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Design and Fabrication of Switched Reluctance Motor for Energy Efficient Operation by Minimizing Torque Ripple

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Abstract:
Around the world, motor is consuming more than 40% of the total-generated electrical energy. Accordingly, energy efficient electrical drives are the needs of the hour. The Switched Reluctance Motor (SRM) is more energy efficient than other kinds. Since SRM has a rugged structure, it has inherent fault tolerance characteristics and is cost-effective than synchronous and induction machines. Nevertheless, the application of such a motor is limited due to low torque density, torque ripples and power losses because of control circuit. In this research work, the author proposed a novel-designed SRM, which is achieved by optimizing stator and rotor pole arc. Alongside, a novel control circuit, which has single transistor, is proposed. The modification of stator and rotor pole arcs assists in the reduction of the torque ripple. The stator pole arc is modified from 32 degree to 36 degree, and the rotor pole arc is modified from 30 degree to 28 degree. Thus, the torque ripple is reduced from 3.25 to 2.92 Nm, and thus, the useful torque is increased from 4.94 to 5.2 Nm. Furthermore, a single transistor switching device is used instead of the conventional one with four switches. Hence, energy loss on the control circuit is significantly reduced. From the experimental analysis, it is found that, with-pole-arc modified SRM has higher efficiency than the one without it.

Keywords: Switched reluctance motor, Pole arc modification, Torque control, Energy conservation, Driver circuits, Harmonic distortion

1. Introduction

Globally, AC electrical drives, such as synchronous and asynchronous machines, are playing a vital role in the industry’s application. Perhaps, synchronous motors do not have self-starting characteristics; therefore, they require a starting mechanism. Also, the motor has brushes and slip rings, so it is costlier than asynchronous machines, but it can operate in lag, lead and unity power factors [1]. On the other hand, the asynchronous induction machines are categorized as squirrel cage and slip ring induction machines, respectively. Among them, a squirrel cage induction machine has low starting torque and high starting current. Besides that, the efficiency of squirrel cage induction machines is higher than that of slip ring induction machine, since slip ring induction machine has slip rings and brushes, which are used for improving starting torque. Also, high initial and maintenance costs are a huge drawback for the squirrel cage induction machine. Nevertheless, speed control of induction machines are achieved through scalar and vector control methods, of which scalar speed control method is cheap and easy to install, but the performance of such control strategy is poor. In contrast, vector control method is more effective than scalar methods. This method of speed control is achieved through varying the frequency and amplitude of supply voltage correspondingly. Types of speed control methods are DTC and FOC. Among them, FOC method brings low current and torque ripples at lower speed, but requires current controllers and frame transformer, pulse width modulator, whereas these are not required in DTC methods [3]-[5].

By DTC methods, motor terminal voltage and current are used to estimate motor flux and torque. In this method, estimation flux is a crucial factor which is based on instantaneous error in torque and stator flux magnitude. Correspondingly, this error is limited by voltage vector control technique. Yet, this vector control technique is based on power electronics device, which require frequent switching on or off, whin in turn increases THD. Added to that, the torque and speed controls are difficult at low speed; besides noise production, it generates current and torque ripples [6]-[8]. Therefore, DC machines are playing a dynamic protagonist in industries, since the speed and torque control is in a simple manner. Also, as an added advantage DC motor is bidirectional. However, the usage of DC motor is limited due to rubbing of brushes and commutator [9].

Basically, electrical motors generate mechanical energy based on the electrical sources, but stepper motor generates mechanical rotation based on the electronic pulses. In any application where high meticulousness position and speed control is required, stepper motor performance is better than the other conventional machine. In Recent years, stepper motor played a vital role in solar panel tracking mechanism as well as bio medical research field. The advantages of stepper motor are: (a) angle rotation is easy to control; (b) outstanding retort to start, stop and reverse (c) Simple control methodology; (d) low speed synchronous rotation is also possible. Perhaps, it is not suitable for high speed application since pulse control technique has become complex. The classification of stepper motors is: PMDC, hybrid motor and Switched reluctance motor [10]-[11]. In Later years, brushless PMDC motor was developed; it has a strong permanent magnet. The advantage of such motor is high efficiency, less maintenance, high thermal with stand ability and it generates less noise than conventional dc motor. In contrast, speed control circuit is expensive and has a complex nature than motor. In addition, demagnetizing effect may occur when PMDC motor draws a high armature current [12], [13]. Consequently, the performance of Switched Reluctance Motor is superior to PMDC machine.

