Acoustic Noise Reduction of Three-Phase SRM with Random Pulse Position PWM and Random Turn-on/off Angle Control

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Abstract - This paper describes a new method using random modulated strategies for switched reluctance machines. The proposed method is combined random turn-on, turn-off angle technique and random pulse width modulation technique. The purpose of this proposed method is to decrease harmonic spectrum, and thus reduce the emitted acoustical noise. A random generator is generated by linear congruential generator (LCG) using random pulse position (RPP) scheme. Simulation results show that the harmonic intensity of proposed method is better than that of conventional method.

1. Introduction

Switched reluctance machines (SRM), because of their simple construction and low manufacturing cost, are gaining importance in consideration for automotive applications. The inherent nature of the SRM is both rugged and fault tolerant. Recently, SRM has been considered as a propulsion motor in electric and hybrid vehicle applications due to its high power density capability, especially at high speeds. In addition, they have high torque density because they can increase their torque even though stator-poles are magnetically saturated. On the other hand, their magnetic saliency cause higher torque ripple, the emitted acoustic noise, the risk of triggering mechanical resonances and vibration compared to other motors. Hence SRM have been used in limited applications. Recently, several papers have been considered to solve those problems as shown in [1,2]. In [1], a presented method is randomly varying the turn-on and turn-off angle within 1° - 3° which is useful in the whole operating area of the SRM. However, this method only gives a small reduction in the acoustic noise emission. Therefore a simple and effective method to reduce acoustic noise will be useful for practice uses.

In principle, acoustic noise can be reduced if the switching frequency is above 18 kHz. However, such high frequency switching results in high switching losses in power inverters. Another method to reduce acoustic noise is to use random pulse width modulation (RPWM) technique that is useful for induction motor [3,4]. In the paper, we propose a simple and effective method using random modulated strategy and random PWM technique for a 6/4 SRM. This technique brings acoustic noise decrease by combining the varying turn-on, turn-off angle within 1° - 3° and RPWM technique.

2. Basic principle of operation of the SRM

A traditional inverter with high flexibility for the SRM is shown in figure 1. Assuming the motor phases are completely decoupled from each other and excited single phase at one time, the voltage across a phase winding is equal to the sum of the resistive voltage drop and the rate of the flux linkages and is given by [5]:

$$v = Ri + \frac{d\psi}{dt} = Ri + L\frac{di}{dt} + \omega_m i \frac{dL}{d\theta} \tag{1}$$

where v is the phase voltage, i is the current, R is the phase resistance, L is the phase inductance, ω_m is the rotor angular velocity and θ is the rotor position.

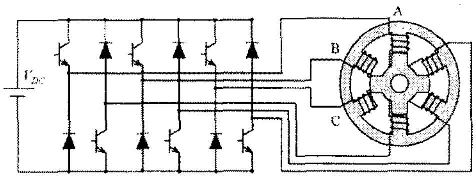


Fig. 1 Traditional three-phase 6/4 SRM.

The instantaneous electric power which is the product of phase voltage and current is as follows.

$$vi = Ri^2 + Li\frac{di}{dt} + \omega_m i^2 \frac{dL}{d\theta} \tag{2}$$

The instantaneous electro-magnetic torque is given by the following equations.

$$T = \frac{1}{2} i^2 \frac{dL}{d\theta} \tag{3}$$

3. PWM Strategy for SRM

In SRM the turn-on angle α_{on} and turn-off angle α_{off} can be controlled as well as the duty-cycle D [1]. The duty-cycle is normally controlled at low speed in order to reduce the current flow in the SRM. At higher speed the current is limited by the back-emf and there is no need for using different duty-cycles. Instead the turn-on and turn-off angles are controlled.

Several methods have been proposed to reduce the acoustic noise in SRM by modulation technique. The first method is to vary the switching frequency randomly. The second one is to change between lagging edge and leading edge modulation. The other method is randomly to vary the turn-on angle α_{on} and turn-off angle α_{off} within 1° - 3° as shown in [1]. However, those methods only give a small reduction in the acoustic noise emission. The proposed method is a combination of the random PWM technique and varying turn-on and turn-off angle that reduces the acoustic noise significantly. In this section, PWM strategies are shown and discussed for various methods.

3.1 Conventional Methods

Conventional method is shown in figure 2 that using PWM technique with fixed turn-on and turn-off angle.

