Indian Journal of Science and Technology, *Vol 8(S8), 297–305, April 2015*

ISSN (Print) : 0974-6846
ISSN (Online) : 0974-5645
DOI: 10.17485/ijst/2015/v8iS8/61919

Analysis of Energy Saving Methods in different Motors for Consumer Applications

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Abstract

Energy saving is important than finding new energy sources, since new traditional energy sources may emit harmful gases to affect the atmosphere. Hence continuous energy saving is very important for developed countries. Most of the energy is consumed by electric motors. Hence comparative analysis of motor is needed for energy efficient operations. This paper compares the consumption energy level in different type of motors like Switched reluctance motor, DC motors and Brushless dc motor.

Keywords: Brushless DC Motors, DC Motors, Energy Saving Methods, SRM

1. Introduction

Nowadays energy shortage and environmental problems are greater challenge for many developed countries. Hence energy management is very helpful to solve the problem of energy consumption. Energy auditing is one of the main roles of energy management. Energy efficiency improvement should be done by entire device and system. This energy management has also helped to reduce 10% to 30% of energy consumption. It is also helpful to reduce the cost of the energy and consumer utilization charge[1]. Hence new technologies and techniques are required for saving the energy in motors Electric motors are definitely the main prime movers for many consumer applications. This paper introduces the working principle of three types of motors like Switched reluctance motor, dc motors and Brushless dc motor. The above motors are easily available in market. Basically all the motors are the categories of electrical family with respect to ac and dc supply.

2. Types of Motors

2.1 Reluctance Motor

Reluctance motor is same as induction motor expect with little modification in rotor. Reluctance motor is divided into two categories namely, SSRM (Singly-Salient Reluctance Motor) and SRM (Switched Reluctance Motor). SSRM has salient pole only at rotor and stator has same as induction motor. SRM is simplest one than other all electrical machines. There are no conductors or permanent magnets in rotor. But it has a salient pole rotor.

2.2 Principle of SRM

Stator winding is used to create the flux. Based on the flux the rotor is rotated from aligned position to unaligned position. Stator winding inductance (L) is inversely proportional to flux path length (l). At this time Magnetic lines tend to travel through the shortest distance when torque is obtained in clockwise direction as the rotor aligns with the stator.

$$L = \frac{\mathrm{N}^2 \mu \mathrm{A}}{1} \tag{1}$$

Electrical energy present in SRM is converted into two categories like energy stored in the inductance and mechanical output. As shown in Figure 1.

$$\lambda = L(\theta) i \tag{2}$$

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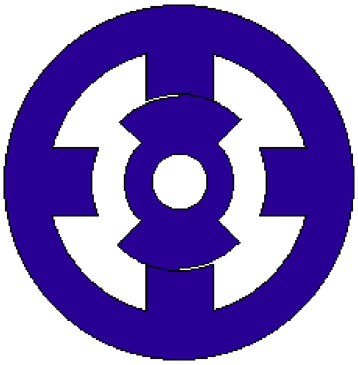

Figure 1. Switched reluctance motor.

Voltage across stator coil is directly proportional to the rate of change of flux. Hence

$$e = \frac{d\lambda}{dt} \tag{3}$$

Power delivered to the motor is $P = \int eidt$ (4)

Energy delivered to the motor is equal to power with time and hence,

$$W_{ei} = \int eidt = \left(\frac{d\lambda}{dt}\right) i.dt \tag{5}$$

SRM is an adjustable high speed machine[2]. It has steel laminations stacked on to a shaft and simple mechanical construction. Hence cost of the SRM is low and it leads to motivate a large amount of research on SRM. Drawback of SRM is high windage losses, noise and torque ripple.

2.3 Energy efficient operation of SRM

Mostly Energy efficient operation of SRM is based on useful torque. The useful torque is depending upon the minimization of torque ripple. Four different approaches are considered for reducing the torque ripple.

- To limit the motor current and inductance profile for reducing the torque ripple.
- To improve the magnetizing characteristics by changing the structure of stator and rotor pole arc.
- To design the suitable working parameters like turn-on, turn-off angles with respect to magnetizing characteristics.
- To select the energy efficient torque controller.

First one is to limit the motor current and inductance profile for reducing the torque ripple[3,4]. It is very helpful to find the phase current for getting minimum torque ripple. The following factors are considered for energy efficient operation with minimum torque ripple like peak current limit, inductance of the phase windings and back emf.

