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A Simplified Torque Ripple Reduction using the Current Shaping of the Flux Switched Reluctance Motor

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Recently, applications of the reluctance torque motor have been quite limited due to their inherent limitation of noise and vibration and thus, researches on the reluctance motor have been limited as well. However, with the tremendous increase in the cost of rare earth material magnets, studies of the reluctance torque motor are being conducted more and more. In principle, reluctance torque is generated when the inductance is changed. Therefore, in order to generate continuous torque in the switched reluctance motor, it is necessary to figure out the exact inductance level corresponding to the rotor position and the current level to be applied in that rotor position, respectively. If the current level or the rotor position is not accurately determined, then the generated reluctance torque becomes unstable and undesirable torque ripples prevail to eventually cause noise and vibrations. In this research, a flux switched reluctance motor (FSRM), which is classified into the switched reluctance motor (SRM), was studied. A methodology using the current shaping control according to the rotor position was proposed. Based on the proposed methodology, the optimal current waveform and the torque distribution function for the FSRM to minimize torque ripple was established and demonstrated in this paper.

Keywords : flux switched reluctance motor (FSRM), torque distribution function (TDF), advanced angle, torque ripple

1. Introduction

The FSRM is a type of SRM motor, which has permanent magnets inserted in the stator to increase air gap flux and eventually produce higher output torque. With the permanent magnets inserted in the stator, it provides advantages such as easy manufacturing and reliability in the high speed operation without any concerns about magnet breakaway from the rotor [1, 2]. On the other hand, due to the permanent magnet flux that is fixed in a certain direction regardless of the rotor position, back electromotive force (EMF) becomes asymmetric. This creates difficulty with regards to formulating the current command according to the rotor position for the constant torque output. It is very difficult to operate the motor with a low torque ripple. A number of researches have suggested methodology to reduce torque ripple and have reported positive results for the reduction of torque ripple in SRM through the enhanced control of the commanding current [3-5]. However, if the same current control method is applied to FSRM, the torque output from the motor fluctuates more than anticipated mainly due to the asymmetry of the back EMF and thus, the noise and vibrations become serious issues resulting from the rapidly fluctuating torque output [1]. In this paper, a methodology for the reduction of torque ripples in FSRM is introduced as follows. Firstly, FSRM is carefully designed and analyzed with a finite element method (FEM) in order to estimate the torque outputs along with the back EMF. Secondly, these results are fed into a torque controller Simulink® model to obtain current shapes and optimal TDF among phases for the best possible reduction of the torque ripple. Finally, experimental results are provided as well.

2. Characteristics of FSRM

2.1 Design of FSRM

FSRM utilizes reluctance torque from saliency and magnetic torque from permanent magnets. Therefore, specific designs for each FSRM are different from each

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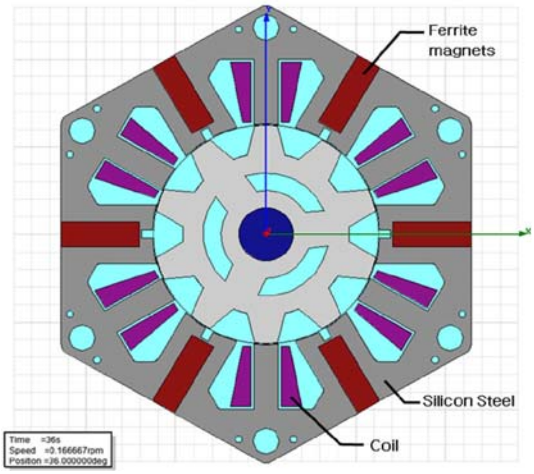


Fig. 1. (Color online) Cross section of FSRM.

