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Switched reluctance drive in industrial application

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This paper presents the developed switched reluctance motor drive for various applications. The various applications related to motoring and generating operations are described. The block diagram schemes of applications are discussed for various control strategy, basic requirements, sensing techniques and torque speed characteristics. The survey of applications with various manufacturing industries is given. The performance of controller and control strategies for various applications are compared. The Switched Reluctance Motor Drive has compared with conventional motors related to various applications and its suitability.

Keywords: *SRM application, SRM converter, fault tolerance, electric vehicle, wind generator, robotics.*

1.0 INTRODUCTION

The general trend in Motor Control is to design low cost, energy efficient and reliable control systems. Therefore low production cost and efficient motors such as Switched Reluctance motors are naturally involved in these designs. It also creates a need to implement more effective and efficient control strategies in order to increase the overall system efficiency by decreasing the size and cost of driver system.

During the last decades new motor types has become alternative to the conventional DC Motor and the induction motor. Most research efforts has been put into Switched Reluctance Motor in order to obtain high efficiency and solution to general problems of torque ripple, sensorless control and optimized control at low cost drive [1]. Today SRM drives are among the main player for important application e.g. electrically assisted power steering, integrated starter alternator, home appliances, aerospace, robotics etc.

The SRM Drives have inherently variable speed drive features like simple construction, a wide speed range, good energy efficiency, high torque to inertia ratio and torque to power density ratio. It can flexibly operates as a four-quadrant drive, independently controlling both speed and torque [2]. This eliminates the need of expensive and troublesome mechanical gears and transmissions.

The Switched Reluctance Motor has possesses unique characteristics like fault tolerance capability, ability to continue operation despite faulted windings or inverter circuitry [2,3]. The magnetic independence of the motor phases and the circuit independence of the inverter phases permit the Switched Reluctance Motor drive to continue operate with one or more faulted phases with reduced capacity.

2.0 COMPARISON OF MOTORS

Different industrial motors have been compared in Table 1, to give an overview of the characteristics of electrical motors [4]. As the theory based

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comparison of the different drive Systems is very difficult. Therefore it is compared based on the data of existing drive systems [5]. The appropriate drive systems can be modified according to the specific need.

TABLE 1

COMPARISON OF DIFFERENT INDUSTRIAL MOTORS

System	**DC Motor (Permanent Magnet)**	**BLDC (Synchronous Motor)**	**Induction Motor (Squirrel Cage)**	**Switched Reluctance Motor**
Brushes	Yes	No	No	No
Sensors	No	Yes	No	Yes
Magnets	No	Yes	No	No
Robustness	Least	Moderate	Highest	High
Electronic Converter	Simple	Complex	Complex	Simple
Costs	Low	High	Low	Low
Weight	Heavy	Light	Light	Light
Efficiency	Low	High	High	High
Performance	Poor	Excellent	Good	Very good
Noise	Medium	Least	Least	High
Over load	Medium	Medium	High	High
Comfort	Less	High	High	High

The conventional DC motor is established with simple in control. The brush and commutator create contamination, noise and wear. The maximum possible speed is low due to short circuit fault is possible.

Synchronous Motor (BLDC) is light in weight, high efficiency with simple converter. The maximum possible speed is 10000 rpm. Motor is expensive due to permanent magnet and rotor position sensor.

The squirrel cage induction motor is robust, cheap and standardized. The maximum torque is depends on voltage and frequency it draws high reactive current. The converter circuit is complex.

The Switched Reluctance Motor is robust, cheap, high power / weight ratio [6]. Better cooling is possible as heat is produced in stator side only. It generates torque ripple with noise. The rotor position sensing is needed for controlling [7].

3.0 SRM IN MOTORING AND GENERATING MODE

The Switched Reluctance Motor drive is advance version to the stepper motor. It optimised the maximum torque for a given excitation can obtained by suitable control of currents as a function of rotor position for continuous rotation of shaft over the wide speed range [8]. The Switched Reluctance drives magnetic circuit is unique from conventional electrical machines with its single magnetic flux source versus two flux sources (rotor and stator) in all other motors [9]. The Switched Reluctance Motor is a singly excited motor with salient pole on both stator and rotor with phase coils mounted around diametrically opposite on stator poles. The energisation of a phase will lead to the rotor move into alignment with the stator poles, so minimising the reluctance of the magnetic path. The rotor is turn as sequentially switching the current from one phase to next phase and synchronise each phase excitation as a function of rotor position. The direction of rotation is independent of current direction flowing through the phase windings. The reluctance of the flux path between two diagonally opposite stator pole varies as a pair of rotor poles moves in and out of alignment. Since inductance is inversely proportional to reluctance as the rotor pole moves from the unaligned position to aligned position, with a stator pole, the inductance of that stator coil is varies from minimum value to maximum value.