Movement of SRM is based on variable reluctance in air gap between the stator and rotor. Magnetic field is produced when the stator winding is energized. At this time, reluctance torque is used to move the rotor to its minimum reluctance position. Principle of Switched Reluctance Motor (SRM) is reluctance which is minimized when the magnet and metal come into physical contact at force that attracts steel to permanent magnets. It has some limitations like the brushless DC motor. SRM cannot run directly from AC or DC line. Electronically commutated control circuit is necessary for operating the SRM to produce reluctance torque. Hence, each phase winding of the SRM is independent physically, magnetically and electrically from the other motor phase windings. Due to the lack of conductor or magnets on the rotor, very high speeds can be achieved. Design and development of SRM for variable speed applications are already described by some researchers[5,6]. The main disadvantage of SRM is high torque ripple which results in acoustic noise and vibration. Noise is also obtained from other sources like driver unit and shaft. The above problem can be overcome by better understanding of SRM mechanical design and the development of algorithms. The sum of each and every phase winding torque is equal to the total torque obtained in SRM. Individual phase winding torque of SRM is controlled separately at each commutation period. Commutation period mostly depends upon the energy transferred from active phase to another phase[7]. At this time acoustic noise is obtained. It is already described by Cameron et al[8]. Hence torque ripple minimization is essential for smooth operation of SRM. Second is to design the suitable Geometrical parameters like shape of stator and rotor pole arc for reducing the torque ripple. It has been already explained in[7]. In literature review, the sensitivity of geometrical parameters of SRM is studied from[9-12]. Optimum pole arc configuration of SRM is explained in[13] for reducing the torque ripple. Nowadays, similarly some researchers have been[14-18] involved in increasing the efficiency of SRM by reducing the torque ripple by changing the pole shape of stator and rotor. Electronic torque ripple reduction technique is also introduced for improving the optimum geometric of SRM[19].

3 Design Parameter of Proposed SRM

The following design Parameter of prototype SRM is selected for fabrication purpose. It is very helpful to calculate the efficiency of motor. In general, the developed torque (useful torque) is equal to the load torque for maximum efficiency conditions. Load torque with corresponding torque ripple varies at different transient load conditions. Design parameter of pole arc is tabulated in Table 1.

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[20] is shown in Figures 2 and 3. 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 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.

Table 1. Design Parameter of Proposed SRM

Design Parameter	Value
Stator pole height	2.0 cm
Stator pole arc β_s	21 degrees
Stator pole pitch	1.6 cm
Rotor pole height	2.3 cm
Rotor pole arc β_r	24 degrees
Rotor pole pitch	2.2 cm
Air gap length g	0.02 cm
Stator inner diameter	(Rotor inner diameter + 2* Airgap)
Stator diameter D_0	15.4 cm
Rotor diameter	7.0 cm
Shaft diameter D	2.0 cm

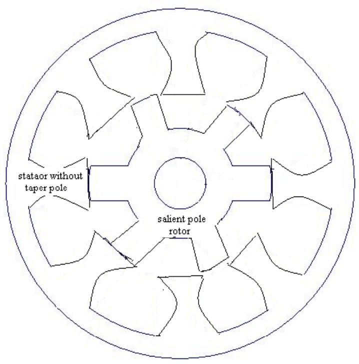

Figure 2. SRM without tapered stator and rotor pole (Existing method).

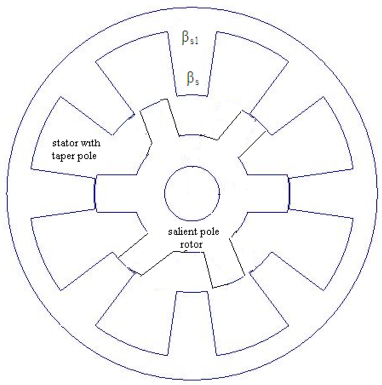

Figure 3. SRM with tapered stator and rotor pole (Proposed method).

At maximum efficiency condition, reduction of torque ripple is essential. The modified pole arc is used to increase the developed torque with respect to load torque. Hence torque ripple is reduced by modified pole arc.

4. Calculation of Efficiency by Torque Ripple Minimization

This torque ripple is calculated by proposed method. Three factors are important for determining the torque ripple of SRM.