other based on the applications under consideration. In this paper, an FSRM with 10 poles is designed and illustrated in Fig. 1. As shown in the figure, the motor has a double saliency structure where the rotor and the stator both have the saliencies. The stator has 6 slots and in between the slots, permanent magnets are inserted for each slot. Just as expected, due to the permanent magnets inserted in the stator, the back EMF signals become highly distorted and asymmetric and thus contribute to the creation of severe torque ripples resulting in uncomfortable levels of noise and vibrations. Such non-linear behaviors of the back EMF signals and the inductance distributions in respect to the rotor position make it quite difficult to come up with closed functional forms to represent themselves. In Fig. 2, the back EMF signals from phase b and c, the electrical angle and the dwell angles to drive typical SRM are displayed for reference. The inductance distribution for the FSRM design in respect to the rotor positions are plotted in Fig. 3. These values are obtained through the FEM for each current value as indicated in the figure. As shown in Fig. 3, the

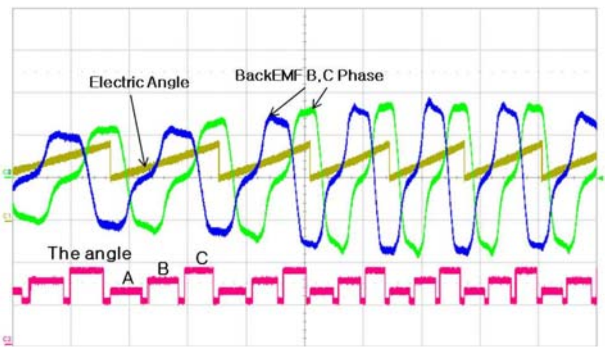


Fig. 2. (Color online) Back EMF signals, electrical angle and dwell angles of FSRM.

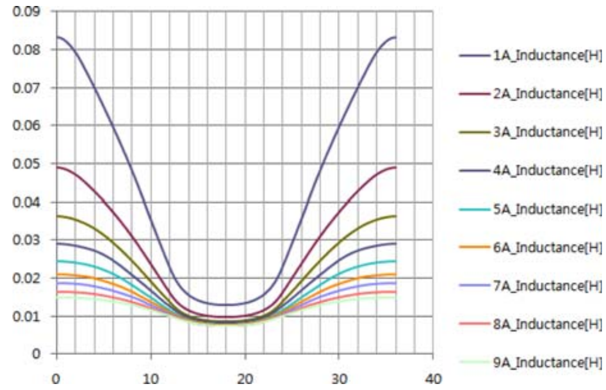


Fig. 3. (Color online) Inductance distributions according to rotor position.

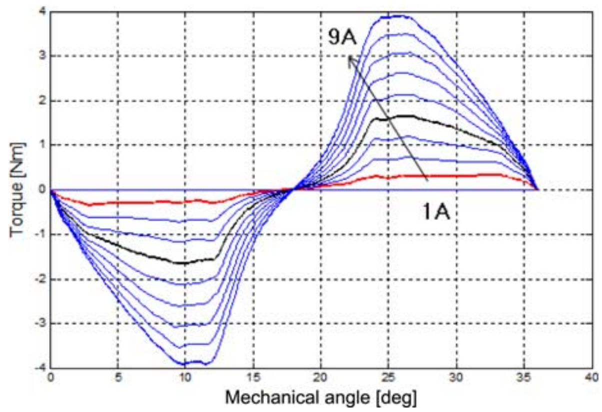


Fig. 4. (Color online) Torque distributions according to rotor position.

inductance distributions of the current FSRM demonstrate some non-linearity to a certain degree. Nonetheless, the overall characteristics of the inductance distributions are similar to those of a typical SRM.

3. Torque Ripple Reduction

As previously mentioned, due to the characteristics of the FSRM, the behaviors of the motor parameters cannot be readily represented in closed functional forms for the purpose of torque control. Therefore, it would be far more effective to prepare sets of commanding current patterns for each rotor position to produce the constant torque output in reverse order. In order to implement the proposed approach, namely to obtain the commanding current patterns to produce the torque outputs in which the ripples are minimized, the FSRM under consideration was modeled with Simulink® from Matlab®. This FSRM toque control was repeatedly executed to generate the commanding current patterns for each phase in order to achieve constant torque outputs. Also, a TDF table is prepared and

