Design Analysis and Development of Reluctance Machine for Low Power Applications

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Abstract—**This research work focuses on the design and development of reluctance drive to low power applications. The major drawback as cited in literature is the adherent ripples generated during the operation. To identify the root cause and to pave for further research in this area a reluctance machine of low horse power is developed and tested under ideal conditions (with lighter load/without load) Attempts to solve the problem of torque ripple through geometrical variation of the physical structure of the stator and rotor is performed. The research also simplified the control process by making the controller and the converter physically distinct. The initial research is performed by modelling and simulating the reluctance drive using finite element analysis (FEA) software to estimate the inductance and torque produced in the motor. The static torque developed using the FEA tool is verified using analytical calculations. Based on the results the optimal dimensions are arrived and the motor is indigenously fabricated. The testing on the machine mechanical (like stress compatibility, ruggedness), electrical (short circuit, open circuit) and thermal (measurement of heat with load) are performed individually and are assembled. The coil dimensions are derived analytically and are would and tested for electrical insulation and isolation between the pole surfaces. The driver and the controller are developed and the research project bed is proposed for further investigations under dynamic conditions. The converter and the controller are designed to maximize efficiency and at the same time deliver rated power. The controller algorithm is design to provide adaptive current control. This allows the driver circuit to adjust the power delivered to the load if more current is needed without reducing the efficiency of the system**

Keywords-Optimization –reluctance machine, machine design

I. INTRODUCTION

Electrical Machines are broadly classified as electro-magnetic (motion produced by the interaction of two magnetic fields) and variable reluctance (reluctance in the air gap betweenstator and rotor) based on the operating principle. Electro-magnetic based machines (in particular to induction motors & DC motors) are the work horse of the industry in the past decades even though their operating efficiency is not Encouraging. Both the induction motor and DC motors drive able to be neither good for better dynamic performance nor for higher power density. In particular, with low rotation speeds or at standstill, both drive types have problems in producing satisfactory torques. Evolution of the modern semiconductor power switches and digital technology has opened up new opportunities in the development of sophisticated and tailor made electric drives for typical applications. The most modern machine drive systems today operate at high speeds, high mechanical torque at low speeds with simpler power devices. With the advancement in the powder metallurgy more new magnetic material leads to different configurations of electrical machines. The newer permanent magnet synchronous motors (PMSM) with surface mounted and interior permanent magnets are replacing the induction machines. Absence of rotor electrical circuit simplifies the analysis, but requires an absolute rotor position sensor in order to maintain the field orientation. However Increase in annual usage of rare earth magnets has brought about the pricing up along with the magnet with high co-ercivity as the additives. For high torque density for small rated power applications a reluctance machines are replacing the PMSM.As such is the doubly salient controlled reluctance machine (commercially known as Switched Reluctance Motor) utilising stepper motor reluctance principle (power range limited to a few hundred watts at maximum) to a power range of a few hundred kilowatts. A shaft-position encoder feedback is used along with the motor to synchronise the commutation of the phase currents for precise rotor position. As the name implies these machine cannot operate without the power electronic switches [1-9]. A SR drive system eradicates the commutation issues of the conventional universal current motors and at the same time gives better dynamic performance than an induction machine. These motors have quite simple constructions and their adjustable speed, current and torque features shows that this motor are really suitable for variable speed drive applications as in electric cars, elevators, centrifugal pumps[10 -17].

II. SR DRIVE SYSTEMS

2.1 Switched Reluctance Machine

SR machines are doubly salient and works on the simple principle of iron/steel get attracted by magnet. Figure 1 shows the operating principle of SR machine

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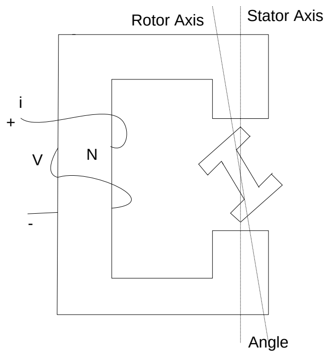


Figure 1 Operating Principle of SR machine

They are characterized by various mechanical and electrical parameters. The operating principle is based on the power effects of the magnetic circuit that tend to minimize the reluctance of the magnetic circuit. With the application of the current in phase A the rotor tries to turn counter-clockwise for minimum reluctance of the magnetic circuit of phase A and thereby minimising the energy of the magnetic circuit. When the energy minimum of phase B has been reached, the magnetic forces try to keep the rotor in a position in which the energy minimum of the magnetic circuit is preserved. Now the magnetic energy has to be removed from phase B to make the machine rotate again and this continue for the other two phases. By connecting the currents to different phases in turn at the correct instants almost smooth torque can be reached over a wide rotation speed range. Switching on and switching off the phases are synchronised with the rotor position for a SR motor.