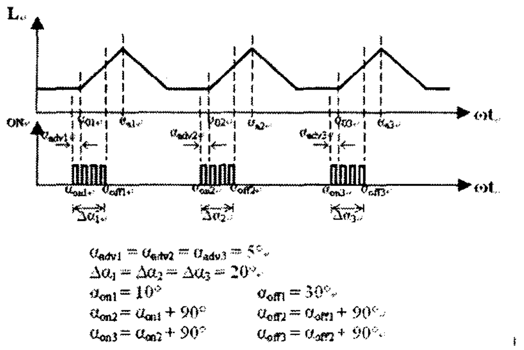


Fig. 2 Conventional method with chopping mode

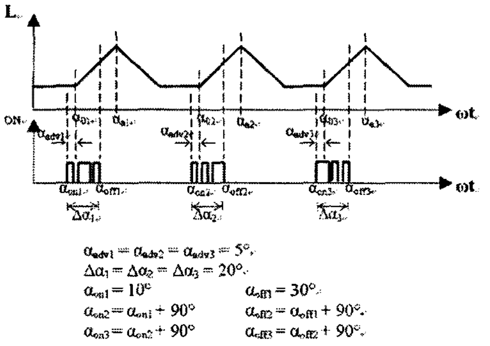


Fig. 3 Conventional method with RPWM technique

In figure 2 the angle α_0 is the angle where the rotor and stator pole starts overlapping physically, α_a is the aligned angle where the rotor is totally overlapped by the stator, α_{adv} is the advance angle (α_{adv} is plus if α_{on} is smaller than α_0 and conversely α_{adv} is minus) and Δ_α is the total conduction angle (α=0° is the rotor position that the axis the rotor slot is aligned with that of the stator pole of the conducted phase). This method is the conventional control method for SRM with disadvantage the emitted acoustic noise and the higher torque ripple.

Another method that can reduce acoustic noise is shown in figure 3. This method employs random PWM technique while turn-on and turn-off angle are fixed. A random generator is generated by linear congruential generator (LCG) [4] using random pulse position (RPP) scheme.

3.2 Proposed Random PWM Method

Proposed method is a combination of the random PWM technique and varying turn-on and turn-off angle. The random strategy is then to vary the turn-on angle α_{on} and turn-off angle α_{off} randomly according to α_0 and α_a within Δ_α from 1° to 3° while Δ_α is kept constant.

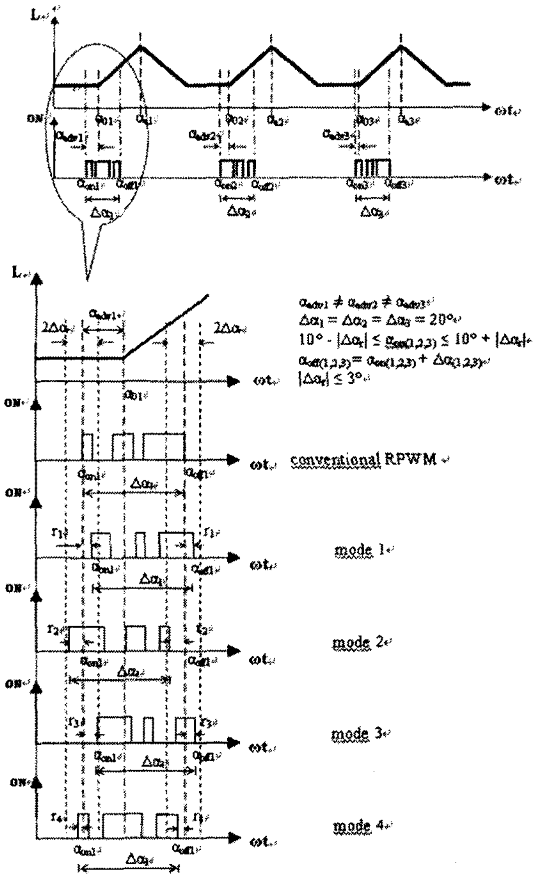


Fig. 4 The proposed RPWM method

The basic principle of the strategy is shown in figure 4. In figure 4 the mode 1, 2, 3, 4 are practical cases for random the turn-on angle α_{on} and turn-off angle α_{off} and r is random angle value from 1° to 3°. The random generator is easy to implement by LCG as mentioned above. The advantage of this new method is to reduce acoustic noise significantly.