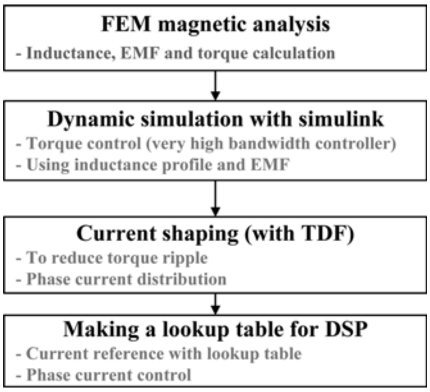


Fig. 5. A procedure to obtain the phase current shape for minimizing the torque ripple.

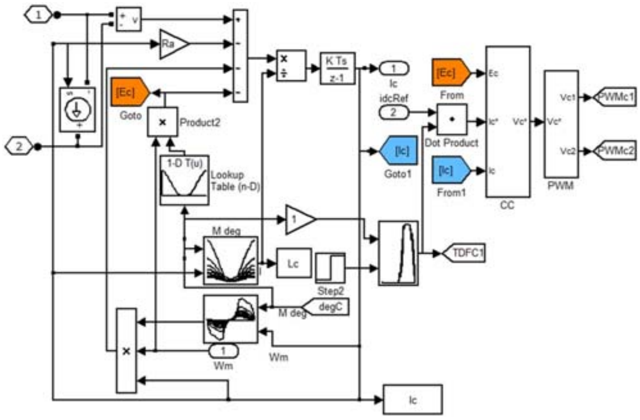


Fig. 6. (Color online) Simulink® model of the FSRM.

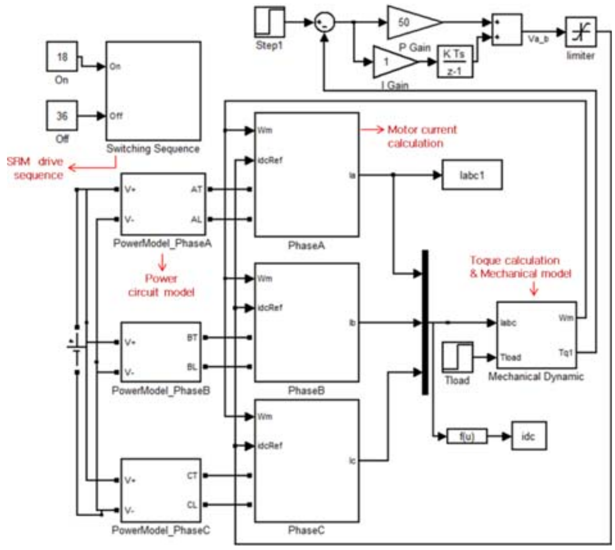


Fig. 7. (Color online) Simulink® model for the FSRM and system.

optimized to balance the torque productions from each phase in respect to the rotor position. Ultimately, the combined torque outputs in the shaft with the minimized torque ripples are achieved through the application of the commanding current multiplied by the TDF in respect to each rotor position. Later on, these commanding current patterns and the TDF are imbedded in the torque controller to produce the stable and constant torque outputs in the experimental validation test. In Fig. 5, the proposed procedure to reduce torque ripples is shown.

3.1 Simulink® Modeling

Using the tables of the inductance and the back EMF signals obtained from FEM analysis, a dynamic simulation model of the FSRM was implemented with Simulink® Matlab®. Torque is calculated with the nonlinear inductance profile and the back EMF table. The torque and the motor phase currents are calculated with Eqs. (1)-(4). According to the rotor position, the excitation phase is determined and the function of torque distribution is used for 2-phase excitation.

In the simulation, the commanding current values of the controller for the constant torque outputs are saved and in turn, the commanding current patterns for each armature phase are identified for continuous torque output.

A power electronic circuit, a controller and a corresponding mechanical system for the current FSRM is modeled with Simulink® Matlab® as well. In this power electronic model, the motor currents are fed back to the IGBTs to implement the free-wheeling effect and the H/W was also built, respectively. The inductance profiles and torque signals for each rotor position are tabulated in order to accommodate the non-linear characteristics of the FSRM.