2.2 Drive Configuration

SRM enjoys quiet a lot of advantageous however smooth torque production for a sufficient rotational speed range requires converters with novel control algorithms. A wide variety of converter circuits for special applications are well documented in [18] including the energy recovery converters (capacitive & magnetic) &converters with external DC-DC circuit. A classical SRM converter for a four phase machine is as in Figure 2.

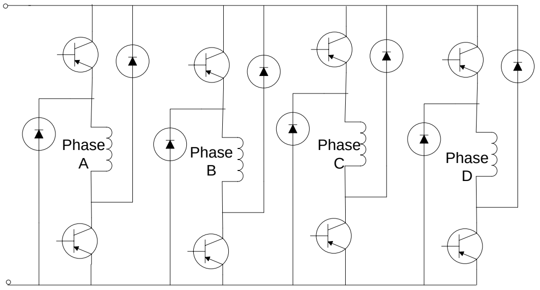


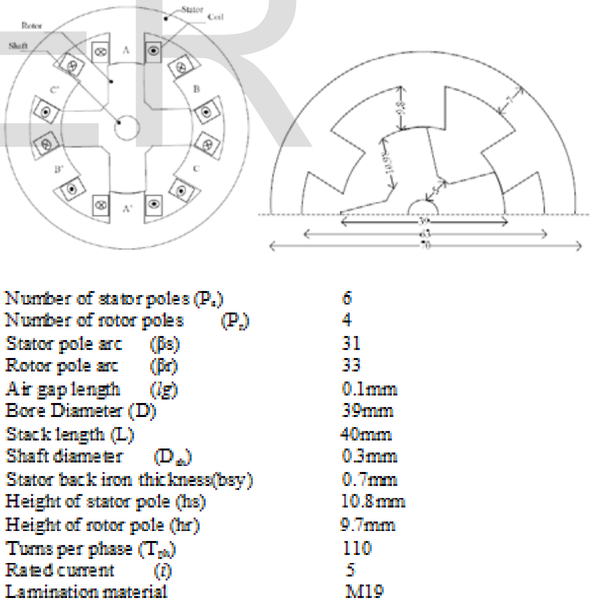
Figure 2 Typical Driver Configurations

2.3 Control Logic

The dynamics of SRM undergo a significant change as speed of the drive increases therefore the typical control modes are position control (for operating above base speed) and current control(for below base speed), the base speed is the speed where the motional back electromotive force ($= i \frac{\partial L}{\partial \theta} \omega$) balances the source voltage and resistive drop. Desired performance can be achieved using current control or hysteresis control. In hysteresis control, we define I_{max} and I_{min} or ∂i . At very low speeds motional back-emf is much smaller than the link voltage and can be neglected. As speed increases back-emf is considerably larger necessitating advancement of the current turn-off angle to achieve higher average torque. In this region the current is limited by the motional back emf and never reaches rated value. Hence hysteresis control is not possible and so the torque is maintained at the optimal value by controlling the theta on and theta off angles. In general the control algorithm variables that are tuneable are (1) turn on angle (θ_{on}) (2) turn-off angle (θ_{off}) (3) the voltage (V) and (4) the reference current (i_{ref}).

