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Analysis of Energy Efficient Current Control Methods in Switched Reluctance Motor

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Abstract: A major problem in any country is availability of energy source. Energy saving is most important than identifying the new energy sources. Hence continuous energy saving is necessary for all developed countries. Electric motors consumed most of the energy from source. Energy efficient current control methods increases the efficiency of Switched Reluctance Motor (SRM). Comparative analysis of current control methods in SRM is needed for energy efficient operation. This paper compares the different types of current control methods in 1.5 HP, 8/6 prototype SRM. Modification of pole arc in stator and rotor current regulation method is better than other control method. The stator pole arc is modified from 32° to 36° and rotor pole arc is modified from 30° to 28°. Hence the useful torque is increased from 1.23 Nm to 1.32 Nm. Based on the analysis; energy efficient control method is identified.

Key words: SRM · Current Control methods · Controller, Modification of pole arc · Efficiency · Energy saving

INTRODUCTION

Switched Reluctance Motor (SRM) is a high speed home appliances motor like vacuum cleaner because there is no rotor winding and permanent magnet [1]. Energy efficient operation of SRM is depending upon the useful torque. The useful torque of SRM is increased by reducing the torque ripple. Minimization of torque ripple is essential for increasing the efficiency. Two approaches are considered for increasing the efficiency [2].

First one is to modify the shape of stator and rotor pole arc for increasing the efficiency of SRM. It has been explained in [3]. The sensitivity of geometrical parameters like shape of stator and rotor pole in SRM is studied from [4-6] in literature review. Optimum pole arc configuration in SRM is described in [7] for reducing the torque ripple. Nowadays, some researchers have been [8-11] worked in the area of SRM for increasing the efficiency by reducing the torque ripple. Torque ripple is reduced by changing the pole shape of stator and rotor. Electronic torque ripple reduction technique is also described for developing the optimum geometric of SRM [12]. Second one is to control the motor current and inductance profile for increasing the efficiency by reducing the torque ripple [13-16]. It is very helpful to find the phase current for getting minimum torque ripple.

Selection of controller for an SRM is more important for efficient operation. Separate switches are provided for each winding at existing system. Number of controller are described by several authors, Chan [17] explained converter design with control circuit. M. Barnes and C Pollock [18] introduced different types of converters. J. Y. Lim introduces [19] machine design with both a radial and an axial air gap. Barnes and Pollock illustrated [20] the selection procedure of the converter. Similarly, a number of converters are introduced for SRM [21]. The disadvantage of the above technology is the power rating of each component is high and it requires additional control circuit. The main objective of this paper is to compare the energy efficient current control methods.

Types of Current Control Methods: Torque is one of the main factors in SRM. Current controller is used to control the torque of SRM. The drive in current controller is used to control the speed for various applications with firing angle. It is explained by Bose with efficiency optimization block. Turn ON of current control is determined by rule of Bose [22] and turn OFF is calculated by Gribble [23]. This firing angle is used to minimize the electrical drive input. Efficiency optimization in current control drive is already described by Acarnley *et al* [24]. He has explained the Chopping current detection technique and it is used

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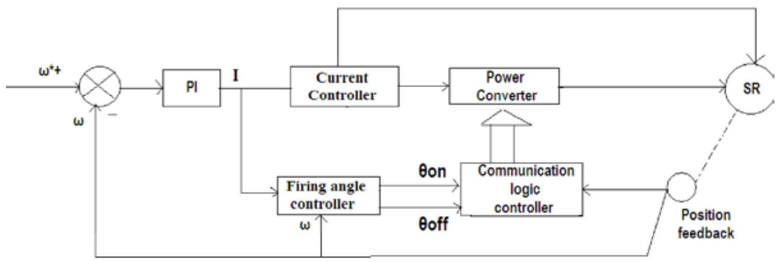

Fig. 1: Block diagram of current controlled Switched reluctance drive

to describe the relationship between inductance, phase current and rotor position. The SRM is controlled by closed loop current control method, namely

- Hysteresis current control
- Delta Modulation
- Current regulation with PWM.
- Current regulation with modification of pole arc in stator and rotor

Hysteresis Current Control: In Hysteresis current control, the phase winding is energized due to ON time demagnetizing of the winding corresponding to OFF time. This controller is used to control the reference current and hysteresis bond. The analog hysteresis control is simple, but one disadvantage is variable switching frequency, which makes subsonic noise in the SRM, moreover the power converter design may also be difficult.

