excitation method

When phase a is excited positively and b negatively, the rotor is moved to minimize the reluctance, where the rotor is defined as $\theta = 0°$ and shown in Fig. 2(a). As the current of phase a is removed and phase c is excited positively as shown in Fig. 2(b), the rotor may rotate 30° to the CCW direction. The rotation is achieved by successive excitation as AC drive excitation does.

The self and mutual inductance are shown in Fig. 3. To develop positive torque, the phase current is to be controlled as i_a , i_b , i_c in Fig. 3, and the torque developed by this current is as (3).

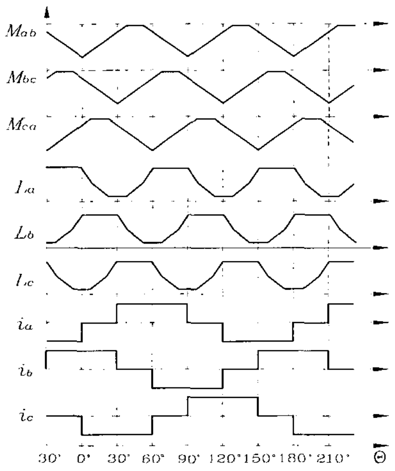


Fig. 3 Inductance profile and phase current of 2-phase excitation

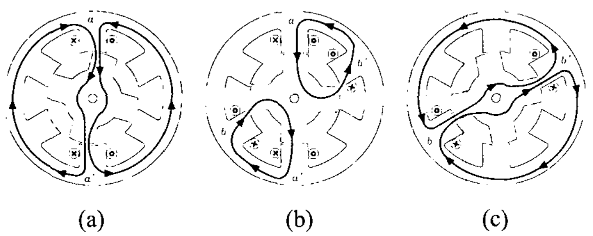
$$T=\frac{1}{2}i_a^2\frac{dL_{aa}}{d\theta}+\frac{1}{2}i_b^2\frac{dL_{bb}}{d\theta}+\frac{1}{2}i_c^2\frac{dL_{cc}}{d\theta}+i_a\cdot i_b\frac{dM_{ab}}{d\theta}+i_b\cdot i_c\frac{dM_{bc}}{d\theta}+i_c\cdot i_a\frac{dM_{ca}}{d\theta} \tag{1}$$

where, $i_a\cdot i_b < 0,\ i_b\cdot i_c < 0,\ i_c\cdot i_a < 0$

2.2 Hybrid excitation method

An SRM is excited by hybrid excitation that combines 1-phase excitation with 2-phase excitation. The phase winding is the same as in the conventional method. The hybrid excitation method is operated using a long dwell angle. The next phase winding absorbs the magnetic energy of the demagnetizing phase during phase commutation. The absorption of the magnetic energy speeds up the phase commutation as well as smoothing it.

However, the switch-off angle is located in the high inductance region, tail angle is increased. This reduces drive efficiency. In this paper, we add a C-dump inverter to the SRM system to improve efficiency..



(a) (b) (c)

Fig. 4 Flux distribution by hybrid excitation
(a) ph. a excited (b) ph. a and b excited (c) ph. a excited

The flux path in hybrid excitation is shown in Fig. 4. Fig. 4(a) and (c) show one phase excitation, Fig. 4(b) shows two phase excitation.

Fig. 5 shows the inductances and phase currents of hybrid excitation. Before phase a is switched off, phase c is switched on. The two phase excitation interval 2-3 of Fig. 5 is the region where noise and torque ripple are reduced.

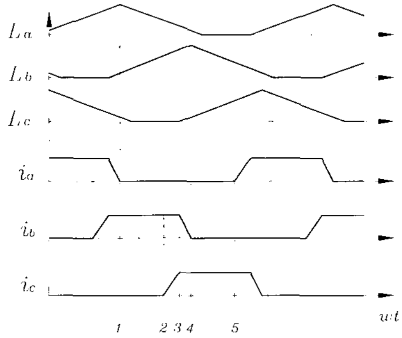
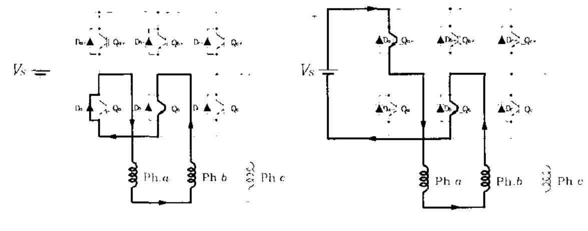


Fig. 5 Inductance profile and phase current of hybrid excitation

2.3 Analysis of excitation methods

A 1-phase excitation method is well known as a conventional method and adopted widely in SR drives. Two phases are excited together in a 2-phase excitation method as shown in Fig. 6[7].



