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Improving the Characteristics of Switched Reluctance Motor

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Abstract

Switched reluctance motor (SRM) has outstanding advantages such as simple structure, absence of commutator, high torque. However, torque ripple and loud noise are the biggest disadvantages of this SRM. Thus, applications in some special areas in industry are restricted. To reduce torque ripple and improve output power, this article provides solutions for control and change the structure of SRM. At the same time, it also proposes a new solution: using of new materials – amorphous materials in manufacturing rotor and stator instead of normal Silicon steel materials. With special physical properties, the amorphous materials used in motor manufacture give a greater speed and lower loss.

Keywords: *switched reluctance motor, torque ripple, amorphous materials.*

Nomenclature

AMN	Associative Memory Networks
APC	Angular Position Control
CCC	Current Chopping Control
CVC	Voltage Chopping Control
FEM	Finite Element Method
PI	Proportional Integral
PID	Proportional Integral Derivative
PWM	Pulse Width Modulation
RBF	Resting Bitch Face
SMC	Sliding Mode Control
SRM	Switched Reluctance Motor
TSF	Torque Share Function

1. Introduction

Switched reluctance motor (SRM), a type of simple structure motor, was proposed since 1842. However, SRM operates under the principle of switching electric current for each phase, so it was very difficult to control SRM at that time. By the 80s, with the rapid development of power electronics, microprocessors and control technology, SRM started becoming the choice for high speed control systems.

Switched reluctance motor has the advantages such as: simple structure, high reliability, the motor can work at an extremely fast speed. Thanks to permanent magnet and winding are absent in the rotor, the rotor temperature can be higher than other types of motor. Torque direction doesn't depend on current direction, so can simplify the inverter, reduce the cost of the system. As there isn't overcurrent that can damage the capacity valve in SRM, the inverter has a high reliability. Big starting torque, high speed controlling performance, there is no impact of the current in the induction motor at the time of starting. Magnetic circuit of motor can work in the linear region and the saturation of the B-H magnetic characteristic curve, using the maximum capabilities ferromagnetic materials, power ratio with weight is large. With the above advantages, SRM is widely used in industry and some specific sectors such as manufactured generators for aircraft launch, the centrifuges require high speed, dynamic the submarine base with large startup torque, etc.

However, due to salient pole structure of rotor such motor flux has strong non-linearity, torque ripple is large and highly noise. Therefore, in some cases, the applications of SRM are limited. In order to overcome these restrictions of torque ripple and improve the quality of motor, based on analysis, comparison and summarization of domestic and international relating documents, the authors of this article have figured out some solutions to reduce torque ripple including solutions of controlling and solutions of changing motor structure. At the same time, the authors also proposed a new solution - using new materials in the motor manufacturing to improve the characteristics of this switched reluctance motor.

2. Mathematical model of switched reluctance motor

2.1. Voltage equation

Survey of SRM operating status requires a mathematical model. Since SRM is a non-linear system, it demands a suitable model which represents the dynamic process in various operating conditions. Assuming the phase of the motor including: resistance of winding R, inductance L(i, θ), the voltage u supply to the phases by total voltage drop and the rate of flux ψ(i, θ), effects of mutual inductances can be neglected, Faraday's law gives:

$$\frac{d\psi(i,\theta)}{dt} = -iR + u$$

$$\leftrightarrow u = Ri + \frac{d\psi(i,\theta)}{dt} \quad (1)$$

where $\psi(i,\theta) = L(i,\theta)i$ (2)

Switched reluctance motor structure is symmetrical so flux circulation cycle $2\pi/n_R$ (n_R is the number of rotor poles). Hence, there are two concepts to be distinguished: mechanical angle θ and electrical angle ($n_R\theta$). Mechanical angle indicates the rotation angle of the rotor position, electrical angle shows angle calculating phase current and voltage. Voltage equation can be rewritten in the form of electrical angle as follows:

$$u = Ri + \frac{d\psi(n_R\theta, i)}{dt} \quad (3)$$

Consider the three phase motor, each phase mismatches of a electrical angle: $\theta_s = \frac{2\pi}{3n_R}$. Continue to ignore mutual inductance, equations for the phase voltages are as follows:

$$\begin{cases} u_a = Ri_a + \frac{d}{dt}\psi(n_R\theta, i_a) \\ u_b = Ri_b + \frac{d}{dt}\psi(n_R(\theta-\theta_s), i_b) \\ u_c = Ri_c + \frac{d}{dt}\psi(n_R(\theta-2\theta_s), i_c) \end{cases} \quad (4)$$