Delta Modulation: Current in Delta modulation is controlled with maximum switching frequencies. The result of high current ripple in fixed frequency delta modulation is higher than the digital linear controller with fixed sampling and switching frequency.

Current Regulation with Pulse Width Modulation (PWM): Current regulation with Pulse Width Modulation gives better solutions for converter design and acoustic noise prediction. However, the dynamics of the current loop is controlled by the sampling time. It is also filtered to smooth the current ripple caused by the switching frequency. The PWM Current controller has current error generator, PI current controller sample and hold block. The PWM controller takes the output of the sample. It holds the circuit and computes the duty cycle, ON and OFF times in a PWM period for implementation. In hardware implementation, the on-and off- time gating pulses are generated by comparing the output of the sample and holding circuit with a triangular carrier signal [25].

Current Regulation with Modification of Pole Arc in Stator and Rotor: A schematic block diagram of current controlled SRM drive is given in Figure 1. Maximum efficiency condition, developed torque (useful torque) is equal to the load torque. But load torque varies with torque ripple at different load conditions. Hence current controller is used to control the developed torque for minimizing the torque ripple and increase the efficiency of SRM. Hence the torque command is executed by varying the current in above loop.

SRM is controlled by correct positioning of the phase current pulses with respect to the rotor position. The turn ON time and the total conduction period are used to calculate the torque and efficiency of the SRM. The phase current builds up very quickly after turn ON due to the negligible back EMF. The current of SRM should be limited by controlling the voltage. The rotor position is identified by position feedback. Error signal between the reference speed and motor speed is based on the current command. It is generated by speed controller and Proportional Integral (PI). The current in each phase winding is regulated with reference current by current controller. Each and every instant the firing angle calculator is used to regulate the turn ON and turn OFF angles with respect to actual speed and reference current. The reference current is calculated from the load condition. The controller needs current feedback information from each winding. The drive also has efficiency optimization block for energy saving applications.

A circuit diagram of current controlled SRM drive is shown in Figure 2. Control signal which depends upon rotor position. The rotor of SRM is in aligned position with stator coil, control signal turns ON Transistor T and hence motor winding Ph_1 is energized.

The rotor of SRM is in unaligned position with stator coil and control signal turns off Transistor T. The current in phase winding Ph_1 takes path through diode D_1 and phase winding Ph_2 connected with capacitor C_d, Energy from phase Ph_1 is partially transferred to C_d. The stored energy from off-going phase winding Ph_1 is dumped into

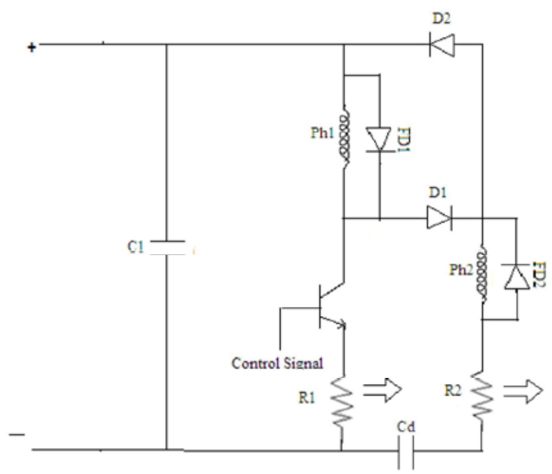

Fig. 2: Circuit diagram of Current control drive with sensing resistance

C_d by freewheeling diode FD_1. Hence suppressing voltage present in off-going phase windings is once again reused in the system. The motor winding Ph_2 is energized by voltage across phase winding Ph_1 and dumped capacitor C_d. Now current path in phase winding Ph_2 is diode D_2 and dumped capacitor C_d. Due to change of rotor position, the transistor T moves to ON position. The stored energy from off-going phase winding Ph_2 is dumped into C_d by freewheeling diode FD_2. The same procedure is repeated. Two current sensing resistors (R_1 &R_2) are used to sense the phase current at load and no load conditions. It is also used to regulate the current with respect to load for increasing the efficiency of motor. Based on the reference speed, firing angle calculator is used to regulate the turn-on and turn-off angles. Hence the proposed current control drive is used to regulate the current in each phase winding with respect to reference current.