(a) mode 1 (b) mode 2

Fig. 6 Operation modes of 2-phase excitation
(a) phase a(+), phase b(-):ON
(b) phase a(+):OFF, phase b(-):ON

Operation modes of the inverter are shown in Fig 6. Mode 1 is excited in the positive direction in phase a and in the negative direction in phase b, which is the torque production interval. In this scheme, the stored energy from the demagnetizing phase is utilized in the next magnetizing phase without using additional circuits. While the stored magnetic energy of most conventional SRMs is regenerated to the source or utilized in the next phase by using additional circuits and control, the applied voltage of phase A is changed from positive to negative through a zero voltage interval which can reduce the deformation of the stator and the noise.

A hybrid excitation method is operated using a long dwell angle to excite two phases. Because the switch-off angle is located in the high inductance region for long dwell angle, the tail angle is increased. This reduces drive efficiency due to the increase in negative torque.

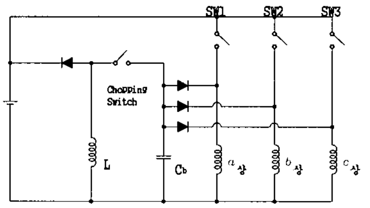
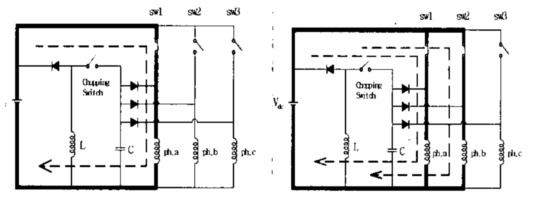
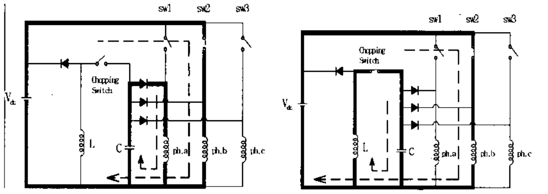


Fig. 7 C-dump inverter for hybrid excitation method

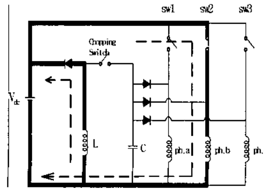
In order to compensate for this problem, a C-dump inverter is used as shown in Fig.7. The inverter of Fig.7 needs a switch and a diode per phase, and ensures perfect independence between phases in order to overlap phase currents using a boost energy recovery circuit. This results in decreasing the tail angle. Therefore, a C-dump inverter can be adopted for hybrid excitation to prevent a loss of efficiency[7].



(a) mode 1 (b) mode 2



(c) mode 3 (d) mode 4

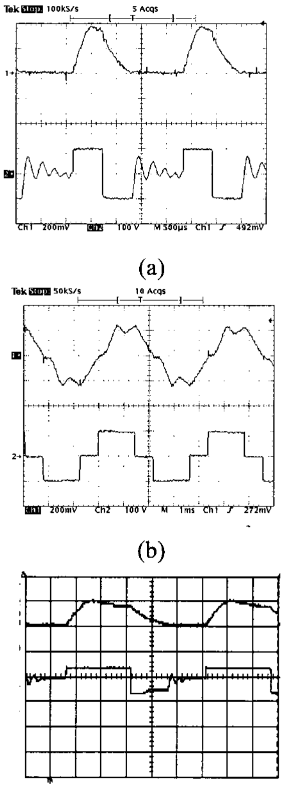


(e) mode 5

Fig. 8 Operation modes of C-dump inverter

Fig.8 shows an operation mode of a C-dump inverter that is commutation process from phase A to phase B. Fig. 8(b) shows the period conducted by two phases (phase A and phase B), and Fig. 8(c), (d), (e) shows the magnetizing process of phase B as well as the demagnetizing process of phase A operated by the recovery circuit.

Fig. 9 shows current waveforms of the conventional 1-phase, 2-phase and hybrid excitation methods.