1. Mean Torque (T_{mean}) or Average Torque (T_{aver}).
2. Maximum Torque (T_{max}).
3. Minimum Torque (T_{min}).

T_{max} - is obtained at Static torque characteristics.
T_{min} - is obtained at instant torque characteristics.
T_{mean} - Average value of maximum and minimum torque.

$$MeanTorque\left(T_{mean}\right) = \frac{\left(W_a - W_u\right)\mathrm{N}_S\mathrm{N}_r}{4\pi} \tag{6}$$

W_a - Power at aligned position
W_u - Power at unaligned position
Ns - Synchronous speed
Nr - Rotor speed.

$$\mathrm{T}_{ripple} = \mathrm{T}_{\max} - \mathrm{T}_{\min} \tag{7}$$

$$T = \theta I \tag{8}$$

$$T = \frac{1}{2} i^2 \frac{dL}{d\theta} \tag{9}$$

Torque ripple is calculated at different level (aligned and unaligned position) of air gap in between the modified stator and rotor poles .It is based on cross section area (a) of modified poles and rotor position angles (θ). If area of stator pole is increased the total reluctance of stator gets decreased and the flux resulting in higher inductances and average torque is also increased. The measured average torque and torque ripple with respect to rotor position and cross section area are tabulated in Table 2.

From the observation of Table 2, the torque ripple is sufficiently decreased at modification of pole arc of rotor with ununiform air gap. Hence useful torque of SRM is increased. The useful torque is directly proportional to output power and efficiency.

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

$$Efficiency = \frac{Output\ Power}{Input\ Power}$$

$$Useful\ Torque = Output\ power = Efficiency \tag{10}$$

4.1 Torque and Speed

Relationship between speed and torque are measured by using following formula.

$$\text{Power } P = \frac{2\pi NT}{60} \tag{11}$$

The speed of the SRM will be increased, when the torque of the motor is decreased.

$$T = (F_1 - F_2)R \tag{12}$$

Table 2. Analysis of Torque ripple at Existing and Proposed method

Sl. No	Status	T_{max} (Nm)	T_{min} (Nm)	T_{aver} in Nm $\frac{T_{max}+T_{min}}{2}$ (Useful Torque)	Torque Ripple $T_{max} - T_{min}$	Efficiency (η)
1.	Without Modification of Pole	0.92	0.12	0.52	0.8	63.8%
2.	With Modification of Pole taper.	1.26	0.68	0.97	0.58	74.6%

R is a radius of the brake Drum. Torque is calculated by corresponding load.

4.2 Torque and Efficiency

From the experimental results the relationship between the torque and Efficiency are calculated from the following equations.

$$Input\ power = Electrical\ power = VI \tag{13}$$

$$Output\ power = Mechanical\ power \tag{14}$$

$$\text{Output Power } P = \frac{2\pi NT}{60} \tag{15}$$

$$Efficiency = Output\ power\ /\ Input\ power$$

The torque and efficiency of SRM are calculated at different mechanical load and tabulated in Table 3.

From the Table 3, we observe that the efficiency of the motor is increased at various torque mentioned.

5. Energy Efficient Operations in DC Motor by using PID Controller

A conventional DC motor has its field system located on the stator. It produces a stationary magnetic field. The axis of the field produced by the armature should be displaced by 90 degree with the axis of stationery stator field coil. The DC motor is a self regulating machine because the development of back emf makes the DC motor to draw as much armature current which is just sufficient to develop the required load torque.

$$\text{Armature current } I_a = V - E_b - R_a \tag{16}$$

Table 3. Analysis of Efficiency at different torque of SRM

SlNo	Torque in Nm	Efficiency in %
1	0	0
2	0.042	52.05
3	0.071	62.55
4	0.136	75.86
5	0.204	87.99
6	0.308	78.98
7	0.381	70.04

5.1 Existing System

5.1.1 No Load Conditions

When the DC motor is operating at no load condition, small torque is required to overcome the friction and windage losses. Therefore back emf is nearly equal to input voltage.

$$E_b = V \tag{17}$$

During the light load conditions at the rated voltage, the magnetizing current drawn by the DC motor is high, where the core losses and copper losses of a DC motor are not reduced and hence the overall efficiency of DC motor is reduced.

5.1.2 Load Conditions

When the DC motor is operating at loaded condition, driving torque of the DC motor is not sufficient to counter the increased retarding torque due to load. Hence, armature slows down (motor speed decreases) and motor back emf E_b also decreases and corresponding armature current I_a increases. The increase torque, the motor continues to slow down till the driving torque matches the load torque and then steady state conditions are reached.