III. MACHINE DESIGN ANALYSIS

By sequential switching of the phases, the motor can be driven in forward rotation (anticlockwise from the shaft end) and in the reverse rotation (clockwise) generating torques either positive or negative. Therefore, all four quadrant operation is possible using this motor. Switching on and switching off the phases are synchronized with the rotor position for a SR motor. Hence a rotor encoder is essential for operation of this type of machine. Figure 3 shows a typical 6/4 SR machine with its dimensions used for the initial design and is optimized to develop the machine using analytical method as described in the next section.Three approaches are performed for validation of the machine design for optimized performance



Number of stator poles (P_s)	6
Number of rotor poles (P_r)	4
Stator pole arc (βs)	31
Rotor pole arc (βr)	33
Air gap length (lg)	0.1mm
Bore Diameter (D)	39mm
Stack length (L)	40mm
Shaft diameter (D_{sh})	0.3mm
Stator back iron thickness(bsy)	0.7mm
Height of stator pole (hs)	10.8mm
Height of rotor pole (hr)	9.7mm
Turns per phase (T_{ph})	110
Rated current (i)	5
Lamination material	M19

Figure 3 SR Machine designed for this investigation

(i) Cyclic Integration Approach

The cyclic integration approach is carried by the assumption of small incremental area and calculating the average flux value between limits over a period of time. Concentric lines are assumed. Figure 4 shows the principle behind the cyclic integration approach and is shown for the partial overlap conditions.

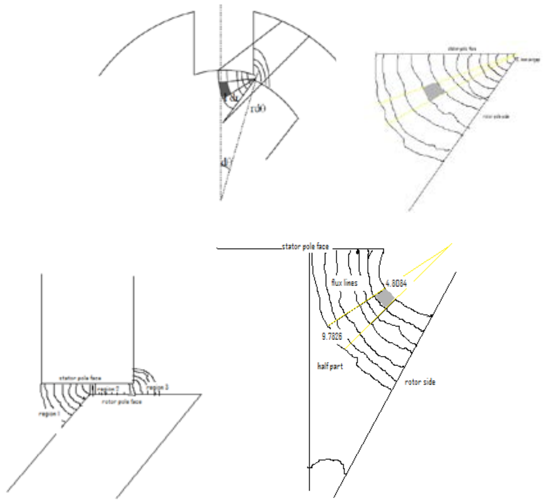
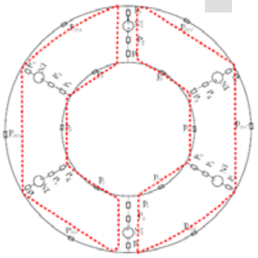


Figure 4 Cyclic integration carried at different pole positions

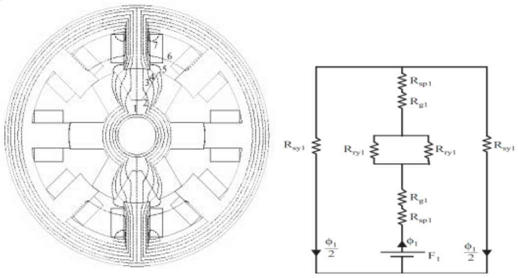
(ii) Permeance Method of Analysis

Permeance method of analysis is performed based on the vector potential modulation. This approach is as used in the literature on the assumption on the permeance values at different parts of the magnetic circuit and then computing the equivalent permeance value, the flux linkage and the computations. Figure 5 shows the equivalent magnetic circuit, the permeance shape component values. Figure 6 shows the magnetic flux lined for the partial alignment and the flux lines assumed and also shown the permeance magnetic circuit. Figure 7 shows the flow chart representations on the optimisation procedure used in the approach.



Element	Permeance equation
	$P = \frac{\mu_0 b}{al}$
	$P = \frac{2\mu_0 l}{\pi} ln\left[1 + \frac{b}{a}\right]$
	$P = 0.52\mu_0 l$
	$P = \frac{\mu_0 la}{b}$
	$P = \frac{\mu_0 A_{mean}}{l_{mean}}$