The general voltage expression of an electrical coil with a resistance R and flux linkage Ψ(t) is given by

$$v = Ri(t) + \frac{d\psi(t)}{dt} \quad \text{....(1)}$$

In Switched Reluctance Motor the inductance L is a complex function of position and current in the coil :

$$\psi(t) = L\{i(t), \theta(t)\}.i(t) \text{ and}$$

$$\omega_m = \frac{d\theta}{dt} \quad \text{....(2)}$$

Where θ is the mechanical angle of the rotor position and ω_m is the rotational speed .

Using equation (1) and (2), the dynamic phase voltage equation of a Switched Reluctance Motor with the rotor position θ and rotational speed ω_m, neglecting mutual coupling effects, can be stated as follows :-

$$V_{ph} = Ri(t) + \left\{L(i) + i(t)\frac{\partial L(i,\theta)}{\partial i}\right\}\frac{di}{dt} + i(t)\frac{\partial L(i,\theta)}{\partial \theta}\omega_m \quad \text{....(3)}$$

The last term in equation (3) is a back emf of the SRM.

$$e = \omega_m i \frac{\partial L(i,\theta)}{\partial \theta} \quad \text{....(4)}$$

With constant current, equation (4) is linked to both increase in magnetic field energy and produced mechanical power. In unsaturated condition, both terms equal each other, and torque can be expressed as

$$T = \frac{i^2}{2}\frac{\partial L(i,\theta)}{\partial \theta} \quad \text{....(5)}$$

When $\partial L/\partial \theta > 0$, the torque is positive and electrical power is converted into mechanical power (motoring), while $\partial L/\partial \theta < 0$, the torque is negative and mechanical power is converted into electrical power (generating). The produced torque is independent of the direction of current.

3.1 Motor Operation

For motor operation, the torque development in reluctance machines is independent of the direction of the current within the windings [9]. Due to the fact that the reluctance force is always an attracting force, the only decisive factors for controlling the machine are the relative position of the rotor and the amplitude of the current.

Some method of self-starting if the motor is to be a viable proposition. The technique must be simple, robust, inexpensive and detrimental effects on the running performance should be minimum.

The general schematic block diagram of Switched Reluctance Motor drive is shown in Figure 1. The output signal of rotor position is obtained from the rotor sensor and current sensor signal and fed to controller. Both rotor feedback signals and stator current feedback signals are processed to control triggering of converter/inverter circuit. The current/voltage protection circuit is used to implement the voltage and current protection of the power switch components in power converter in order to avoid the damage of the power converter.

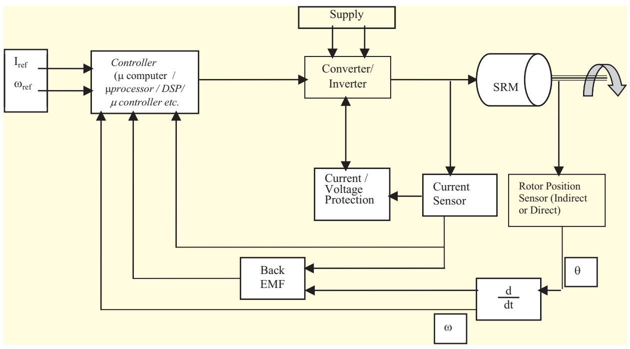

FIG. 1 SCHEMATIC BLOCK DIAGRAM OF SR DRIVE IN MOTORING MODE

3.2 Generator Operation

The generator operation of a reluctance machine is differs from the conventional ac & dc generators. According to the rotor position, one phase of the reluctance machine has to be magnetized at the beginning of each electrical period. With the stator and the rotor teeth aligned to each other, the converter is applies a positive dc-link voltage to the phase. The current within the phase rises until it reaches the upper level of the tolerance band. At this point, a negative dc-link voltage limits a further increment of the current, and the machine works as a generator. The current is reduced until it reaches the lower limit of the tolerance band. Zero voltage is applied to the phase and, due to the declining inductance of the phase, the current rises again. At the end of the electrical period, the phase is demagnetised using a negative dc-link voltage. The performance of a reluctance machine working as a generator mainly depends on the setting of the power inverter. Parameters such as the starting and the demagnetising angle or the upper and lower limit of the tolerance band are decisive [4].