When the load of DC motor is decreased, the driving torque developed is momentarily in excess of the load requirement so that, motor armature is accelerated (motor speed increases). As the motor speed increases, the back emf (E_b) also increases causing armature current to decrease. The decrease in armature current causes decrease in driving torque and steady state conditions are reached, when the driving torque is equal to the load torque.

Under rated voltage in load Conditions, the magnetizing current drawn by the DC motor is less. Under full load condition, efficiency of the DC motor is high. The maximum efficiency of the DC motor is as shown in Figure 4.

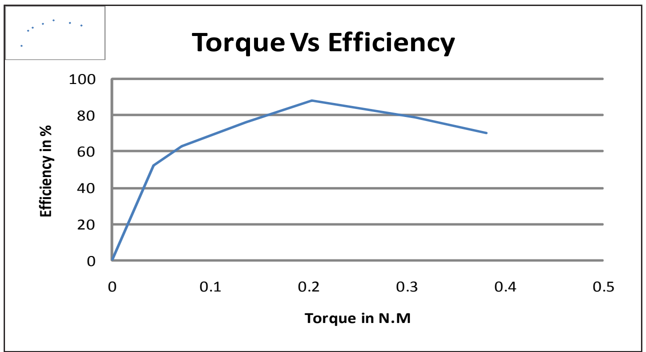

Figure 4. Torque-Efficiency characteristics of SRM.

6. Modified Systems for Energy Efficient Operation in DC Motor

6.1 No Load Condition

During the light load conditions, current is minimum. At this time the PIC controller will reduce the input armature voltage of the DC motor. Hence the power consumption of DC motor is reduced and overall efficiency of DC motor will be increased.

6.2 Load Condition

During heavily loaded conditions, current is maximum. At this time the PIC controller will increase the input armature voltage of the DC motor in Figures 5. Hence the output power of DC motor is increased and overall efficiency of DC motor will be increased.

It is tabulated in Tables 4 and 5.

From the Table 4 and 5, current in modified DC motor converter (armature voltage of 170 V and 190 V)

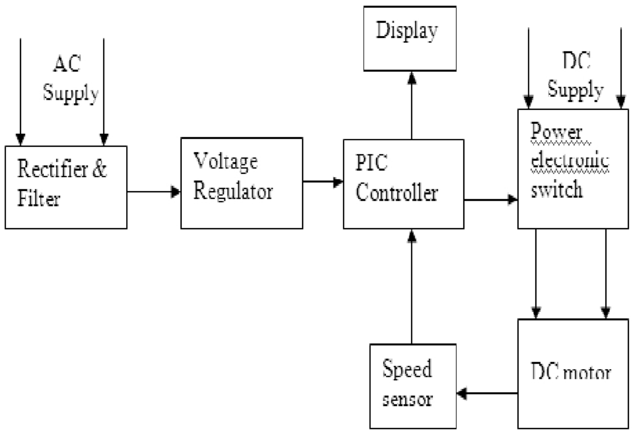

Figure 5. Modified system using PIC controller on DC motor.

Table 4. Result for modified DC motor converter (Armature 170V)

Sl. No.	Armature Voltage (V)	Current (A)	Torque (Nm)	Input Power (W)	Output Power (W)	Efficiency (η)
1.	170	4.2	0.736	714	98.15	13.74
2.	170	5.2	2.06	884	270.38	30.58
3.	170	7.5	4.42	1275	612.61	48.04
4.	170	9.2	6.03	1564	785.1	50.19

Table 5. Modified DC motor converter (Armature 190V)

Sl. No.	Armature Voltage	Current	Torque in Nm	Input Power	Output Power	Efficiency
1.	190	4.2	0.44	798	62.83	7.8
2.	190	5.2	1.18	988	168.50	17.05
3.	190	7.5	4.12	1425	596.99	41.89
4.	190	9.2	5.89	1748	847.28	48.47

is constant. But the total power consumed by motor is very low at 170 V armature voltage .It leads to improve the overall efficiency of the DC motor.

7. Energy Efficient Operations in BLDC

The BLDC motor is known as Brushless D.C. Motor, Basically the stator BLDC consists of a three phase winding as in a 3 phase induction motor and permanent magnet rotor. The three phase winding in stator produces sinusoidal distributed magnetic field. The permanent magnets are shaped to produce a sinusoidal distributed magnetic field in the air gap.