2. Materials and Methods

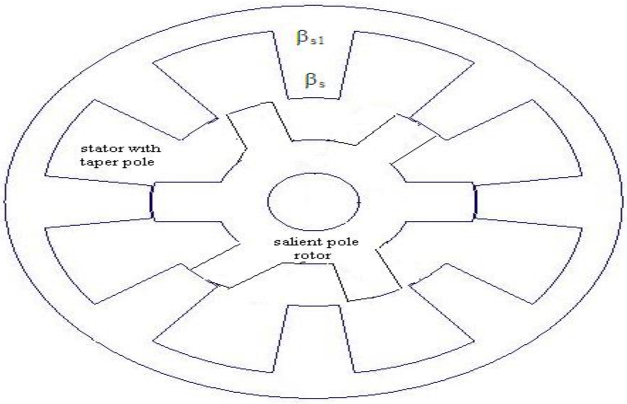

Fig 1.SRM with tapered stator and rotor poles

Fig 2.SRM with a tapered rotor pole (Proposed method)

The ratio between the stator and rotor pole is 8/6, and its capacity is 1.5HP. Then stator pole arc is varied from 32° to36° and 30° to 28° for rotor pole using Computerized Numerical Control lab. This design modification is forming the non-uniform air gap in the SRM. Figure 1 shows SRM with tapered stator and rotor poles, and figure 2 shows the tapered stator pole model. The ratio ‘a’ between the enlarged stator pole arc at base β_{s1} and initial constant width stator pole arc at base β_s was varied from 1 to 2, keeping β_s constant. The increase in ‘a’ increased the overall area of the cross section, leading to a reduction in the reluctance of the stator pole sections. The maximum efficiency is attained at a condition when the developed torque is equal to the load torque. Perhaps, the load torque and torque ripple vary under transient load. Thus, it causes the acceleration of the motor; therefore, a critical electrical and mechanical characteristic of SRM is poor. Furthermore, the life span of SRM is drastically abridged. Hence, torque ripple minimization is essential for obtaining maximum efficiency [21] - [23]. Therefore, the modified pole arc was used to increase the developed torque corresponding to the load torque. The technical specification stator and rotor pole arc modified SRM are shown in table 1.

Table 1 Technical Specification of Pole arc modified SRM

Number of stator poles	8
Number of rotor poles	6
Rotor pole height	2.5 cm
Stator pole height	2.2 cm
Rotor pole pitch	2.2 cm
Stator pole pitch	1.6 cm
Core length	5.076 cm
Stator back iron width	1.5 cm
Rotor back iron width	0.8 cm
Air gap	0.02 cm
Number of turns per phase	536
Stator inner diameter	(rotor diameter + 2 x Air gap)

Stator diameter	15.4 cm
Rotor diameter	7.0 cm
Rotor bore diameter	7.02 cm
Shaft diameter	2.1 cm
Stator pole arc β_s	36°
Rotor pole arc β_r	28°
No of turns per phase	536 turns
Capacity of the SRM	1.5 HP
DC link voltage	100 V

3. Mathematical Verification

In SRM, the torque is made by the predisposition of its movable parts to move a position of minimum reluctance, which corresponds to the position of maximum inductance so that modification of inductance is influencing the torque. The useful torque is directly proportional to the square root of current as shown in equation (1). Hence, developed torque depends on the divergence of current flowing in the coil. This is used to estimate the useful torque for pole arc modified SRM. The results are compared with the modified SRM without pole arc.