The following equations are used in the current modeling for FSRM in regards to the mechanical system and the electrical system. With these equations, a Simulink® model for the commanding current analysis of the FSRM was developed as shown in Fig. 6 and a Simulink® model for the overall mechanical motor driving system of the FSRM was implemented as illustrated in Fig. 7.

$$T_e - T_{load} - B\omega = J\frac{d\theta}{dt} \tag{1}$$

$$i_\alpha = \frac{1}{L}\int\left(V_\alpha - R_\alpha i_\alpha - i_\alpha \omega_m \frac{dL}{d\theta} - e_\alpha\right)dt \tag{2}$$

$$e_\alpha = k_e \phi_f \omega_m \tag{3}$$

If $k_e = 1$ then $e_\alpha = \phi_f \omega_m$ therefore,

$$i_\alpha = \frac{1}{L}\int\left(V_\alpha - R_\alpha i_\alpha - i_\alpha \omega_m \frac{dL}{d\theta} - \phi_f \omega_m\right)dt \tag{4}$$

Where, T_e, T_{load}, B, ω, J, θ are motor torque, load torque, motor speed, inertia, and rotor angle, respectively. And e_α, k_e, ϕ_f, ω_m, i_α, V_α, R_α, L are emf, emf coefficient, magnetic flux , motor speed phase current, phase voltage, motor resistance and inductance, respectively.

3.2. Extraction of Current Patterns through Torque Controller

In order to obtain the current shape to minimize the torque ripples, a torque controller is implemented. The controller gain was set to ensure the rapid response characteristics to a specific torque command. During this torque commanding, torque values in respect to a specific rotor position for each phase were calculated in proportion and the commanding currents were distributed to the adjacent phases accordingly. Results of the current, the TDF and the torque from a single phase obtained from the described analysis are provided in Fig. 8. Mainly due to the high response setting in the torque controller, higher harmonics are heavily imbedded in the commanding current signal as noted in Fig. 8. With this control strategy, the torque ripple was drastically reduced although it was not removed completely.

3.3 Application of Advanced Angle

Careful observation of Fig. 8 would reveal that the torque control did not function properly during the current off period. This phenomenon can be explained with the slow current response due to such a high inductance in the power electronic circuit. As shown in Fig. 9 for further investigation, it was monitored that the reverse torques were developed periodically from each phase for the same reason. In order to accommodate and compensate for this generation of reverse torque, it was necessary to apply the current shape with a certain advanced angle. Three different cases were evaluated with the advanced angles of 5°, 10° and 20° and results for those three cases

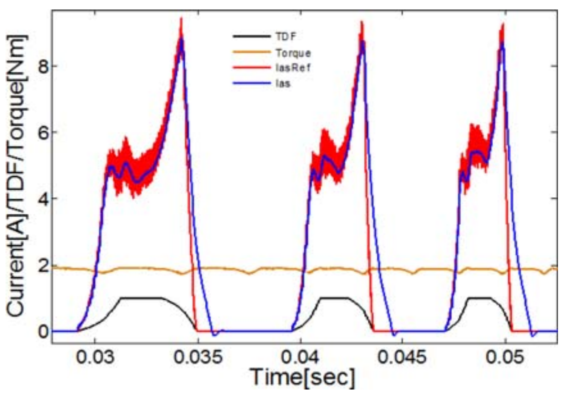


Fig. 8. (Color online) Simulation results to minimize torque ripples (current, TDF and Torque).

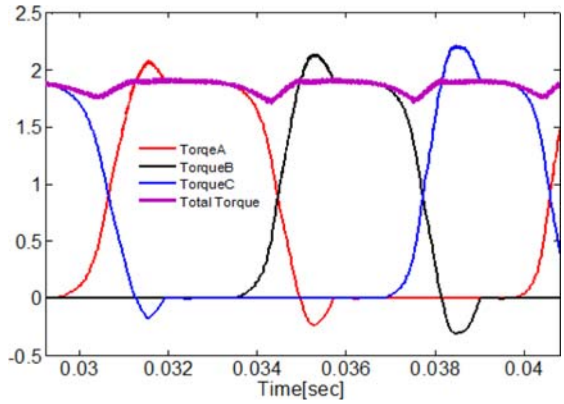


Fig. 9. (Color online) Torque output before the application of advanced angle.