7.1 Operation of BLDC Motor

In a brushless DC motor, the field system is placed in rotor and armature is placed in stator. Armature is supplied with current through solid state switches. To produce torque, the axis of the rotor field is sensed by the rotor position sensors, which in turn actuate the proper solid state switches to fulfill the connection for the production of torque. Figure 6 shows the arrangement of the transistorized brushless DC motor. Optical position sensors using LDRs are made use of to sense the position of the axis of the rotor field. The LED signal is amplified and fed to a proper winding to produce torque.

7.2 Control Circuit for Energy Efficient Operation in BLDC Motor

Rotor position sensors determine the instant at which the stator current is to be switched as a function of the rotor angular position. Three lamps and LDRs are sequence arranged. It is shown in Figure 7. These LDRs signals are turned to make cutting off a power transistor. Each stator phase currents are controlled by separate Power transistor.

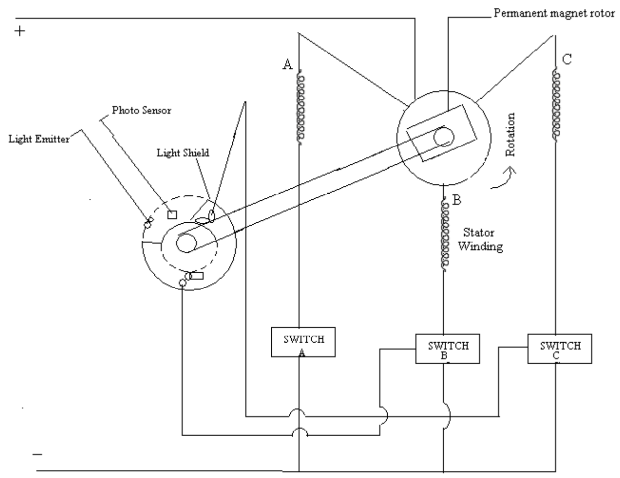

Figure 6. Modified systems in BLDC motor.

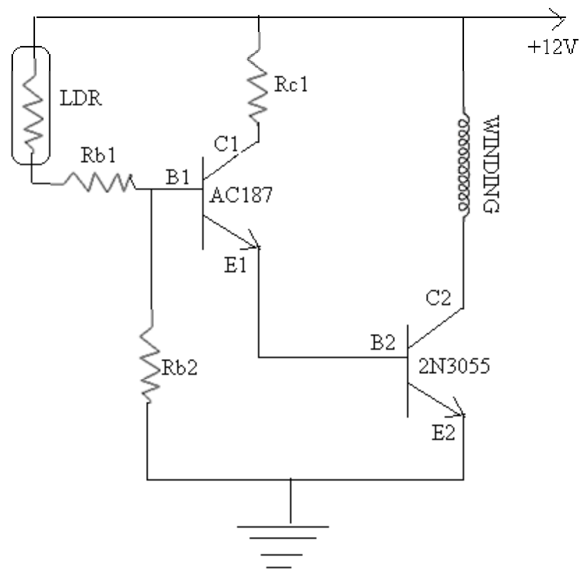

Figure 7. Control circuit of BLDC motor.

7.2.1 *Stator Winding Design*

Since the power supply rating was fixed, the copper conductor which has the current carrying capability of 2 A was selected. For 2 A current carrying capability 25 gauge 0.51 mm diameter copper was selected for stator winding.

$$\text{Resistance of the copper winding } R = \frac{\rho l}{a} \quad (18)$$

Where a - cross sectional area of copper in cm^2

$3.14/4\ (0.051)^2 = 2.04 \times 10^{-3}$

ρ - Specific resistance of the copper

$= (1.7) \times 10^{-6}$ ohm-cm

l = length of the copper wire required in cm.
Let the required ohm rating of one coil R =10 ohms.
$R = 10 = (1.7) \times 10^{-6} \times l/2.04 \times 10^{-3}$
l = 120.16 m.
Length of the copper wire per turn (regarding to core) = 14 cm.
Hence number of turns required = 120.16/0.14 = 858 turns.

7.2.2 Calculation of Back EMF and Air Gap Flux

From the following parameters Back EMF Equation and air gap flux are calculated at no load condition of Brushless dc motor.