2.2. Torque equation

In any rotor position of a phase, according to the principle of total of magnetic energy, the torque formula of the SRM is calculated as follows:

$$T(i,\theta) = \frac{\partial W^{'}(i,\theta)}{\partial\theta} \quad (5)$$

θ is rotor azimuth
i is phase current
$W^{'}(\theta, i)$ is the total of magnetic energy

Total of magnetic energy is defined as the area under the curve of magnetization shown in Figure 1, it can be expressed as follows:

$$W^{'}(\theta,i) = \int_0^i \psi(\theta,i)di \quad (6)$$

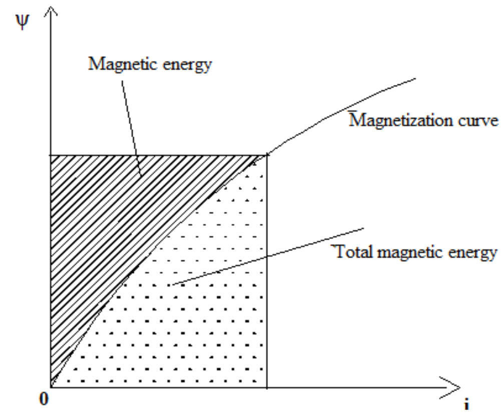


Figure 1. The chart outlines the total magnetic

In certain cases, SRM is not affected by magnetic saturation and inductance is independent of electric current, depends only on rotor position (2), the torque generated as follows:

$$T(\theta,i) = \frac{1}{2}\frac{\partial}{\partial\theta}\int_0^{i^2} L(\theta,i)di^2 \quad (7)$$

If L changes linearly with rotor position, torque equation is as follows:

$$T = \frac{1}{2}i^2\frac{dL(\theta,i)}{dt} \quad (8)$$

Torque of three phase motor equal to total of phases torque: $T_e = T_a + T_b + T_c$.

2.3. Mechanical equation

According to the torque balance theorem of motor:

$$T_e - T_l = J\frac{d\omega_m}{dt} + B\omega_m \quad (9)$$

T_e is total torque
T_l is load torque
Ω_m is speed
J is inertia torque
B is constant friction

Based on three equations above, we can build model of switched reluctance motor. This model based on the change of voltage equations:

$$\begin{cases} \frac{di_a}{dt} = \frac{-Ri_a - \frac{\partial}{\partial\theta}\psi(n_R\theta, i_a)n_R\omega + u_a}{\frac{\partial}{\partial i_a}\psi(n_R\theta, i_a)} \\ \frac{di_b}{dt} = \frac{-Ri_b - \frac{\partial}{\partial\theta}\psi(n_R(\theta-\theta_s), i_b)n_R\omega + u_b}{\frac{\partial}{\partial i_b}\psi(n_R(\theta-\theta_s), i_b)} \\ \frac{di_c}{dt} = \frac{-Ri_c - \frac{\partial}{\partial\theta}\psi(n_R(\theta-2\theta_s), i_c)n_R\omega + u_c}{\frac{\partial}{\partial i_c}\psi(n_R(\theta-2\theta_s), i_c)} \end{cases} \quad (10)$$

3. Solutions to improve the characteristics of switched reluctance motor

Switched reluctance motor torque ripple is really complicated and affected by many factors. Therefore, to reduce torque ripple, strategic solutions to be given are using SRM control method with definite motor structure and parameters [1] or changing motor structure. In this paper, the authors have presented, analyzed and compared with domestic and international researches relating to reduction of torque ripple and improvement of SRM characteristics.

3.1. Solution using control method of switched reluctance motor

According to equation (1) and (8), motor control method can be performed by current control i, or adjust angle θ. These are two important parameters to calculate the voltage and torque of SRM.

3.1.1. Traditional control strategy

There are three ways in typical traditional control including angular position control (APC), current chopping control (CCC) and voltage chopping control (CVC).

The angular position of the control means at a certain voltage across the winding provided by changing θ_{on} and θ_{off} of main switch to change power-on and power-off. Thus, to control closed loop speed, it needs to adjust the phase current waveform signal. Opening angle θ_{on} and off angle θ_{off} can be revised, however in fact, we often have to fix θ_{off} and change θ_{on} according to control mode. θ_{on} and θ_{off} must be adjusted separately, then SRM is able to achieve optimum operating angle position control (APC) mode. There are some advantages of this control method such as greater torque adjustment range, multi phase windings simultaneously powered, high motor efficiency, suitable for higher speeds but unsuitable for low speed operation.