$$T = 0.5i^2\ (dl/d\theta) \ldots.\ (1)$$

The estimated inductance at the aligned position is 40.7 H (7.8 H for unaligned position). However, stator pole arc (β_s) is 32° while rotor pole arc (β_r) is 30°. Also, the total current in the SRM is 3 A. The modified stator pole arc (β_s)is 36° and that of the rotor (β_r) is 28°. These are used to estimate the useful torque. If the stator pole area is increased, the total reluctance of the stator decreases. This increases the flux linkages, resulting in higher inductances and average torque [25]. The pole arc modification has significantly increased the useful torque, which is evident in table 2.

Table 2 Comparative analysis of the useful torque in with and without pole arc modified SRM

Sl. No	Status	Inductance at aligned position	Inductance at unaligned position	Stator pole arc β_s	Rotor pole arc β_r	dL	dθ	Useful Torque T N-m
1.	Without Pole arc modification	40.7	7.8	32	30	32.9 H	30	4.94
2.	With Pole arc Modification	40.7	7.8	36	28	32.9 H	28	5.2

4. Experimental Verification

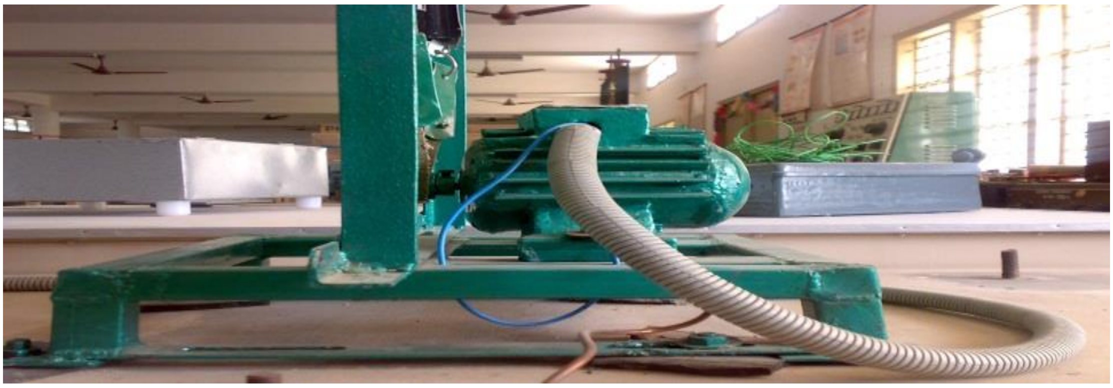

Fig 3. Experimental platform of 8/6 SRM

Fig 4.SRM control Panel

The SRM operation depends on the control signal which is used to energize the stator pole of an SRM. This control circuit has converter units and switching units. The converter made up on diode rectifier is used to rectify ac to dc; then it is fed to the switching circuit. Normally, SRM driver circuit contains four switches which are made by thyristor, MOFET and IGBT etc. The switches are having resistance due to which power loss occurred [26], [27]. Besides that, the stator winding excitation is a continuous process which requires frequent switching between ON and OFF is required. These problems are rectified by proposing a new novel control circuit containing single switch which not only enhances the energy conservation but also rectifies the harmonics issue.

The experimental setup of the developed system is depicted in figures 3 and 4. The equivalent circuit of the proposed control circuit is shown in figure 4. The torque development mechanism is controlled by control signal fed to the transistor. The generated control signal is depending upon the rotor position of the SRM. When the rotor of the SRM is with the stator coil, the control signal turns on transistor T, and hence the motor windings S1, S2 and relay are energized. At this time, the auxiliary normally close (NC) contact of the relay is opened. When the rotor of the SRM is in an unaligned position with the stator coil, the control signal turns off the transistor T, and hence motor winding S1 and Relay are de-energized. At this time, the auxiliary NC contact of the relay is closed. As a result, the motor windings M1 and M2 are energized. The stored energy from the off-going phase winding S1 is transferred to C_d by the freewheeling diode FD1. Hence, the suppressing voltage present in the off-going phase windings are reused by the system. Because of changes in the rotor position, the switch T goes to the 'ON' position once again. The same procedure is repeated. At this time, the stored energy from the off-going phase winding M_1 is transferred to C_d by the freewheeling diode FD_2. Hence, the operation of relay and coils in the stator windings depends on the position of the rotor.