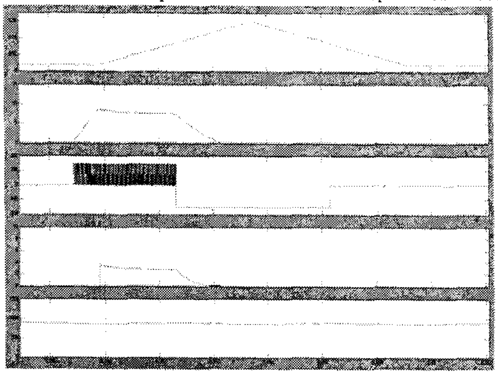
4. Simulation Results

In this section, simulation results are presented and compared for various strategies. A switched reluctance machine prototype are used for the 6/4 SRM shown in table 1. The simulation shows that combination of random turn-on, turn-off angle technique with random PWM technique reduce the emitted acoustical noise significantly.

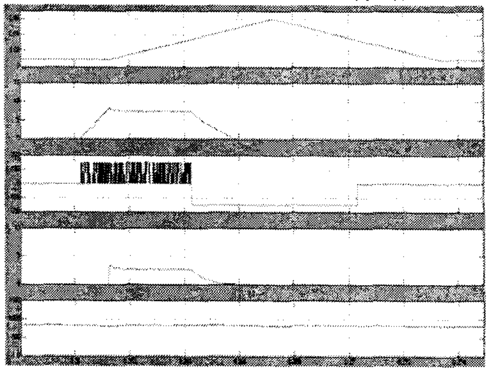
Table 1: SRM Parameters

number of phases, m	3
number of stator poles, N_S	6
number of rotor poles, N_R	4
nominal phase resistance, R_m	1.3 Ω
nominal aligned inductance, L_a	60 mH
nominal unaligned inductance, L_u	8 mH
DC bus voltage, V_{bus}	150 Vdc

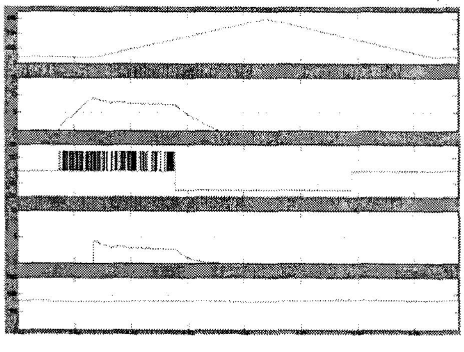
Figure 5 shows the waveform of one phase at switching frequency (f_{sw}) 6 kHz for each method. In figure 5a the first waveform is inductance profile. The second is phase current. The third is phase voltage. The next is torque. And the final is speed of motor.



a) Conventional method with chopping mode



b) Conventional method with RPWM technique



c) The proposed random PWM method

Fig. 5 Waveform of inductance, phase current, phase voltage, torque and speed at 800 rpm

To fully explore the merits of the new method, figure 6 illustrates harmonic spectrum of phase voltage. As shown in Fig. 6a for conventional method, the amplitude of the all components is more dominant than that as shown in Fig. 6c for proposed method. Sub-harmonics in area (a) of figure 6c are smaller than these of figure 6a and 6b. In addition, in Fig. 6c for the proposed method, the dominant harmonic cluster at frequency around 19 kHz (area (b)) is dramatically reduced in comparison with Fig. 6a and Fig. 6b for conventional method.

Furthermore, for evaluating the random PWM technique, a simple indicator of quality of voltage spectrum would be useful. For this purpose, the concept of statistical deviation can be employed and the Harmonics Spread Factor (HSF) [4,6] is defined as,

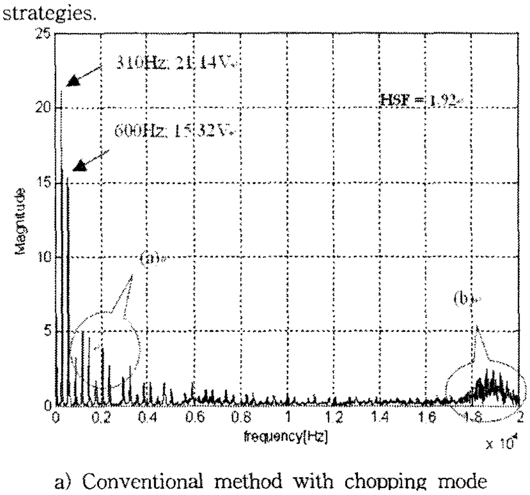
$$HSF = \sqrt{\frac{1}{N}\sum_{j>1}^{N}(H_j - H_0)^2} \tag{4}$$

where N denotes the total number of frequency components considered, Hj is the amplitude of the jth component, and H_0 is the average value of all components and given by,