The general block diagram of Switched Reluctance generator is shown in Figure 2. Control of the SRM is more complicated for generator operation than motor operation. In order to obtain maximum Switched Reluctance Generator efficiency, the ratio of average power output to given average input mechanical power should be high. The magnitude and shape of the phase current is directly depends on the turn on and turn off angles. The amount of power generated is dictated by the phase current and relative position with respect to inductance profile. The close loop power control can provide optimum turn on and turn off angle for a given speed. The voltage regulator controls output voltage to the required level with respect to reference voltage.

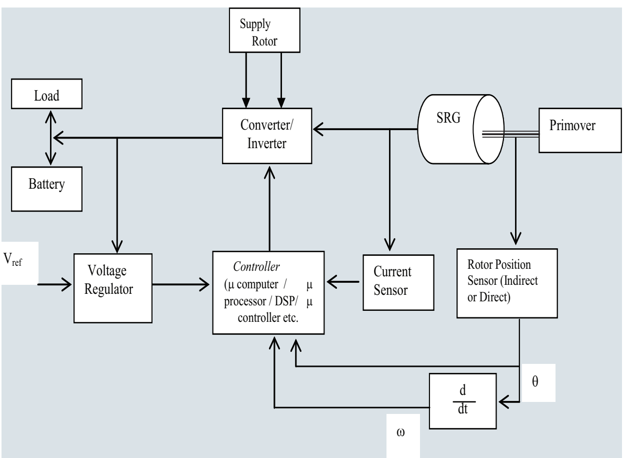

FIG. 2 SCHEMATIC BLOCK DIAGRAM OF SR DRIVE IN GENERATING MODE

4.0 APPLICATIONS

4.1 Traction System

Recently Switched Reluctance Motor has emerged as a serious competitor for both dc and induction motor in traction applications. DC series motors traditionally employed for railway propulsion are troublesome machines. The tough electrical and mechanical conditions are making these machines operation make commutation very difficult. The presence of large quantities of dirt and dust in the cooling air can damage the armature insulation [10]. The rapid wear in brush and deterioration of the commutator surface is occurs. Some parameter of switched reluctance motor and induction motor is compared in Table 2.

TABLE 2

PARAMETERS COMPARISON OF MOTORS

Parameter	**Switched Reluctance Motor**	**Induction Motor**
Dimensions	Small in size and low winding overhang.	Large is size, high winding overhang
Torque speed characteristics	Better acceleration and sustain high speed	Suitable for medium range speed
Power Supply	Accept dc pulses and it gives flexibility for drive circuit.	Due to ac supply bidirectional converter is required.
Cost of motor	About 10% less	More costly
Speed Control	Wide range is available	Limited range

One of the attractive features of the Switched Reluctance Motor system is the possibility of maintaining full power over wide speed range, where as a dc series motor exhibits falling power characteristics unless the commutation conditions allow field weaken through resistors or tapping. The cost of electrical components of the Switched Reluctance Motor is lesser than for an equivalent induction motor. By using pulsed dc rather than bi-directional currents, it is possible to halve the number of switching elements in the control equipment.

The Switched Reluctance Motor has a greater specific volume in terms of stator core volume to produce an equivalent output. The low winding overhang enables this to be achieved within the same space envelope as the induction motor. To obtain the best performance of SRM, it is necessary to make the inductance slope of the stator coils the largest possible with rotor position [10]. It is essential to keep the air gap between rotor and stator teeth as small as possible. A value of 0.5 mm or less is ideal but mechanically such small gap is unacceptable due to the motor shaft deflections. Increasing the air gap 1.0 mm causes the reduction of 6% in rated output of the motor.

The torque/speed characteristics of the Switched Reluctance Motor have the familiar traction curve knee point at the end of the constant torque region [10]. The Switched Reluctance Motor has better acceleration characteristics. In general, for accelerating and sustaining high speed, the motor is more suitable. However for hauling heavy loads at low speeds or for stop/start duty cycle with a mid range average speed, the induction motor is the most suitable machine. This condition is more often in rail traction application [11].

The Switched Reluctance Motor is accept pulsed dc waveform and it is important that the voltage must be allowed to reversed in order to satisfy the demand of rapid negative flux changes. The applied average winding voltage can be regulated by pulse width control and relative angular timing of the pulse to optimize the output [10]. At low speed chopping mode of control is used to obtain a smooth torque output. The Switched Reluctance Motor has one of its most important advantages in its commutation circuit. It is possible to use one commutation circuit to commutate all phases of the drive. This is termed as group commutation and it give overall economy of components. It is necessary to use switches in series or parallel configuration to achieve the required rating.

4.2 Crankshaft Starter/ Generator

The need for electric power in motor vehicles has increased steadily in recent years, and in the future will exceed the output capacity of the belt-driven generator. The general block diagram of crankshaft starter generator is shown in Figure 3.

