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SWITHCED RELUCTANCE MOTOR ELECTRIC DRIVE

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Abstract. This paper describes the design and implementation of a switched reluctance motor (SRM) drive. The SRM, which consists of three phases, requires a complex power electronic circuit for operation and requires a microcontroller to switch between the different phases. A low cost popular microcontroller was selected for this function. The hardware implementation and the results obtained shall be presented in the paper.

Keywords: SRM (Switched Reluctance Motor), Speed control, Microcontrollers, Power electronic converter.

1. INTRODUCTION

The Switched Reluctance Motor (SRM) is generally regarded as a relatively new type of electrical machine. However, the principle of this motor was first used in the early 19th century. Due to low performance of this motor in the past, it was no longer used. Nowadays, with the development of power electronics, processing speed and machine design, the switched reluctance motor has become a good competitor to the conventional drives. Furthermore, the rotor of a conventional machine requires windings and therefore some sort of cooling. A SRM does not have a commutator or windings on its rotor and analysis of the SRM shows that with the correct control strategy and electronics, it can be more efficient than a conventional machine such as the induction motor. Due to the simple construction of a SRM, the cost of the machine is relatively low and it achieves a high power to weight ratio. The rotor consists only of steel laminations and does not have any conductors or permanent magnets. This makes the rotor of a SRM cheaper to manufacture and extremely robust. Figure 1 shows the four poles rotor of the SRM used in the project. Applications of this motor include low power wind generation, electric vehicles and air conditioners.

Fig. 1. Rotor of the SRM used

The SRM will not rotate by plugging it directly to the mains as in the case of induction motors. For this motor to rotate, a power electronic controller is required as in the case of brushless dc motors. The SRM drive system requires control electronics, which makes the power converter expensive and complex. Nowadays, this is no longer regarded as a main issue, because the cost of semiconductors is reducing rapidly.

2. PRINCIPLE OF OPERATION

In a SRM, the torque is produced by the variable reluctance in the air gap. This is different to the case of a dc machine where torque is produced by the interaction of the armature and magnetic field from the stator. The principle of a SRM, is the same as that of the magnetic circuit shown in figure 2. In this magnetic circuit the air gap has different reluctance for different values of x. This will affect the amount of flux passing through the air gap. When the magnetic circuit is energised, a magnetic field is produced and this will attract the plunger until the distance x is nil. The same principle is used by the switched reluctance machine and a similar arrangement is shown in figure 3. As can be observed in figure 3, both the rotor and stator have salient poles and this double-salient arrangement makes the machine different from the conventional synchronous motor. When one of the three-stator poles is energised, a single magnetic field is produced and this will force the nearest rotor poles, to align with the energised stator poles. For this to occur, the rotor needs to rotate. At the alignment instant, the reluctance will become equal to a minimum value. For the rotation to continue, the next stator poles should then be energised.

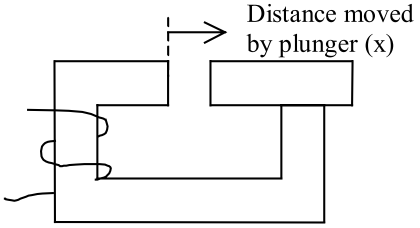


Fig.2. Basic Magnetic Circuit

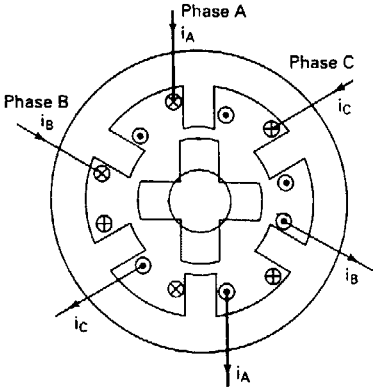


Fig. 3. Cross section of a three-phase 6/4

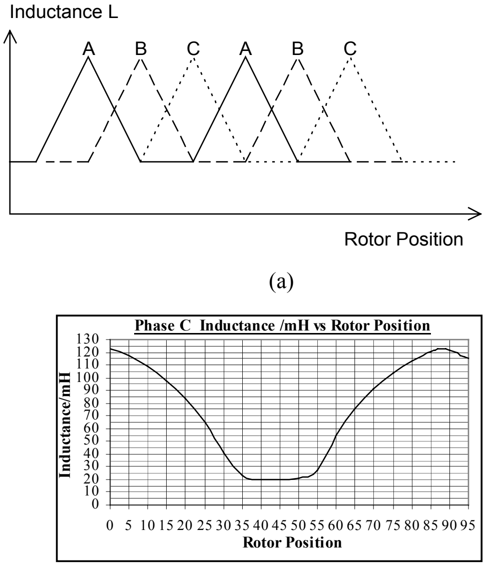
The motor that was used in this project, has three stator phases with two poles per phase. In figure 3, the stator coils that are opposite to each other are connected in series.