Current chopping control is mainly used for motor running at low speed. Because of increasing rapidly of the current, in order to avoid damage caused by current pulse, it requires to limit the peak current. This control method rarely involves θ_{on} and θ_{off} control, so select the position of each phase winding's conduction to control the current by chopper. The main advantages of this control method are simplicity and accuracy, reduction of torque ripple, suitable for the low speed operation of fixed load motor.

Voltage chopping control means keeping θ_{on} unchanged and changing θ_{off}, the power switching devices operate in pulse width modulation (PWM) mode. Keep the pulse period T fixed, simply adjust the duty cycle of the PWM waveform, thereby adjust the size of the voltage across the winding, which cause changes in winding phase current to achieve the regulation of motor speed. Advantages of the method are followings suitable for both high speed and low speed operation, enable quick adaptation to change of the load.

3.1.2. Torque distribution strategy

Torque distribution strategy shows that by defining the torque share function (TSF), electromagnetic torque corresponding to the current phase can be distributed reasonably to ensure each phase torque being at a constant value. Accordingly, phase current values can be calculated and combined with appropriate control strategies to reduce torque ripple.

Reference [2] proposes an optimized solution based on conventional torque distribution strategy to maximize the torque/ampere ratio within the allowable error range of torque ripple in adjusting the opening angle θ_{on} and off angle θ_{off} of SRM. Under the premise of guaranteed output torque, to achieve the optimal purpose, it is important to ensure lower the winding phase current. After testing, the results show that the optimized ratio of torque and current will improve the system performance.

For the SRM torque ripple, Reference [3] adopts the torque distribution based on controller to obtain the desired torque of each phase, and then synthesize the constant torque through each phase, effectively eliminate torque ripple.

Reference [4] combines the current torque distribution and current to achieve efficient suppression of the torque ripple. Up to a point, the method has achieved certain results, but choosing to divide torque has omitted necessary physical factors.

In order to extremely minimize the torque faults, reference [5] dissects the optimization by using flux linkage as optimized variables. With discrete method, the torque reducing problem is transferred into a mathematical programming issue. Its feasibility has been proved by simulation. But this method ignores the correlation between electromagnetic and winding.

3.1.3. Intelligent control

Intelligent Control is a type of control of which object is mathematical non-linear, its properties are strong self-learning ability and adaptive capacity. Applying the intelligent control theory in designing SRM controller is one of the effective ways to solve thorny issue of SRM meaning torque ripple reduction. Performance control of SRM is significantly improved

a. Fuzzy control

Typical application of fuzzy control is an adaptive fuzzy control strategy of minimum SRM torque ripple proposed by Sayeed [6].

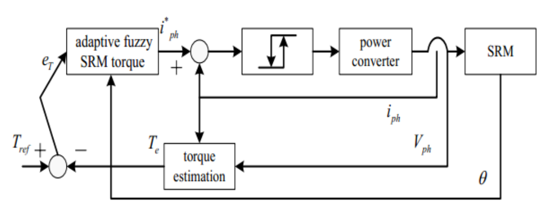


Figure 2. The block diagram of adaptive fuzzy torque control

Figure 2 shows the adaptive fuzzy SRM torque control system regarding position as an input, phase current as an output. Changing the membership function gave broken phases in the most appropriate area. The initial value of the fuzzy parameter is randomly selected. During the operation, the parameters are adjusted by the real time controller, able to adapt to the motor characteristics of any changes.

Reference [7] applies fuzzy neural algorithm constantly adjusting the size of the current compensation signal to optimize the phase current waveform and then to suppress torque ripple. Because of the difficulty in measuring the real time of the dynamic torque and expensive torque sensor, it is hard to apply this method.
Reference [8] through the fuzzy neural network speed controller determines the desired torque output, calculates the current value of each phase.
Reference [9] proposes a new method of mathematical modeling of a motor switched reluctance, based on the static inductance curve and torque - angle characteristic curve, apply the adaptive network based on fuzzy inference system to the whole modeling of SRM.