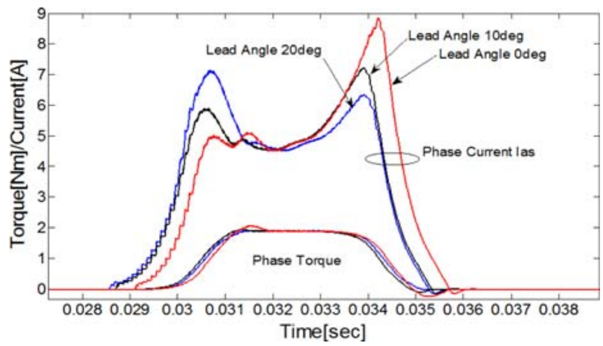


Fig. 10. (Color online) Torque output according to the advanced angle of 5°, 10° and 20°.

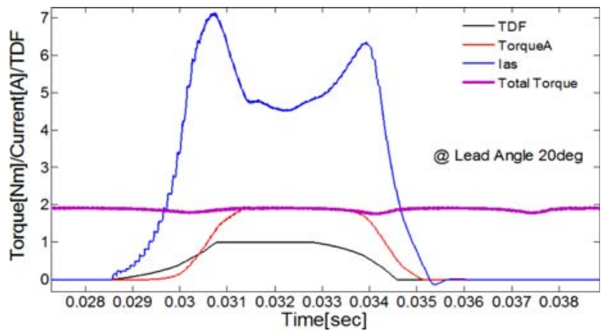


Fig. 11. (Color online) Torque output with the advanced angle of 20°.

were provided in Fig. 9. With the advanced angle of 20°, the reverse torque was found to be near zero as shown in Fig. 10.

As a result of the application for the advanced angle, the commanding current pattern has changed quite differently from the original pattern. Coincidentally, the maximum commanding current for the phase was reduced and became less affected by the high inductance of the system. As illustrated in Fig. 11, the torque output revealed a significant reduction in torque ripples.

Fig. 12. (Color online) FSRM torque ripple measurement on the dynamometer.

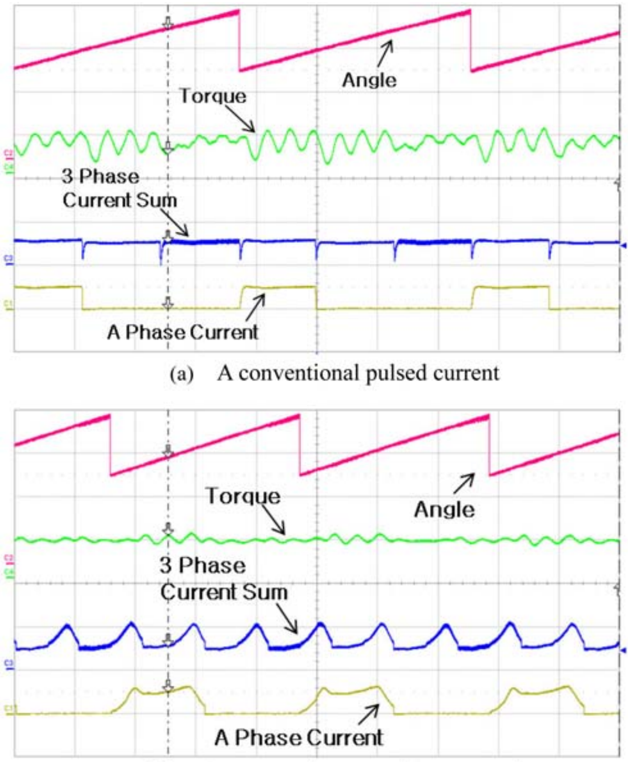
3.4. Validation of Torque Ripple Reduction of the FSRM