Capacity of the BLDC Motor = 30 Watts.
Lowest speed with only one LDR is 100 RPM.
Highest speed with two LDR is 1500 RPM.

Ia - Armature current in amps =1.52 Amp
R_a - Armature resistance (one coil) in ohms = 8 ohms.

$$BackEMF = E_b = I_a \times R_a \tag{19}$$

$$Eb = 1.52 \times 8 = 12.18V$$

$$E_b = \frac{\phi PNZ}{60} \text{ volts} \tag{20}$$

Where,

E_b - Back EMF
Φ - Air gap flux in Weber.
N - Speed of the BLDC Motor in rpm.
P - No. of Poles. (P = 2)
Z - Total number of conductors.
Z = 2 × Total number of turns
Z = 2 × 850 = 1700 turns
N = 2150 rpm.

From equation 18

$$\phi = E_b \times \frac{60}{PNZ}$$
$$= 12.18 \times 60/\ 2 \times 1500 \times 1700$$
$$= 1.43 \times 10^{-4} \text{ Weber}$$

8. Summary and Conclusion

The above comparative evaluation between Switched reluctance motor, DC motor and BLDC analysis is for application purpose. From the foregoing review the following observations could be arrived. It is tabulated in Table 6.

From the observation of table 6, the efficiency of SRM is higher than other motors. From the review of above motors, torque ripple of SRM is sufficiently decreased at modification of pole taper with ununiform air gap. Hence useful torque of SRM is increased. The useful torque is directly proportional to output power and efficiency.

The BLDCs are also used in washing machines, vacuum cleaners, fan and robotics control applications.

Table 6. Comparison of Three Motors Performance

Sl.No.	Features	Switched Reluctance Motor	Conventional DC Motor	BLDC Motor
1	Mechanical Structure	Salient pole stator and rotor	Field Magnets on the stator	Field Magnets on the rotor
2	Maintenance	Maintenance is low	Maintenance is high	Maintenance is low
3	Winding connection	It has salient pole on both rotor and stator, but only one member carries windings.	Ring connection (Delta connection)	Star or Delta connected three phase connection
4	Commutation Method	The rotor has no windings, magnets, (or) cage windings. Hence there is no commutator.	Mechanical contact between brushes and commutator	Electronic switching using power semi conductor devices ie transistors, MOSFETS.
5	Detecting methods	Rotor position can be detected by using sensor or sensor less method.	Automatically detected by brushes	Rotor position can be detected by using sensor ie, Hall sensor, optical encoder.
6	Reversing Method	Rearranging logic sequencer.	By a reverse of terminal voltage	Rearranging logic sequencer.
7	Arcing	Electromagnetic interference due to arcing is eliminated because of the absence of commutator and brushes.	Arcing is high than other two motors.	Electromagnetic interference due to arcing is eliminated because of the absence of commutator and brushes.

(*Continued*)

Table 6. *Continued*

Sl.No.	Features	Switched Reluctance Motor	Conventional DC Motor	BLDC Motor
8	Control Techniques	Many control techniques can be employed to control Switched Reluctance Motor as power circuit is induced as a part of the motor.	1. Armature control 2. Field control	Minimum control techniques can be employed to control BLDC Motor
9	Operation condition	Pulse operated D.C. Motor	Pure D.C. Motor	Permanent magnet D.C. Motor.
10	Life time	Long life with good reliability as it does not have commutator and brushes and so maintenance time required is also less.	Life time is less	Long life with good reliability as it does not have commutator and brushes and so maintenance time required is also less.
11	Design of Motor	A properly designed Switched reluctance motor efficiency is more than a BLDC motor	Efficiency is minimum than other motors.	A properly designed BLDC motor efficiency is more than a conventional DC motor.
12	Speed	Speed of the SRM is high (nearly 40,000 rpm)	Speed of the DC motor is low (nearly 1500 – 3000 rpm)	Speed of the BLDC motor is low (nearly 1500 – 3000 rpm)
13	Energy Savings	The energy from the off going phase is feedback to the source, which results in useful utilization of the energy.	There is no feedback for energy savings.	There is no feedback for energy savings.

By using the control algorithms, the SRM can be applied where constant load, varying torque, and positioning system are required.

9. Acknowledgement

Mr. M. Ravindran sincerely thanks the Defence Research and Development Organization (DRDO), New Delhi, for generous funding (ERIP/ER/07 04364/M/01987 dated 24/07/2011).

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