The advantages of the current control circuit can be summarized as follows.

- Circuit uses only one switch for total winding.
- Topology endows independent phase current control in SRM.
- During the current control and commutation period, energy present in the dumped capacitor is utilized.

Modification of Pole Arc in Stator and Rotor: Current is also calculated by proposed modification of pole arc of stator and rotor method. Three factors are important for determining the current from useful torque of SRM.

- Average Torque (T_{aver})
- Maximum Torque (T_{max})
- Minimum Torque. (T_{min})

T_{max} - Maximum Torque is received from Static torque characteristics.
T_{min} - Minimum Torque is received from instant torque characteristics.
T_{aver} - Average value of maximum and minimum torque.

$$MeanTorque(T_{mean}) = \frac{(W_a - W_u)N_S N_r}{4\pi} \quad (1)$$

W_a - Power in aligned position
W_u - Power in unaligned position
Ns - Synchronous speed in rpm
Nr - Rotor speed in rpm

$$W_a = L_a idt \quad (2)$$

$$W_u = \frac{1}{2} i^2 L_u \quad (3)$$

$$T_{ripple} = T_{max} - T_{min} \quad (4)$$

$$T = \theta I \quad (5)$$

$$T = \frac{1}{2} i^2 \frac{dL}{d\theta} \quad (6)$$

Current is calculated at different levels (aligned and unaligned position) of air gap in between the stator and rotor poles by reducing the torque ripple. Torque ripple is based on cross section area (a) of modified poles and rotor position angles (θ). If the area of stator pole increases, then total reluctance of stator decreases and increases the flux, resulting in higher inductances and average torque.

MATERIALS AND METHODS

8/6, 1.5 HP prototype SRM is purchased from Precision Products for increasing the efficiency. The prototype SRM is modified by changing the pole arc in both stator and rotor. The stator pole arc is varied from 32° to 36° and rotor pole arc is varied from 30° to 28° by CNC lab. After the modification of stator and rotor, air gap in SRM is un- uniform. The tapered stator pole model [25] is shown in Figures 3 and 4. The ratio 'a' between the enlarged stator pole arc at the base β_{s1} and initial constant width stator pole arc at the base β_s is varied from 1 to 2

Table 1: Useful Torque in Existing and Proposed method

Sl. No	Status	Inductance at aligned position	Inductance at unaligned position	Stator pole arc	Rotor pole arc	dL	dθ	Useful Torque T N-m
1	Without Modification of Pole arc	38.4	30.2	320	300	8.2 H	300	1.23
2	With Modification of Pole arc	38.4	30.2	360	280	8.2 H	280	1.32

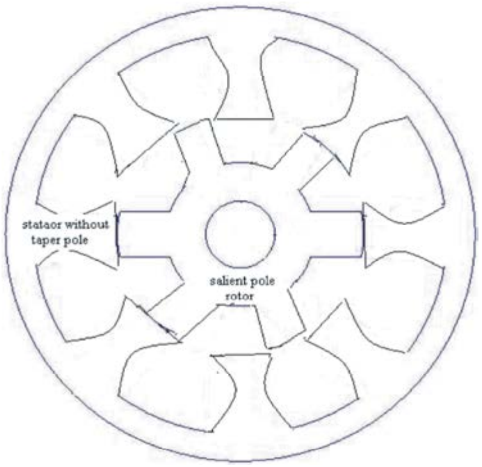

Fig. 3: SRM without tapered stator and rotor pole (Existing method)