(a)

(b)

(c)

Fig. 9 Phase current and voltage, (a) Conventional 1-phase excitation, (b) 2-phase excitation, (c) hybrid excitation method (upper : current, lower: voltage)

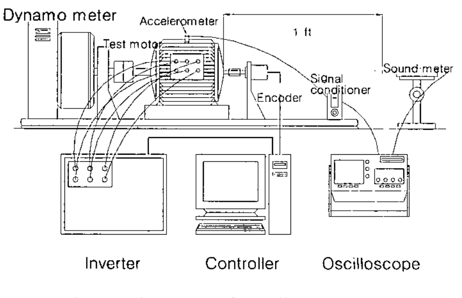
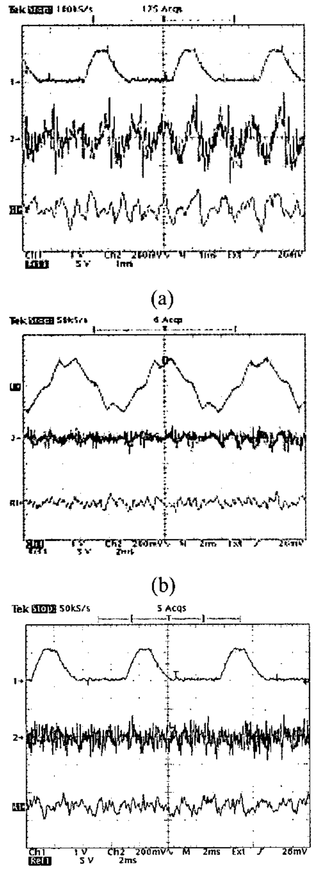


Fig. 10 Experimental set-up for vibration and acoustic noise measurement

Fig. 10 shows current waveforms of the conventional 1-phase, 2-phase and hybrid excitation method.

3. Experiments and Results

The tests are executed with 12/8, 600[W] SRM, which has 17° stator pole arc and 16° rotor pole arc. Fig. 10 shows a test set-up for vibration and noise measurement. Vibration and noise tests are executed and compared with that of a conventional SRM. Vibration is detected using an accelerometer and acoustic noise is detected using a sound meter as shown in the figure. The accelerometer is attached to the stator frame.


(a)

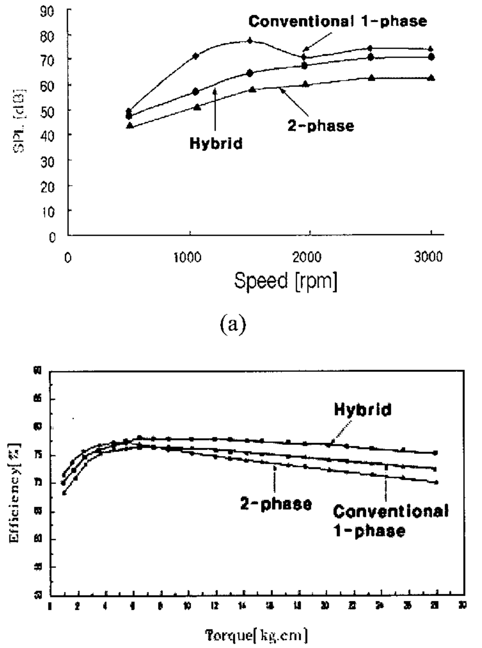
(b)

(c)

Fig. 11 Vibration and acoustic noise comparison (a) 1-phase conventional excitation, (b) 2-phase excitation, (c) hybrid excitation [upper trace : current, middle trace: acoustic noise, lower trace: vibration]

The output of the accelerometer is 99.5[mV/g] at 5kHz~10kHz. The sound meter is 1 [ft] apart from the motor radially.

Fig. 11 shows current waveforms and vibrations. This test is known as vibration characteristics that the vibration of 1-phase excitation shown in Fig.11 (a) is larger than that of 2-phase and hybrid excitation in Fig.11 (b) and (c).



(a)

(b)

Fig. 12 Comparison of noise and efficiency (load 5[kgcm]) (a) noise (b) efficiency

Fig. 12 shows a characteristic comparison of 1-phase, 2-phase and hybrid excitation according to speed. The noise of 2-phase and hybrid excitation is smaller than that of 1-phase excitation over the speed range and a specific high noise and vibration point does not appear in one phase excitation. The efficiency characteristics are almost the same but slightly higher at high speed range in high speed range and at low speed range in 2-phase and hybrid excitation.

4. Conclusion

The electromagnetic structure of an ac motor has been designed so as to be suitable for operation with a sinusoidal wave source. But an SRM has the proper electromagnetic structure to be operated with a current pulse. The inherent torque ripple and noise derives from the torque production mechanism of an SRM.

In this paper, a 2-phase and a hybrid excitation method are proposed to reduce vibration and acoustic noise of the switched reluctance drive. The 2-phase excitation excites 2 phases simultaneously. The hybrid excitation has a 2-phase excitation using a long dwell angle as well as a conventional 1-phase excitation. The vibration and acoustic noise are reduced because the scheme reduces the abrupt change in the excitation level by using distributed and balanced excitation.

Acknowledgments

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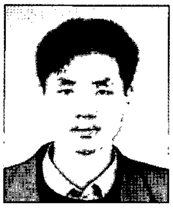

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