The use of a crankshaft starter generator (CSG) can meet power demand and in achieve emission-reducing functions such as start-stop operation or recovery of braking energy. The crankshaft starter generator is offers the best possibility of absorbing braking energy, storing it temporarily in the battery and using it for subsequent acceleration of the motor vehicle [12].

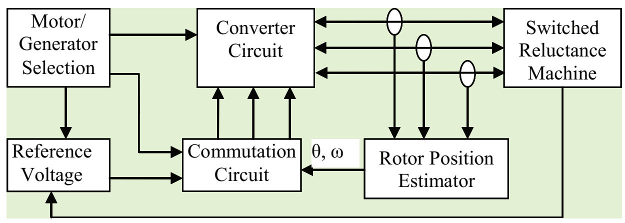

FIG. 3 GENERAL BLOCK DIAGRAM OF CRANKSHAF GENERATOR

The small available installation space and the high starting torque needed represent the main restrictions for all machines that could be chosen [13, 14]. The normal specification of starter/ generator is given in Table 3.

TABLE 3

SPECIFICATION OF STARTER / GENERATOR

Bus Voltage or Supply Voltage	240 V – 270 V DC or 110 V DC
Stator/ Rotor poles	Multiple poles per phase example 12/8
Speed	5000 – 24000 rpm at starter mode 24000 – 47000 rpm at generator mode
Capacity	Depends on application.

The asynchronous machine is in principle inexpensive and robust. On the other hand, an expensive stator winding and a complex control system with high reactive-current consumption are drawbacks to its use as a CSG. In view of the allowable working air gap, the synchronous machine excited by permanent magnets can be assessed as favorable. One negative aspect is the large induced voltage developed at high speeds. Another is the fact that the machine is mounted on the internal combustion engine, exposing it to high ambient temperatures that reduce the ability of the permanent magnets to withstand demagnetization. The reluctance machines presented here do not need any complex winding systems; transform the electrical energy without using excitation by permanent magnets.

4.3 Wind Generator Application

The wind energy application is characterized by low-speed high-torque operation. The machine is inherently a variable speed drive, which makes SRM ideally suited for a frequency wind prime mover such as the wind. The mechanical structure is not as stiff as synchronous machines and coupled with the flexible control system the machine is capable of effectively absorbing transient conditions, which will provide flexibility to the mechanical system.

The schematic setup of Switched Reluctance wind Generator is presented in Figure 4. In wind energy applications, variable speed operation is needed to extract additional energy from the wind stream. The shaft power is proportional to the cube of speed, implying a substantial increase in torque and power as the wind speed increases [15].

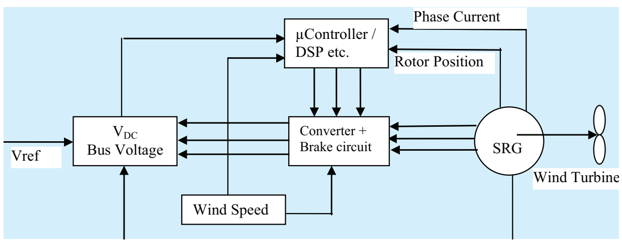

FIG. 4 SWITCHED RELUCTANCE WIND GENERATOR

The prime mover torque–speed characteristic must be considered carefully when determining the electromechanical specifications of the generator. Equally important are the characteristics of the electric power system into which the SRG provides energy.

TABLE 4	
SPECIFICATION FOR WIND POWER GENERATION	
Wind Speed	6 m/s – 12 m/s
Speed	Low 100 rpm – 5000 rpm
Efficiency	85% - 93%
Stator/rotor poles	24/16, 12/8 etc.
Converter	Bidirectional IGBT based
DC link voltage	750 V

It also consist of braking arrangement, when wind speed fall below minimum speed or above maximum speed, the braking system is come into action. The Table 4 presented required specification for wind power application. [2,15].

For the SRG, mechanical energy is converted to electrical form by virtue of proper synchronization of phase currents with the SRG. The SRG produces negative torque that is trying to oppose rotation, thereby extracting energy from the prime mover [15]. The SRG requires a source of excitation in order to generate electrical energy. This excitation is driven from a switching inverter, such as when the controllable switches are closed, current builds in the SRG phase winding. The excitation is generally begins near the aligned position for relatively low-speed operation. The excitation is often advanced with increasing speed so that excitation begins before the aligned position. This is analogous to the advances introduced in the control of the SRM. After the controllable switches are turned off, more energy is returned to the source than was provided for excitation.