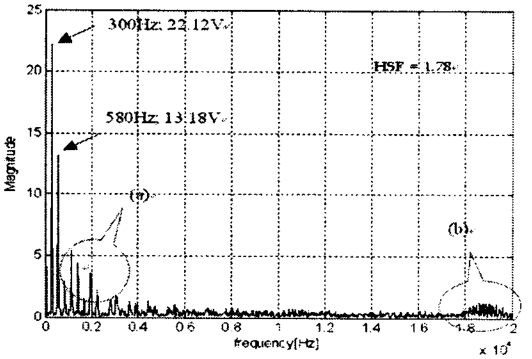
$$H_0 = \frac{1}{N}\sum_{j>1}^{N} H_j \tag{5}$$

The HSF quantifies the spread spectra effect of random PWM and it should be possibly small. For an ideally flat spectrum of white noise, the HSF would be zero. This HSF are shown in figure 6. The HSF of the proposed method reaches at 1.61 lower than those of the conventional method.

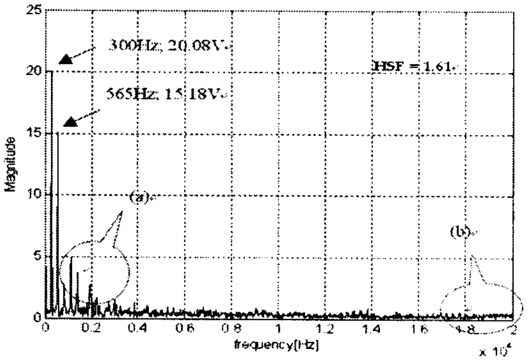
Figure 7 shows acoustical spectra in the whole operation area of the 6/4 SRM for different switched frequency. In comparing these results, it can see that acoustic noise is reduced significantly when using random modulation. It is clear that, as expected, the proposed strategy results in a significant improvement in the acoustic noise reduction relative to other strategies.



a) Conventional method with chopping mode

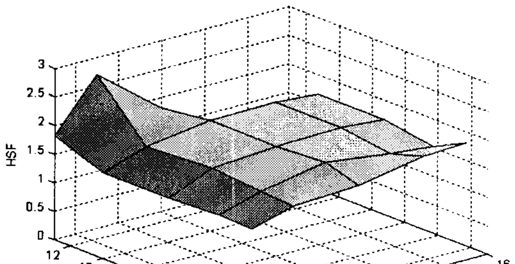


b) Conventional method with RPWM technique

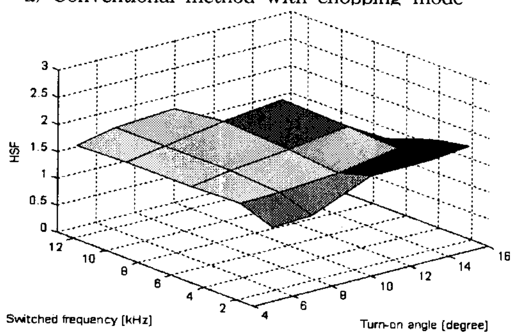


c) The random PWM method

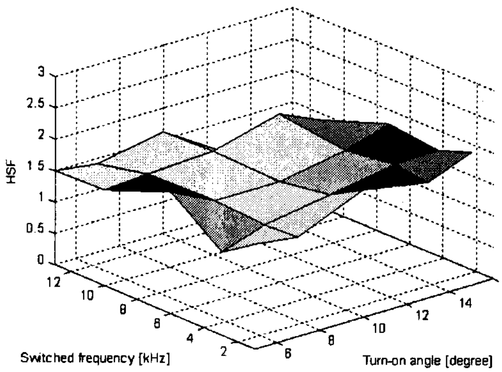
Fig. 6 Harmonic spectrum of voltage at frequency spans 0 - 20 kHz



a) Conventional method with chopping mode



b) Conventional method with RPWM technique



c) The random PWM method

Fig. 7 Calculated acoustical spectra for different switching frequency.

5. Conclusions

This paper has discussed implementation techniques for various random PWM and random turn-on, turn-off angle strategies in switched reluctance machine (SRM). The proposed random technique has been compared with the conventional methods, to analyse their influence on acoustic noise reduction. The HSF is used to evaluate the random PWM technique. Simulation results demonstrate that the new proposed strategies provide better harmonic spectrum performance than conventional strategies in spreading the harmonic power over a wide frequency range. Thus, acoustic noise in SRM is reduced significantly.

Acknowledgments

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