Figure 5 Magnetic Equivalent circuit and the permeance values assumed



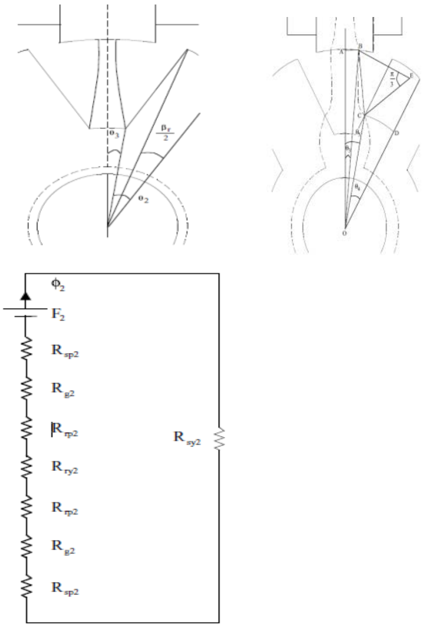


Figure 6 Permeance method of analysis for partial aligned positions

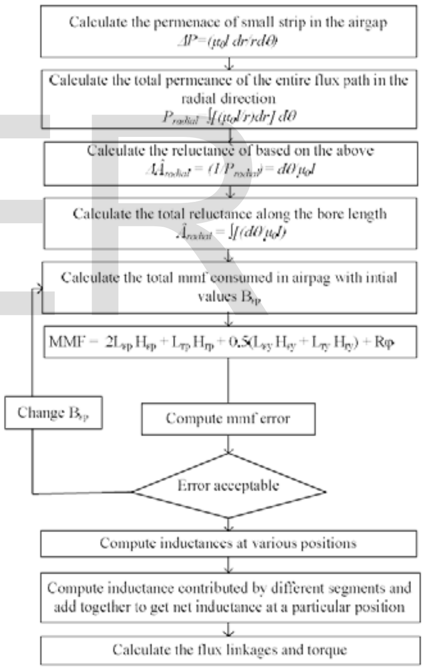


Figure 7 Flow chart for the optimisation procedure

(iii) FEA Analysis

FEA analysis is performed using the commercial industrial standard software for various positions of the rotor over one rotor pole pitch. All the three approaches are compared and is evaluated as shown in Table 1.

Table 1. Comparison on performance of the proposed structure

Parameter	Analytical			FEA
	Reference Work [2]	Cyclic Integration Method	Permeance Method	
Unaligned Inductance (mH)	1.3443	1.4518	1.823	1.1
Aligned Inductance (mH)	16.3	15.39	16.83	14.6
Motoring Slope	0.023	0.0239	0.0246	0.025
Average Torque (N-m)	0.287	0.299	0.3075	0.28

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IV. EXPERIMENTAL DESIGN

The proposed machine is built in the laboratory conditions for testing performance of the machine. Figure 8 shows the stator with the wound coil and the rotor made up of silicon material. The shaft is non-magnetic and is embedded with the rotor body.

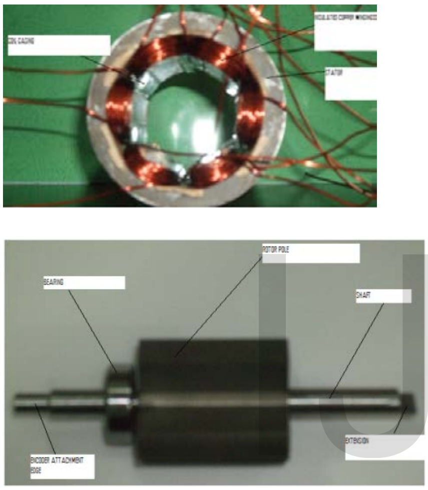

Figure 8 Rotor design and assembly with bearing

The control algorithm for the operation, the driver and the controller are shown in Figure 9 – Figure 11 respectively.