The commutators are determines the appropriate turn-on and turn-off angles at below base speed to above base speed. The turn-on and turn-off angles contribute to peak phase current above base speed. Control of the SRG is usually accomplished via a computer, whether it is a digital controller. Implementation of the excitation parameters and current regulation are the most time critical because small implementation errors in excitation angles can have a significant impact on the electromechanical performance. The commutator and current regulator typically operate on very short time scales. For SRG systems that deliver energy to a dc bus of variable voltage, control linearity is commonly optimized. The SRG is capable of support high system efficiencies over a wide speed range. Essentially constant system efficiency for constant power output is typically achievable over a 3:1 speed range, with acceptable system efficiency over a 10: 1 speed range [15].

4.4 Robotics

Now robots are require new types of motors that operate at speed with high torque and that perform commutation with satisfactory smoothness. Direct drive robot is consist of a mechanical arm with electrical motors directly coupled to the joints [16, 17]. The main requirement of direct drive robot is

1. Minimum toque ripple,
2. High torque at low speed
3. Self-starting.

The Figure 5 presented schematic diagram of robotics system using S R drives [18]. The torque produced depends on the geometric features of the design, including the tooth arcs of the rotor and stator, the length of the air gap and other linear dimensions are generally constrained by the overall frame size [16]. If the SRM operates with its phase current switched on and off in sequence, the rotor advances in step angle is given by equation (4)

$$StepAngle = \frac{360^0}{qN_r} \quad ....(6)$$

where q is no. of phases and N_r is no. of rotor teeth.

SR motor has the minimum tooth arc design and larger winding slots between poles to accommodate higher excitation and produce peak torque in the same overall frame size. To achieve higher torque at lower speed without gearbox in robotics by SR motor should have larger number of rotor and stator teeth.

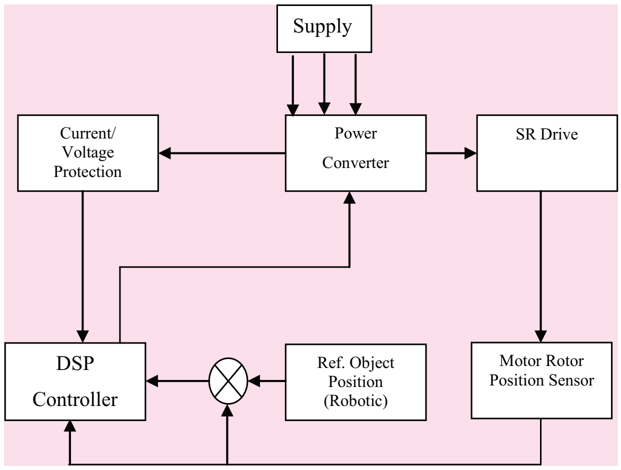

FIG. 5 BLOCK DIAGRAM FOR ROBOTICS SYSTEM USING SR DRIVE

4.5 Electric Vehicle

New generation motor vehicles will have numerous new functions for the passengers and the function of driving will improved with respect to driving comfort towards environmental compatibility [19,20]. Driving comfort is largely built into the motor-vehicle design. Any improvement in environmental compatibility is essentially depends on reduced consumption of primary energy. The “stop-and-go” function and recovery of braking energy has great potential for savings in urban traffic. In the stop-and-go strategy, the internal combustion engine automatically turns off even during relatively short stoppages of the vehicle, and it restarts, ideally imperceptibly for the driver.

An electric machine for electric vehicle application is required the following characteristics [12].

a) High torque density:- In the electric vehicle, the vehicle mass is directly related to torque. Therefore an electric machine is required high torque density. It is possible by improving electric and magnetic loading of machine. Selecting material that has high saturation flux density. An extremely small air gap is chosen along with tight tolerance to increase the machine saliency and torque density. Multiplicity has increased the number of stroke per revolution, which is presented in Table 5.

TABLE 5									
MULTIPLICITY OF SRM AND VARIATION OF ROTOR STEP ANGLE									
Parameter	**Single tooth**			**Multiplicity of two**			**Multiplicity of three**		
No. of phases	3	4	5	3	4	5	3	4	5
Stator teeth	6	8	10	12	16	20	18	24	30
Rotor teeth	4	6	8	10	18	24	20	30	36
Step angle	30^0	15^0	9^0	12^0	5^0	3^0	6^0	3^0	2^0

The torque per pole pair decreases due to the reduction in the saliency ratio, the average torque developed is increased due to multiplicity.

b) High efficiency, especially low torque points:-- The selection of rectangular magnet wire and small air gap are mostly improving the efficiency without affecting toque density.

c) Peak over load capability:-- The peak torque for short time is require to satisfy the vehicle acceleration.

d) Low acoustic noise:-- The multiplicity divides the radial forces along the machine circumference, which results in reduction of acoustic noise.

e) A constant power operating range:-- Generally electric vehicle drives needed constant power range of three to four times of base speed which gives good compromise between peak torque and the inverter volt-ampere rating.

f) Low torque ripple:-- Torque ripple at low speed is unpleasant sensation for the driver. The current profiling is generally done in the Switched Reluctance Machine control to minimize the torque ripple.

g) Low cost of the motor drive system.