b. Neural network

Reducing torque ripple based on neural network was first proposed by JGO Donovan [10]. SRM non-linear characteristics, SRM torque - current - angle relationship are analyzed based on the knowledges, experiences of professional experts.
Reference [11] applies AMN (associative memory networks) neural network online to get the motor phase current waveform optimization. Disadvantages of this approach are expensive torque sensor, inaccurate measurements at high speeds and no torque feedback during normal operation.
Reference [12] proposes combination of traditional PID with neural network to make adaptive PID control applied for serious non-linear SRM. The non-linear transformation properties and parallel processing ability at a high degree of neural network made it suitable for the establishment of non-linear predictive model parameters to predict. Through predicting the parameters of the control system, the dynamic response performance of the system can be improved as shown in Figure 3. The results show that the system is stable, quick, accurate, strong anti-disturbance and easy control.

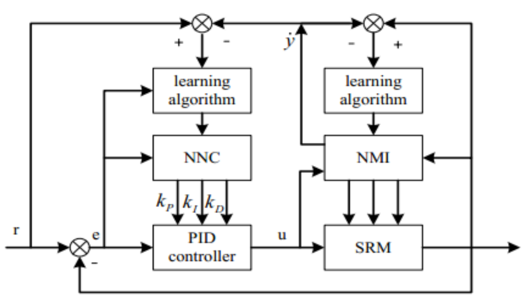


Figure 3. Block diagram of the non-linear model based on RBF neural network

Reference [13] proposes a SRM instantaneous torque control method which is based on radial basis function neural network. Using data generated from the SRM dynamic simulation for RBF neural network's offline training, learning to optimize current waveforms under different speed and torque, and then RBF network is used for controlling motor torque. Experimental results show that the control strategy can effectively reduce SRM torque ripple with high control accuracy, able to adapt to speed changes.

3.1.4. Sliding mode control

Reference [14] proposes a new method to minimize torque ripple of a switched reluctance motor, which is based on the control of the sum of the square of the phase currents by using only two current sensor and analog multipliers. In addition, the sliding mode control (SMC) technique has been applied to SRM speed control loop that compensates the low frequency oscillations on the torque output. The results show that the continuous sliding mode controller is effective compared to PI or Fuzzy controllers in reducing the torque ripple of the motor, compensating for non-linear torque characteristics and making drive insensitive to parameter variations as well, low frequency vibration in torque variation has been eliminated.

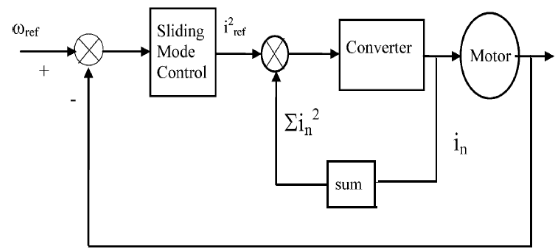


Figure 4. Block diagram for the speed control with SMC

In addition to the methods described above, the issue of SRM control to improve the work quality, reduce torque ripple which researchers overcome by the other control methods such as linearization control, Iterative Learning Control, Internal Model Control, etc.

3.2. Solution for change of switched reluctance motor structure

Equation (5) and (9) show the torque of motor directly affected by the magnetic flux density $\psi(i,\theta)$ which is closely related to the motor structure. Therefore, motor structural change solution is presented to improve torque characteristics and SRM performance.

3.2.1. Change the shape and size of stator and rotor pole

General purposes of designing switched reluctance motor is to maximize torque, reduce torque ripple by optimizing control manner and strategy. In terms of trade, however, the design target is not only to meet the requirements of torque at both low and high speed but also to reduce the cost of motor production. Reference [15] uses the finite element analysis method (FEM) to simulate the shape of SRM with many different configurations by changing the shape of stator and rotor poles.
Rotor is usually made of ferromagnetic materials (silicon). Ferromagnetic materials have a direct influence on making flux. The author changed iron ratio in the rotor (62%, 76%, 91%). In there, this rate of SRM rotor is 62% for max flux (0.031Wb). Thus, because of strong nonlinearities, inductance dependent of angle θ and current i, changing ferromagnetic materials rate in SRM rotor contributes only to optimize calculations in design while has not shown a

clear positive correlation between ferromagnetic materials rate and flux in the motor.