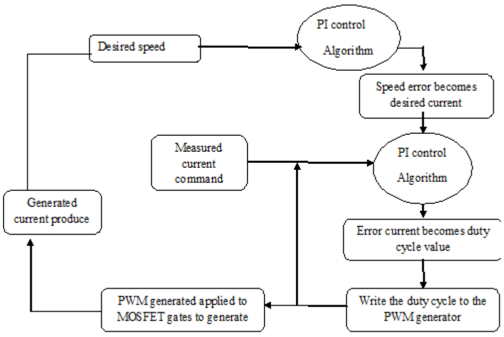

Figure 9 System Algorithm

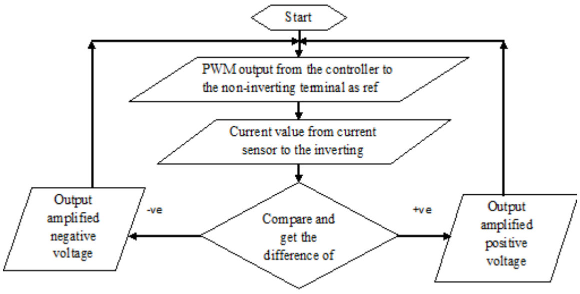

Figure 10 Driver Algorithm

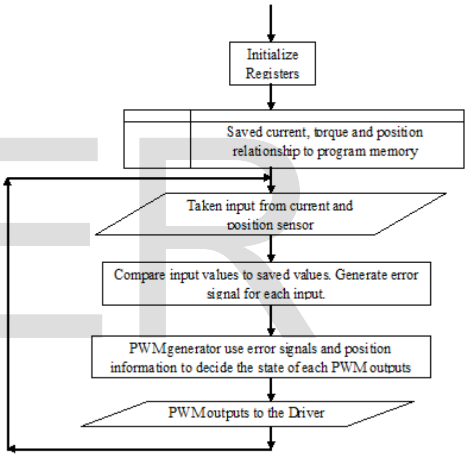

Figure 11 Controller Algorithm

After the controller and converter have been built, an experiment is conducted to verify that the right phase of the motor is excited with the right voltage. While the controller provide the entire system PWM to trigger the gate of the power MOSFET in the converter circuit, the converter does the job of transferring the input voltage to the output whenever the gate of the MOFET is turned on.

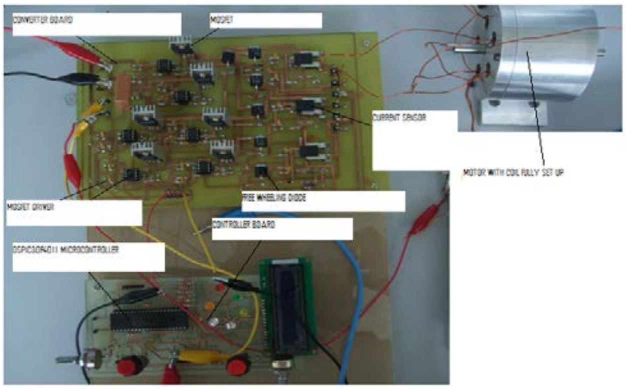

Figure 12 Experimental Test Bench

Every phase of asymmetric half bridge converter has two switches which determine the voltage applied to each phase of the winding. When both switches are turn on, positive voltage is applied to a copper winding. And when either of the switches is turned on, zero voltage is applied to the phase and for both switches being turned off, negative voltage is applied. Each switch in the converter is provided with a freewheeling diode that helps conduct current away from the coil when any or both of the switches are turned off. Figure 13 shows the output for the phase A-A'.

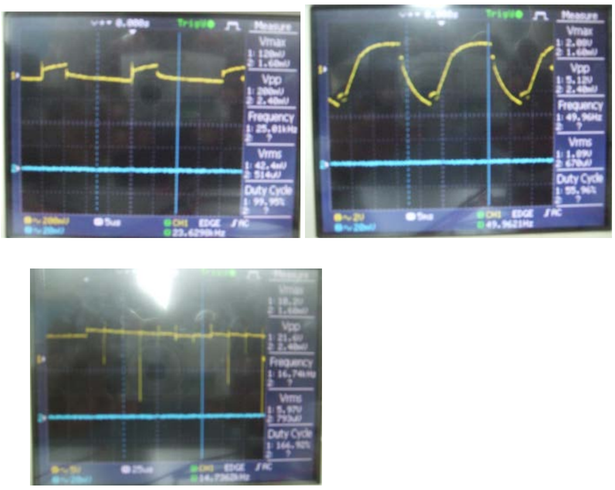

Figure 13 Excited output for the motor for phase A-A'

V. CONCLUSIONS

The simplicity of switch reluctance motor and its robustness has been an intriguing feature throughout this project. The converter has been built and tested. The controller also has been built and was used to produce the PWM that was used in the experiment under static condition. All experiment conducted on the setup has been done under static conditions. However, the controller, the converter and the machine will be made available for further study under dynamic conditions.

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