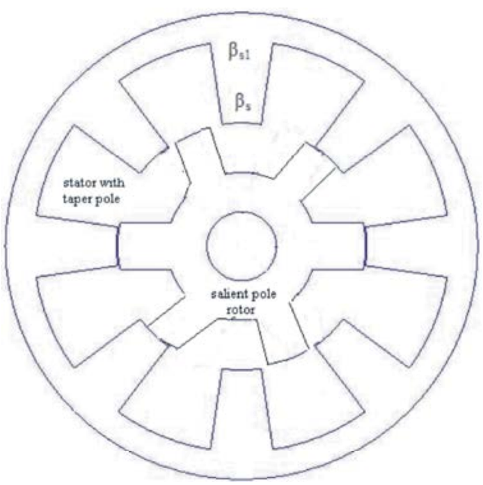

Fig. 4: SRM with tapered stator and rotor pole (Proposed method)

keeping β_s constant. Increasing 'a' has the effect of increasing the overall area of the cross section, leading to decrease in the reluctance of the stator pole sections.

Comparison of Useful Torque in Existing and Proposed Method: Torque is one of the important factors in SRM. Useful torque in existing and proposed methods are calculated and tabulated in Table 1.

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

dL - Difference in inductance at aligned and unaligned position

dθ - Difference in Pole arc of Stator and Rotor

$$dL - 38.4 - 30.2 = 8.2\text{H}$$

Total current in SRM = 3 Amp

Existing Method:

$$d\theta = \frac{\left(32^\circ + 30^\circ\right)}{2} - \frac{\left(32^\circ - 30^\circ\right)}{2} = 31^\circ - 1^\circ = 30^\circ$$

Proposed Method:

$$d\theta = \frac{\left(36^\circ + 28^\circ\right)}{2} - \frac{\left(36^\circ - 28^\circ\right)}{2} = 32^\circ - 4^\circ = 28^\circ$$

$$T = \frac{1}{2} 3^2 \frac{38.4 - 30.2}{30^\circ} = 1.23 Nm \quad \text{(Existing Method)}$$

$$T = \frac{1}{2} 3^2 \frac{38.4 - 30.2}{28^\circ} = 1.32 Nm \quad \text{(Proposed Method)}$$

Calculation of Efficiency: From the simulation results, torque ripple is decreased by the proposed method of poles area of stator and rotor. Hence useful torque of SRM is increased.

$$\text{Output Power} P = \frac{2\pi \text{NT}}{60}$$

$$Efficiency = \frac{OutputPower}{InputPower} \tag{7}$$

$$Inputpower = Electricalpower = VI \tag{8}$$

The useful torque is directly proportional to output power, efficiency and moreover it is inversely proportional to the current. Hence current is controlled by varying the torque level in the proposed method.

An observation of Tables 2 and 3 shows that the torque ripple is sufficiently decreased and useful torque is increased. Hence the Efficiency of proposed method is also increased thereby power consumption in proposed method is decreased.

Fig. 5: Experimental Plat form of SRM

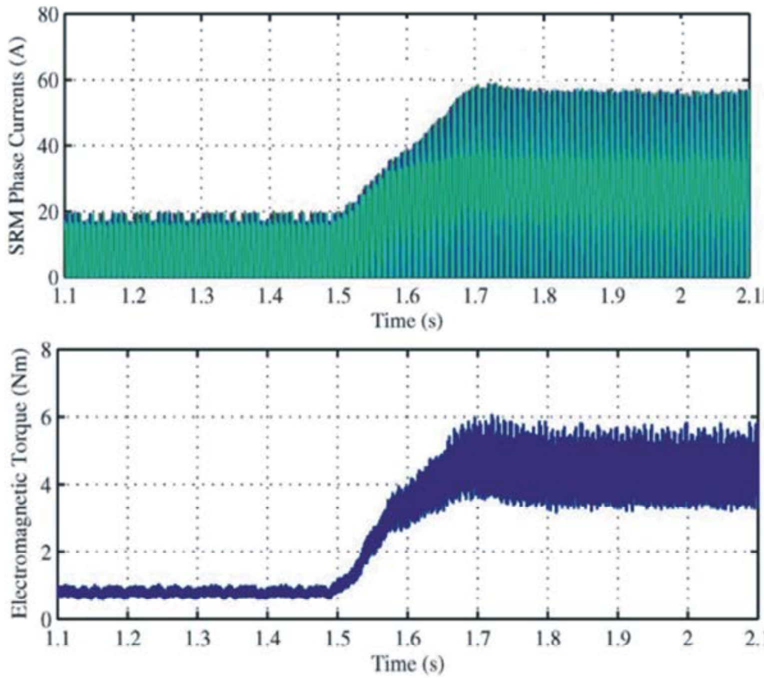

Fig. 6: Simulation results of phase current and torque in proposed method.