The SRM is capable of producing a long constant power range when stator phase current is controlled in optimized manner [20]. The performance of SRM with induction motor and BLDC motor is compared for fixed acceleration time to raise the speed of vehicle 0 – 60 miles/h. The input power and voltampere are presented in Table 6.

TABLE 6							
PERFORMANCE COMPARISON OF DIFFERENT MOTORS							
Acceleration time	**Switched Reluctance Motor**			**Induction Motor**		**BLDC Motor**	
	No. of Poles	**kW**	**kVA**	**kW**	**kVA**	**kW**	**kVA**
14.8 s	6/4	34.6	59.35	51.86	64.6	67.39	74.88
8.7 s	8/6	69.95	109.3	83.04	103.8	109.6	121.8

The two examples indicate that the SRM require much lesser power as compared to induction motor and BLDC motor. The SRM also has wide range of speed at constant power and good overload capability.

4.6 Electric Power Steering

Electric Power Steering specification is required rack performance, steering wheel input, and a mechanical power balance between the motor output and the steering rack output. The dc bus nominal voltage is 12V. The motor drive system should not draw excess current from dc bus. The motor maximum torque for such application with consideration of safety margin is to account for losses in the mechanical interface between the electric motor and the tires [21].

The SRM operates in a constant torque region below base speed, and a constant power region above base speed. This base speed point is a key design point and defines the torque-speed profile for the motor and it satisfy all requirements. This requires the motor and power electronics to have efficiencies in the range of 93%. A 4-phase switched-reluctance motor designed for this application. Base speed is between 1,600 rpm and 1,800 rpm. While certain points in the design exceed the battery current requirement, those points are well outside of the envelope of expected torque required of the system. The SRM is reasonably good at behaving as a constant power motor above base speed. The BLDC motor, on the other hand, often loses power output capability rapidly as the speed increases. Consideration of the currents that must be supported by the switches shows that the BLDC inverters are significantly more expensive than the SRM inverter. This is before consideration of any one of a number of SRM inverter topologies that support operation with five controllable switches (the number of phases plus one). Inverter costs favor the SRM. The SRM uses a smaller air gap than the BLDC motor; however, the cost of the magnet compensates for this. Relative to motor and inverter cost considerations, the SRM appears to have an advantage over the BLDC motor in this application.

4.7 Electric Passenger Vehicle

Fuel based vehicle traffic is one of the most important factors of air pollution. Low emission cars and electric vehicles can contribute, provided their energy consumption is reduced. Recently, SR motor/drive has a potential to replace the original brushless dc (BLDC) drive on the Electric Vehicle. [22,23]

The general requirements of any electric vehicles are low cost, high reliability, long life cycle, low acoustic noise, variable speed control, integrated protection functions, energy efficient low pollution etc.

The SR motor can generates more torque and draws less current than the competing specific PM BLDC motor. The SRM is compatible to solar system also which add extra advantage. Noise is substantially equal to that of the BLDC motor [24]. The alternative SR design included prototype development of the motor and controls. The features of SRM, BLDC and DC Motor are given in Table 7.

TABLE 7

FEATURES OF DIFFERENT MOTORS

Switched Reluctance Motor	**BLDC**	**DC Motor**
multi-phase, double-salient, single-excited high power density, high efficiency, long life cycle, high reliability, low cost, variable speed control	high efficiency, quiet, variable speeds small size, medium reliable costly: converter and PM	Inexpensive large, noisy, low efficiency, low life cycle, low reliability

This switched-reluctance motor meets positioning accuracy requirements. The SR approach further satisfies severe temperature and vibration demands found in an automotive environment.

The Hybrid Electric Vehicle (HEV) utilizes the advantages of fossil fuel vehicles as well as electric vehicles. The electrical machine used in HEV is important from the requirements of the vehicle and its operation [23]. The electric vehicle system requirement [25, 26] are mentioned Table 8.