The resizing rotor and stator poles size related directly to the change in order to achieve the ratio γ (γ is the ratio between rotor pole angle and pole pitch) and β (β is the ratio between stator pole angle and pole pitch). The stator and rotor pole angles are important variables in SRM design, it affects to the motor torque and it also has been studied to find precisely range of the stator and rotor pole angle in practice. A parameter obtainedfrom generation ofresults in changing the poles is the ratio between the polar angle and pole pitch (pole pitch is the angle between two consecutive stator poles or rotors). Survey results in 3 phase SRM, reference [15], give the optimal value γ and β (γ = 0:38, β = 0.5) for the highest performance.

The advantage of this method is figured out the optimal parameter γ, β and torque increased. However, the torque also depends on many other motor configuration parameters; motor is only surveyed to stop at 3 phase SRM 6/4 poles and 8/6 poles, low speed range.

3.2.2. Change rotor and stator pole surface

The non-linear torque in the overlap region is the main cause of torque ripple. Also, the radial force is generated in the whole overlap area of stator and rotor poles and the tangential force is generated at the edges of stator and rotor poles, respectively. To reduce the fringing flux at the overlap angles, a rotor shape made by method of laminated layer of the asymmetry rotor is proposed [16], as Figure 4a. To have the asymmetry angles, the width of each steel sheet at rotor pole arc needs to be different. Research results conducted with SRM 12/8 poles show that the torque ripple was reduced by 15% against the initial SRM and increased by 12.5% compared with normal structures. However, switched reluctance motor was tested with quite small capacity, just 1.5kW.

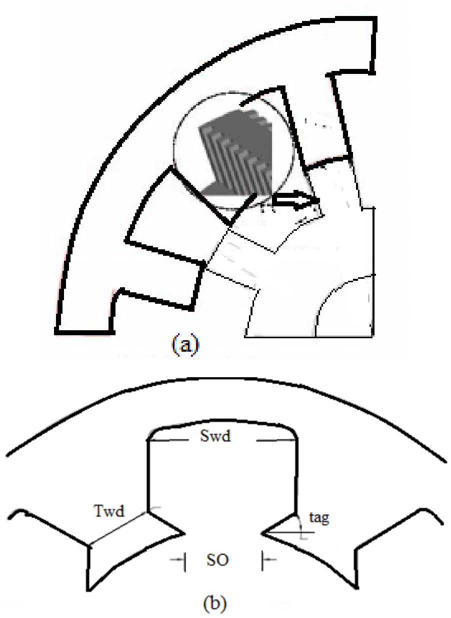


Figure 4. Surface structure of rotor pole (a) and stator pole (b)

Stator pole shape has been changed in the reference [17]. Stator pole surface is constructed in tip shape as shown in Figure 4b, flared wide at the tip to increase the amount of magnetic flux passing, the magnetic flux density exists in the stator poles increased, resulting in increased torque. The author used multi domain simulation environment (ANSYS workbench) to simulate the magnetic field, torque of switched reluctance motor.

3.2.3. Change the number of rotor pole

The number of stator pole in initial SRM is more than number of rotor pole (6/4, 8/6, 12/8, etc). However, 6/10 SRM introduced in reference [18] is a new motor concept, in which the rotor poles are more than the stator poles, focusing on creation of greater torque, improving torque density, reducing torque ripple while maintaining continuous thermal energy density. These advantages are thanks to structure of 6/10 SRM with pole pitch and rotor angle smaller than traditional structure. The more aligned positions between rotor and stator are created the more flux with maximum value increased.

The author has made a comparison of 6/10 SRM and 6/4 SRM about the flux in stator winding, thermal efficiency, torque density and torque ripple. With 6/10 SRM, torque performance increases (up to 119.82% compared with the 6/4 SRM). However, the winding temperature is more than 40% and torque ripple is not reduced.

Reference [19] showes the new structure of SRM with equal number of rotor poles and stator poles (6/6 pole). However, with such a structure of pole, the motor can not be started by itself. But this is also a special point because this motor uses only single phase. Thus, the system has a simple converter having two important roles: to improve the input power factor and to stimulate the motor phase. A test was conducted for 6/6 pole motor with rated power of 400 W and speed of 1800 rpm. However, this study is just applied for the survey of current and voltage during engine operation with the expectation of high performance at low cost of system.