Table 2: Result Analysis of Torque ripple and Efficiency at Existing and Proposed method

Sl. No	Status	T_{max} (Nm)	T_{min} (Nm)	T_{aver} (Nm)(T_{max} + T_{min})/2 (Useful Torque)	Torque ripple T_{max} - T_{min}	Efficiency (%)
1	Without Pole Modification of SRM	1.23	0.58	0.905	0.65	68.90%
2	With Pole taper Modification of SRM	1.32	0.72	1.02	0.6	73.04%

Table 3: Result Analysis of Current and Efficiency at Existing and Proposed method

	Without Modification of Pole for Current Analysis			With Modification of Pole taper for Current Analysis.		
Sl.No.	Torque (Nm)	Current (A)	Efficiency (%)	Torque (Nm)	Current (A)	Efficiency (%)
01	0	0.3	0	0.0	0.18	0.0
02	0.58	0.9	43.4	0.72	0.69	52.4
03	0.76	1.4	51.5	0.81	0.8	58.7
04	0.84	2.1	63.4	0.97	1.7	64.9
05	0.905	3.0	68.9	1.02	2.8	73.04

Table 4: Comparison of Current controllers

Sl.No.	Features	Hysteresiscurrent control	Delta Modulation	Current regulation with Pulse Width Modulation	Current regulation with sensing resistance (with Pole Modification)
1	Switching frequency	Disadvantage is variable switching frequency.	Current is controlled with maximum switching frequencies.	It is also filtered to smooth the current ripple at the switching frequency.	High Switching frequency
2	Noise	It makes subsonic noise in SRM	It makes noise in SRM	It is the better solutions for acoustic noise prediction.	Less noise in SRM
3	Power Converter Design	Moreover the power converter design may also be difficult.	Converter design is so difficult.	It is the better solutions for converter design	Simple power converter Design
4	Switches	Each winding is having separate switch	Separate switch is required for each winding	More than one switch is required.	Only one switch is used for total winding.
5	Phase current control	---	---	----.	Topology endows independent phase current control in the SRM.
6	Capacitor	There is no dumped capacitor for charging.	There is no dumped capacitor for charging.	There is no dumped capacitor for charging.	During the commutation period, energy stored in dumped capacitor is utilized
7	Useful Torque	Normal	Normal	Normal	Increased from 1.23 Nm to 1.32 Nm.
8	Efficiency and Energy Savings	Efficiency is very low because switching losses is high.	Efficiency is very low because switching losses is high.	Efficiency is very low because switching losses is high.	Efficiency is very high because only one switch and hence switching losses is low

Experimental setup and Result Analysis

Calculation of Current: The Prototype SRM is shown in Figure 5. Simulation results of torque and current in modified pole arc system is shown in Figure 6. Different efficiency levels are calculated and tabulated in Table 3. The speeds of SRM for various turn ON and turn OFF are tested. Current is calculated at aligned and unaligned position of air gap in between the stator and rotor poles.

From the observation of Table 4, the efficiency of SRM in Current regulation with modification of pole arc in stator and rotor control method is higher than other controller. From the review of above controller, number of switches in current regulation with modification of pole arc method is less. Hence switching losses in current regulation with modification of pole arc in stator and rotor method is sufficiently decreased. Hence useful torque of SRM is increased. The useful torque is directly proportional to output power and efficiency.

CONCLUSION

In summary, the review of current control method in 1.5HP, 8/6 prototype SRM is as follows

- Efficiency of SRM
- High Switching frequency
- Noise
- Power converter Design
- Operating Switch
- Energy stored in dumped capacitor is reused.

Based on the above factors, Current regulation with modification of pole arc in stator and rotor method is very suitable for energy efficient operation of SRM.

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