TABLE 8

ELECTRIC VEHICLE SYSTEM REQUIREMENT

Type of motor	Switched reluctance motor
D C Supply voltage	48V, 110V or 336 V depends on vehicle
Operating temperature	Upto 80^0C at normal loading
Controller	Digital control DSP based
Position sensor	Optical sensor
Converter	IGBT based

The optimum firing angles (turn on and turn off) were selected to achieve the high drive efficiency with lowest torque ripple in entire torque – speed and power speed range of drive. [19] This is achieve by multidimensional optimization, DSP controller, PI current regulators.

4.8 Braking System Of Electric Vehicle (EV)

The braking operation of electric motors in EVs occurs frequently. The requirement of EVs on the braking operation of electric motors can be summarized as follows: (a) high braking torque, (b) little excitation energy, (c) low copper loss, and (d) controlled braking torque.

SRM drives are much suitable for EV applications. Effective braking operation of SRMs is important for EVs with high performances [27].

SRMs have the particular braking mechanism. The braking operation of SRMs includes two modes. One of which is named as the excitation mode and the other is named as the generation mode. During the generation mode, the SRM converts mechanical energy and into electrical energy.

The electro-brake is one of the advantages of electric motors in EVs. During braking operation, mechanical (kinetic) energy of electric motors can be converted to electric energy to generate braking torque. It is helpful to fast the hydraulic brake systems of EVs and its dynamic performance is better than conventional hydraulic brake systems. In addition, instead of conventional hydraulic brake systems, electromechanical systems employing an electric motor that drives the brake caliper through a gear assembly.

4.9 Aircraft Engine Fuel Pump

Presently aircraft fuel delivery system is that the fuel pump is driven by the engine shaft at a fixed gear ratio. The fuel pump is design such that to provide the maximum engine fuel requirement at the minimum engine speed to obtain maximum thrust for takeoff and the engine is at higher speed and less thrust is required, the excess fuel must be recirculated. This decreases the efficiency of fuel pump [28].

In the electric motor driven fuel pump with variable speed, the overall engine/aircraft performance is increase. The elimination of engine gearbox, reducing engine frontal area through increased freedom in locating the fuel pump; this provides flexible engine starting capability with aircraft electronic propulsion / flight control.

The SRM has advantage that it does not generate heat significantly into a shorted phase winding when it is faulted, it does not have magnet saturation at high temperatures, it has independent phases. These characteristics give the SRM drive system greater reliability and fault tolerance compared to conventional motor drive systems [3,7].

The SRM designed for fuel pump has a maximum speed of 25000 rpm to meet system requirements of high power density. The fuel pump drive system control is divided into two parts. The first part includes the current regulators and protection circuits. The second part of the control includes a microprocessor. The processor implements the control equations, producing the turn on angle, turn off angle and the current command from the inputs commanded torque, motor speed and bus voltage.

4.10 Air Compressors, Pumps, Fans & Blowers

Air compressors represent a prime industrial application for SR drives. The reciprocating- and screw-type air compressors in the 1-300 kW power range are apply in SR drives to precisely match power consumption to air demand.

Field trials has shown average energy efficiency gain and operational cost savings of over 25% compared to conventional air compressors of the same rating using an ac drive and inverter, the efficiency of high efficiency induction motor, standard induction motor and switched reluctance motor are presented in Figure 6. The SR drive includes soft starting to eliminate current peaks during start and acceleration. With speed regulation of the compression element, SR maintains a steady delivery pressure enabling further energy savings by optimizing air system pressure levels [4].

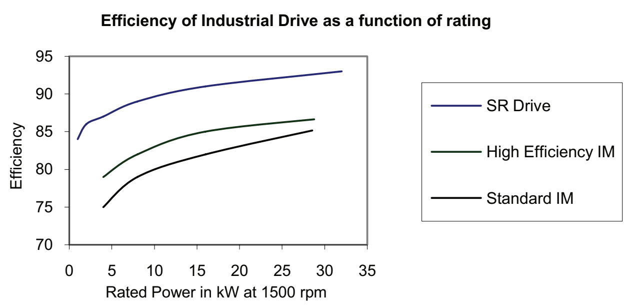

FIG. 6 EFFICIENCY OF CONVENTIONAL MOTORS AND SRM

SR motor-blower units are seeing industrial usage in pneumatic systems, transporting plastic pellets from a storage area to the molding machines. The SR Drives replaces existing series universal motor-driven units which extended service life and lack of carbon emissions are prime motivations. Motor-blower unit with integral controls and cooling fan makes size reduction was a basic design goal. Brushless motor drive has not proved cost-effective. This approach was preferred for the product, compared to remote sensing requiring a sophisticated microprocessor. Motor-blower units find their early application in higher volume floor-care equipment. Three or more times longer motor life compared to brush dc motors is a significant benefit.