Table 3 Comparison of speed, torque and efficiency

Sl. No.	Vin (V)	I (A)	P (W)	N in rpm	Without pole arc modification			With pole arc modification		
					Torque in Nm	Output in Watts	η%	Torque in Nm	Output in Watts	η %
1	100	4.2	420	1,720	0	0	0	0	0	0
2	96	5.7	547.2	1,560	1.69	276.9	50.6	2.28	373.46	68.25
3	87	6.8	591.6	1,200	3.16	398.16	67.3	3.79	477.54	80.72
4	85	8.7	739.5	1,120	4.94	580.94	78.56	5.2	611.52	82.69

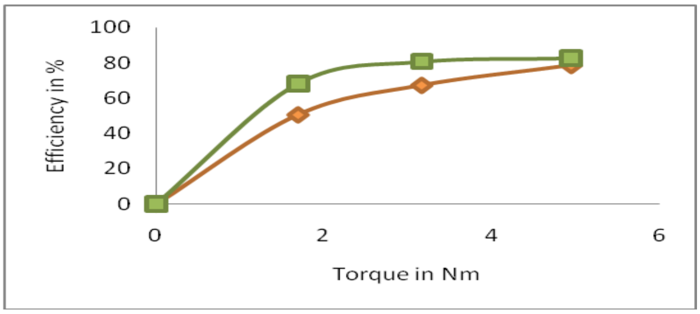

Fig 5 Torque –efficiency characteristics with and without pole arc modification

The applied voltage, load current and speed are measured which is used to estimate the torque, output and efficiency, respectively. The torque and efficiency values with and without pole arc modification were measured at different mechanical loads of SRM as shown in figure 5. From table 3, it is clear that the value of the useful torque was reduced when the pole arc was not modified, compared with the pole arc which was modified. Correspondingly, at the same mechanical load and speed, the efficiency of the modified pole arc was higher than that of the unmodified pole arc. The useful torque in the modified stator arc is changed from 32^0 to 36^0. Similarly, the useful torque in the modified rotor arc is changed from 30^0 to 28^0. Furthermore, the torque ripple was reduced in the proposed method.

4.1 Torque Ripple Minimization

Torque ripple minimization is essential for improving SRM efficiency. The existing and proposed modification of SRM pole arcs increased the developed torque with respect to the load torque. Moreover, the torque ripple is directly proportional to the difference between maximum and minimum torque as shown in equation 2[29].

$T_{ripple} = T_{max} - T_{min}$ …….. (2)

T_{max}– Maximum torque is obtained at static torque characteristics.

T_{min}– Minimum torque is obtained at instant torque characteristics.

T_{mean}–Mean value of maximum and minimum torques

The torque ripple was calculated at different levels (aligned and unaligned positions) of an air gap between the modified stator and rotor poles. It is based on the cross section area (a) of the modified poles and rotor position angles θ. The torque ripple for the existing method is 3.25 Nm, whereas it is 2.92 Nm for pole arc modified SRM. From the experimental validation, it is found that stator and rotor pole arc modification has significantly reduced the torque ripple of SRM.

5. Conclusion

Based on the analysis, it is found that pole arc modified SRM develops higher useful torque than others. Likewise, with–pole-arc modified SRM generates low torque ripples than the without–pole-arc modified SRM. Besides, the pole arc modification also increases efficiency. Added to that, the proposed control circuit consumes lesser power than others, because it uses just a single transistor as a switching device. Hence, pole arc modification associated with single transistor switching circuit enhances the SRM as an energy efficient electrical driver.

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