3.2.4. Change the number of stator teeth

In principle, it is expected that increasing the number of teeth per stator pole may be increase more advantages, limit disadvantages and enlarge widely certain applications of switched reluctance motor. It seems generated torque has increased owing to increasing number of teeth, the losses in the motor are limited, particularly at high speeds. These losses are lower than that in SRM with only one tooth per stator pole. The first SRM with many teeth per stator pole which is 6 pole 3 phase 12/10 slotted motor with 2 teeth per pole stator. Other version of 4 teeth per stator pole is 3 phase motor with 22 tooth rotor and 24 stator teeth [20], as shown in Figure 5. Both these motors are designed with same frame size and air gap for easy comparison. The simulation result in two bands speed is 300 rpm and 750 rpm showing greater motor performance and high torque. However, at a speed of 300 rpm, 24/22 SRM has higher performance than 12/10 SRM; at speed of 750 rpm, the result is opposite.

Besides the methods described above, some researches continue to be made to improve the characteristics of SRM as adjusted inclined slotted, perforated on the rotor teeth, tilted stator pole, rotor, etc. Those methods have contributed to improve the work quality of the switched reluctance motor in certain cases, but the contribution in reducing torque ripple is not thoroughly made.

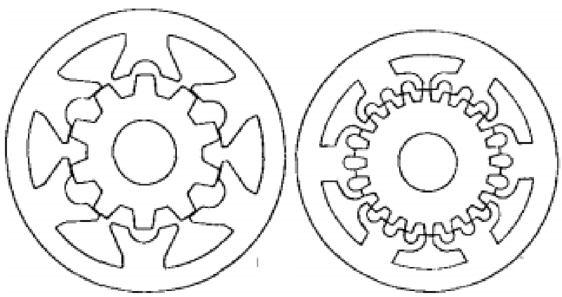


Figure 5. Stator pole structure many teeth

3.3. Propose a solution using new materials

Equation (2) shows the relationship between magnetic flux ψ with current i and angle θ. This flux curve is non-linear, depends on the materials of rotor, stator. In equation (5), (6), the effect of magnetization of materials to torque, torque ripple is quite clear. Therefore, changing the motor manufacturing materials is an effective solution in order to improve motor characteristics.

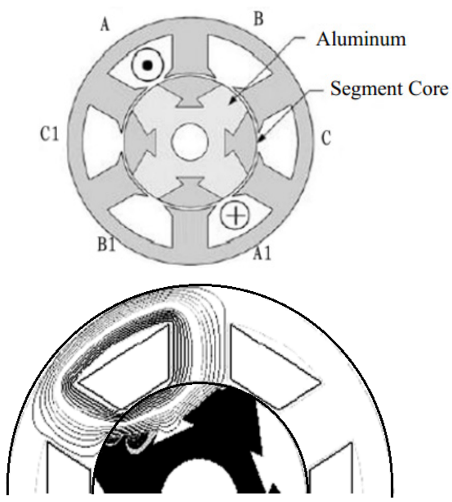
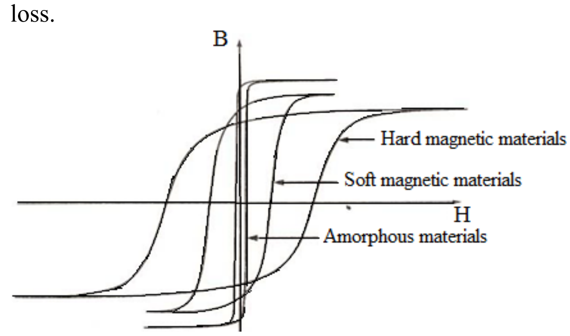


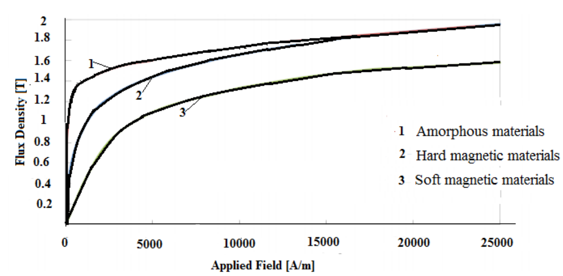
Figure 6. Rotor structure used aluminum materials and magnetic field lines

Currently, both switched reluctance motor in particular and other motor types in general use electrical steel in manufacturing rotor and stator. Electrical steel is a soft ferromagnetic, large magnetic permeability, small degaussing magnetic, low hysteresis loss (due to narrow magnetic hysteresis curve). However, ferromagnetic materials exists limitations such as low operating frequencies (silicon steel cores can be used only for low frequency, at high frequency, losses will be greater due to low resistivity of silicon steel), small coercivity force, etc. Moreover, due to the requirements of environmental protection and saving energy, reducing core losses and magnetic losses, the solutions using other materials instead of ferromagnetic materials started to be proposed.