The existing centrifugal fan system is a low cost design small enough to fit directly onto a chamber above the molding machine. It is limited by carbon brush life of the dc motor and brush emissions. SR system provides much improved service life (estimated at 4 times) and control capabilities without dc brush problems. Furthermore, The SR drive can be implemented at about the same cost and within the same space configuration as the existing product.

Dosing pumps for industrial processes is require high starting torque and accurate speed control. SR motors have proved to be a good alternative to frequency inverter controlled induction motors for dosing pumps. Higher efficiency compared to induction motors and a wide speed range is other benefits.

Plunger and diaphragm pumps are especially difficult to control due to their pulsating torque. Sensorless SR drives plunger pumps for chemical injection at the water treatment plants has shown high static speed accuracy of the motorsresults in nearly pressure-independent flow rates (excluding pump leakage).

4.11 Domestic Applications

Smart building technologies are being developed in order to optimize energy usage of electrical systems in residential and commercial [29].

The smart building and appliance applications that benefit from variable speed drives. This particularly benefits energy management systems for refrigeration and air conditioning compressor drives, blower motors and fluid pumps.

Switched Reluctance Motor is more accepted for domestic applications. The single phase Switched Reluctance Motor is suitable for high-speed fans [30].

(a) Vacuum Cleaner :- The vacuum cleaners have been steadily increasing suction power over the years. This increasing power level and shorten the brush life on the universal motors typically used in such applications. A brushless DC motor is one solution, but an expensive.

A single phase Switched Reluctance Motor provides better performance, ultra high speed and longer life at a reasonable cost. A vacuum cleaner with SR motor delivers more suction power, offering long life operation than a typical universal motor [30].

4.12 Miscellaneous Applications

(a) Servo Application :- The Switched Reluctance Motor has about half inertia as compare to other servo drives. It is suitable for servo application. For low speed operation, the SR drives can accurately programmable control. A novel encoder-actually a miniature SR motor handles closed-loop positioning for the servo type

control. This approach proved to be a low-cost way to sense and interpolate the main SR motor's coil induction variations for servo control. Its usefulness as a servo motor has been limited because of torque ripple. The three phases SRM is the simplest machine for servo operation because of at least three phase windings are required to ensure self staring capability in either direction. The servomotor is required high torque and low speed. The rolling rotor switched reluctance motor is work as servo drive. In which rotor does not has bearing and forces are tangential between stator and rotor and air gap between stator and rotor is zero.[31] it also eliminate the gearbox to reduce the speed of drive.

(b)Wood Turning Lathe:--The traditional lathe incorporates a constant speed motor with a pulley system to select one of several different speeds of operation. To change the speed of the lathe the belt must be manually shifted from one position to another. These speed range from 190 rpm to 3500 rpm. The wood turning lathes operate at constant power. The load torque requires high torque at low speed and low torque at high speed [32].

There are three types of variable speed drive with meet the required performance criteria for this purpose.

1. Variable speed AC motor (Squirrel Cage Induction Motor).
2. Variable speed DC motor.
3. Variable speed Switched Reluctance Motor.

The DC drive will invariably be supplied with a motor that is provided with through ventilation to allow it to operate continuously at low speed without over heating. The standard induction motor has no provision for low speed operation, having been designed for fixed frequency full speed operation. The inverter may be capable of driving the induction motor with full torque at low speeds, it is possible the motor may overheat. The Switched Reluctance Motor is of a simple construction and provides very good torque and speed performance. The torque requirement of wood turning lathe at low speed is meet by Switched Reluctance Motor. The Switched Reluctance Motor is work with good power over, high efficiency and limited noise over required speed range of wood turning lathe.

5.0 CONCLUSION

The Switched Reluctance Motor drives have excellent performance characteristics with variation in speed, phase current, number of stator and rotor poles. The motor is able to gives the characteristics of induction motor, dc shunt motor or series motor or combination of motors. The major draw back of this motor is noise and torque ripple. The switched reluctance motor is attractively simple in its mechanical construction and appearance, but it requires a controller that is designed and tuned for each specific application. Presently the enormous investment in tooling and infrastructure related to the design, manufacturing, sales, commissioning, maintenance, and control for the switched reluctance motor is improving. Internationally some important manufacturer of Switched Reluctance Motor drives are Emerson/ SRDL UK, Ametek Lamb Electric USA, Oulton (Tasc Drives) Uk Fadong Power Co., Ltd., China, VS Technology Corporation Jordon, Composite Motors, Inc. Brooksville, Fl, Dongda Power Industry Co., Ltd, China etc. also are involve to cater the advantages of SRM drive over other motor in specific applications.

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