A dynamometer with a 3 phase permanent magnet synchronous motor (PMSM) equipped with a torque sensor is prepared to experimentally evaluate the torque ripples of the developed FSRM and to validate the torque ripple reduction methodology for the FSRM. In order to minimize the torque ripples propagated from the load motor, the PMSM with torque ripples of less than 1% and the back EMF THD of less than 1% were used for this validation experiment. The experimental setup for the FSRM torque ripple measurement is shown in Fig. 11. The load PMSM was used as a generator and by consuming the generated electrical energy with the resistive load, the load torque was provided to the driving FSRM motor under the evaluation.

The FSRM was operated at 700 rpm with a rated torque output and the torque ripple was measured. The commanding current pattern from the torque controller was processed with the TDF, and then the method regarding the advanced angle of 20° was applied. The results for the final torque outputs were measured with an oscilloscope through A/D conversion of the torque sensor signal. The results of the torque ripple measurements from the conventional pulsed current control method and the newly proposed current control method are provided in Fig.

Table 1. Specifications of FSRM and Driver.

Items	Value
Motor Rated Speed/Max	700/12,000 rpm
Motor Torque	1 Nm
DC Voltage	300Vdc
IGBT	600V/20A
Switching Frequency	20 kHz



(a) A conventional pulsed current

(b) The proposed current shape control

Fig. 13. (Color online) Test results of torque ripple (Angle [0-2π], Torque [Nm/div], Phase Current [5A/div], Current Sum [5A/div]).

13(a), (b).

For both experiments, the commanding current patterns were applied to produce the torque of 1.0 Nm. Based on results from the current validation experiments, the newly proposed control method achieved the torque ripple reduction of approximately 65.5% compared to the torque ripple from the conventional pulsed current control method. While this achievement in was quite phenomenal, the torque ripple was not removed completely. One of the reasons can be explained as the difference in the back EMF from each phase existing due to the motor manufacturing process.

4. Conclusion

In this research paper, a very effective torque ripple reduction methodology for the FSRM, which typically has high torque ripples due to distorted and asymmetric back EMF signals, is suggested and the results from the validation experiments are provided. One of inherent issues in the proposed method is to compose the commanding current using the current patterns imposed with the higher harmonics. In other words, a certain limitation in the proposed torque ripple reduction method would exist at high speed operation due to the limitation of the current response characteristics. Generally, the Inverter switching frequency is less than 20 kHz in the industry applications so that the current controller has a limited cut off frequency. Also, for the 3 phase SRM, the overlapped period of the torque between phases is not long enough and therefore, it is expected to have a certain limitation in the torque ripple reduction effect. However, it is fully expected to have a significant torque ripple reduction for the case of 4-phase SRM. Furthermore, for motors with a low number of poles and for the case of relatively low speed operation where the current response characteristics are reasonably favorable, it is fully anticipated to provide noteworthy torque ripple reduction effects.

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References

[1] T. H. Kim, Ph.D. thesis, "A Novel Design Method for Flux-Reversal Machine and Characteristics Analysis under PWM Drives", Hanyang University, Korea (2005).

[2] Y-H. Kim, H-S. Lyoo, and J. Lee, "Advanced Torque Control of Switched Reluctance Motor", IEEE International Symposium on Industrial Electronics, **3**, pp. 1798-1803 (2001).

[3] A.M. Stankovic, G. Tadmor, and Z. Coric, "Low Torque ripple control of current-Fed Switched Reluctance Motors", IEEE Industrial Application Society Annual Meeting, pp. 84-91 (1996).

[4] K. Russa, I. Husain, and Elbuluk, "Torque Ripple Minimization in Switched Reluctance Machines Over a Wide Speed Range", IEEE Industrial Application Society Annual Meeting, New Orleans, LA. pp. 668-675 (1997).

[5] I. Husain and M. Ehsani, IEEE Trans. Power Electron. **11**, 83 (1996).