Reference [21] gives a new type of SRM model used unibody aluminum for rotor core, the purpose is to reduce motor weight, as shown in Figure 6. At the same time, to create magnetism in the rotor, the magnetic core is embedded in the rotor blocks. This design has been used to make the low speed motor. The simulation results shows that torque did not significantly increase. due to the fact that the magnetic field lines didn’t go through the central rotor (rotor core made of aluminum) causing the low density of magnetic flux. However, thanks to removing the radial magnetic force, noise is significantly reduced.
Based on the results of research using new materials being low-iron-loss such as Super E-Core brand, reference [22] also made comment that strip steel has improved performance of the SRM and prevent steel loss.



Firgue 7. Magnetic hysteresis curves of magnetic materials



Firgue 8. Saturation of flux density with the different materials

Through the synthesis of researches on some new materials with good magnetic and high conductivity, authors have proposed solutions using new materials in order to replace conventional ferromagnetic material. This new material is amorphous alloys. Amorphous alloy is a kind of alloy made of iron or cobalt (Co), in the amorphous state, so its resistivity is much higher than crystalline alloy. At the same time, this material is resistant to corrosion, high mechanical strength, can be used at higher operating frequencies than crystal material of metal base. Without crystal structure of amorphous material permits elimination of, anisotropic so its properties is highly soft magnetic. Cobalt amorphous materials has magnetostrictive by 0 so it has a very small coercive force, can be compared with nanocrystalline materials. Magnetic hysteresis curve of this material is much narrower than silicon steel – soft magnetic materials (Figure 7). Natural thickness of the amorphous steel sheets is very small around ~ 0.03 mm compared with ~ 0.3 - 0.5 mm of silicon steel, resistivity greater ~ 130 - 170 $\mu\Omega cm$ compared with ~ 50 - 60 $\mu\Omega cm$ of silicon steel. Therefore, steel core loss reduced significantly compared with silicon steel. To demonstrate the effectiveness of the research results, the research team has developed the characteristic curves for evaluation that is described in figure 8. Thus, it is shown that amorphous steel is capable of spontaneous magnetization and long-lasting magnetizing energy which increased the magnetic flux density and improved motor torque (Figure 8). Moreover, amorphous material weight is very light useful for motor operation at much higher speed than normal motor. Analytical result shows that steel core losses in amorphous materials decreased by about 20% compared with silicon steel, magnetic flux density increased by over 12% and the motor speed can be up to 140% compared to the motor manufactured by conventional silicon steel. The analytical result is shown in Table 1.

Table 1. Result of the study compared with the traditional SRM [23] at speed n = 3000 rpm and current I = 4 A.

Motor specs	New SRM	Traditional SRM
Copper losses (W)	2.24	2.8
Core losses (W)	1.2	1.4
Motor efficiency (%)	83.7	75.4
Aligned inductance (mH)	4.2	3.75
Unaligned inductance (mH)	0.78	0.7
Average torque (Nm)	0.053	0.047

Therefore, the research and design of switched reluctance motor using amorphous materials is an important and necessary solution. However, it is necessary to evaluate the relationship of the magnetic field in the motor to give a specific design technology and manufacture using amorphous materials. Research result announced by the authors in this paper is initial, the standardized assessment results through the simulation of physical transformation process of the motor parameters will be announced in the appropriate time.

4. Conclusion

This article presents different solutions in order to improve the characteristics of switched reluctance motor. With the development of various intelligent control theories, SRM controller has achieved good results in reducing torque ripple. At the same time, research of solution changing the internal structure of motor which will be continued because of its effective solution to strictly overcome the disadvantages of the switched reluctance motor.

5. References

[1] X. Gao, X. Wang, Z. Li and Y. Zhou. A review of torque ripple control strategies of switched reluctance motor, International journal of control and automatic, vol. 8, no. 4, pp. 103 - 116, 2005.

[2] B. L. Zhang, Y. W. Qi and G. S. Xu. Switched reluctance motor torque distribution Strategy optimization, Journal of HeFei University of Technology, no. 12, vol. 35, pp. 1615 - 1619, 2012.

[3] Z. L. Shi, Y. S. Huang and X. Chen. Research on control system of Switched Reluctance Motor Based on torque distribution strategy, Coal mine machinery, vol. 31, no. 12, pp. 59 - 61, 2010.

[4] B. Yang, J. Y. Cao and Y. P. Chen. A new method to reduce the torque ripple of switched reluctance motor, Small and medium sized motor, vol. 28, no. 4, pp. 11 - 15, 2001.

[5] J. Y. Cao, Z. D. Zhou and Y. P. Chen. A new method of switch reluctance motor torque control, Proceedings of the CSEE, 2005.

[6] S. Mir, M. E. Elbuluk and I. Husain. Torque ripple Minimization in Switched Reluctance Motors Using Adaptive Fuzzy Control, IEEE Transactions on Industry Applications, vol. 35, no. 2, pp. 461 - 468, 1999.

[7] L. O. A. P. Henriques, L. G. B. Rolim and W. I. Suemitsu. Torque Ripple Minimization in a Switched Reluctance Drive by Neuro-fuzzy Compensation, IEEE Transactions on magnetics, vol. 36, no. 5, pp. 3592-3594, 2000.

[8] Z. Q. Fan and P. Wang. Methods of inhibiting intelligent torque ripple of switched reluctance motor, Micromotor, vol. 28, no. 2, pp. 28 - 30, 2000.

[9] D. L. Liang, W. Ding and Z. M. Yu. Modeling for Switched Reluctance Motor Based on adaptive network based fuzzy inference system, Proceedings of the CSEE, 2008.

[10] J. G. O'Donavan, P. J. Roche and R. C. Kavanagh. Neural Network Based Torque Ripple Minimization in a Switched Reluctance Motor, IECON, pp. 1226 - 1231, 1994.

[11] D. S. Reay, T. C. Green and B. W. Williams. Application of Associative Memory Neural Networks to the Control of a Switched Reluctance Motor, IECON, vol. 1, pp. 200 - 206, 1993.

[12] C. L. Xia and J. Xiu. Switched reluctance motor adaptive PID prediction model of non-linear control based on RBF neural network, Proceedings of the CSEE, 2007.

[13] C. L. Xia, Z. R. Chen and B. Li. Switched reluctance motor instantaneous torque control based on RBF neural network, Proceedings of the CSEE, 2006.

[14] Nihat Inanc, Veysel Ozbulur. Torque ripple minimization of switched reluctance motor by using continuous sliding mode control technique, Electric Power Systems Research, vol. 66, pp. 241 – 251, 2003.

[15] Wadah Abass Aljaism. Switched reluctance motor: Design, simulation and control, PhD thesis, University of Western Sydney, 2007.
[16] Lingquan Zeng,Haiwei Yu. Research on a novel Rotor Structure Switched Reluctance Motor, International Conference on Applied Physics and Industrial Engineering, Physics Procedia, vol. 24, pp. 320 – 327, 2012.
[17] Jawad Faiz , J.W. Finch , H.M.B. Metwally. A novel switched reluctance motor with multiple teeth per stator pole and comparison of such motors, Electric Power Systems Research, vol. 34, pp. 197 – 203, 1995.
[18] Piyush C. Desai, Mahesh Krishnamurthy, Niegel Schofield, Ali Emadi. Design and performance evaluation of a novel 6/10 switched reluctance machine, IEEE Xplore, 2009.
[19] Sang Hun Lee, Feel Soon Kang, Sung Jun Park, Su Eog Cho, Man Hyung Lee. Single stage power factor corrected converter for switched reluctance motor drive, Electric Power Systems Research, vol. 76, pp. 534 – 540, 2006.
[20] M. Sundaram, P. Navaneethan, M. Vasantha Kumar. Magnetic analysis and comparison of switched reluctance motor with diferent stator pole shapes using a 3D finite element method, ICGST-ACSE Journal, ISSN 1687 - 4811, Volume 9, Issue II, December 2009.
[21] Ju Hwan Oh, Byung Il Kwon. New rotor shape design of SRM to reduce the torque ripple and improve the output power, IEEE Xplore, 2010.
[22] Takanori Suzuki, Shinya Ito, Naoki Tanaka, Akira Chiba, Tadashi Fukao, Hironori Ninomiya. Development of high efficiency switched reluctance motor, Electrical Engineering in Japan, Vol. 162, No. 2, 2008.
[23] Torsten Wichert. Designed and construction modifications of switched reluctance motor, PhD thesis, Warsaw University of Technology, 2008.

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