A SRM starts to rotate by energising the phases in a particular sequence. The configuration shown in figure 3 will rotate in an anticlockwise direction, if the sequence is C, B, A, and a clockwise rotation if the sequence is A, B, C. As it can be noted, the rotor rotates opposite to the sequence that is applied to the stator. When any phase is energised, the nearest pair of rotor poles is pulled into alignment with the appropriate stator poles by reluctance torque action.

2.1 Properties of SRM

2.1.1 Inductance

Figure 4a shows how the inductance of each phase varies with rotor position. The inductance profile of the motor used in this project was measured and is shown in figure 4b. When the stator pole of the phase is between the rotor poles, the inductance is a minimum. On the other hand, when a rotor pole is underneath the stator pole, the inductance is a maximum. This diagram was obtained by measuring the inductance at various rotor positions.



(a)

(b)

Figure 4 - Variation of L with rotor-position of a three-phase SRM

2.1.2 Torque Characteristics

The torque equation for such motor is given below:

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

where: T is the torque in Nm

i is the current through the motor's phase

$\frac{dL}{d\theta}$ is the inductance gradient

From the above equation, it can be noted that the torque has a non-linear relationship with the current and moreover it does not depend on the current direction.

The machine will behave as a motor or generator according to the inductance gradient. Therefore, it is extremely important to apply the current at the right moment. For motoring action, the current should be turned on when the inductance is growing. The advance angle θ_0' will help to achieve the required output torque. The current is switched on at an advance angle θ_O', and rises linearly to a magnitude of I at the point where the inductance starts to grow, as shown in figure 5.

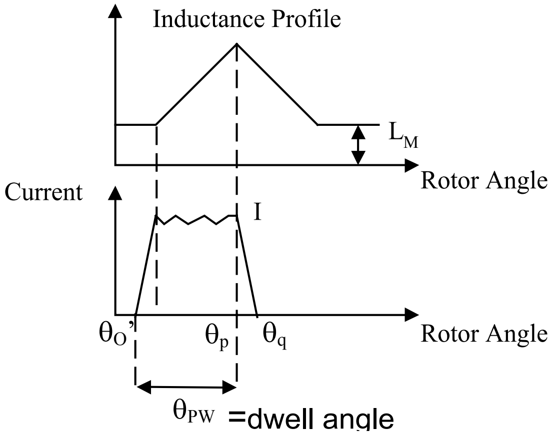


Fig. 5. Advance Angle.

The current I is related to the advance angle by the following equation:

$$I = \frac{V_d}{L_m \omega_r} \theta_0' \qquad (2)$$

where: L_m is the minimum inductance.
ω_r is the rotor speed.
V_d is the dc link voltage.

The current I is maintained constant by a chopping control method, and then turned off at an angle θ_p, so that the angle at which I is again zero i.e. θ_q, does not extend too much in the negative inductance slope region as illustrated in figure 5. If this happens, the machine will start to brake.

The current pulse during forward braking is the same as that of forward motoring at low speed. However, during braking the current pulses are applied at the point when the inductance slope is negative. During braking, current application will start on the positive slope, which will cause motoring for a small angle. In reverse motoring, current should be established when the inductance slope is negative, because the latter appears as positive in the reverse direction.

2.1.3 Torque-Speed Characteristics

The torque-speed characteristics of a SRM is shown in figure 6. This figure shows the operation of the machine in two quadrants i.e. motoring and generating and the direction of rotation is the same in both cases. Similarly to other existing drives, the torque is limited by the maximum current and the speed by the bus voltage.

Referring to figure 6, point B is called the *base speed*, and below this point, maximum current and rated torque can be obtained at rated voltage. The current amplitude should be controlled by chopper action. Above the base speed, there is the constant power region, and the torque will be controlled by the advance angle θ_0'. In this region, torque output must decrease with increasing speed. thus the current must be controlled to a value less than rated. As speed increases, the back emf increases and finally the falling power region is reached. In this region, the current will be limited to very low values and zero eventually [3].

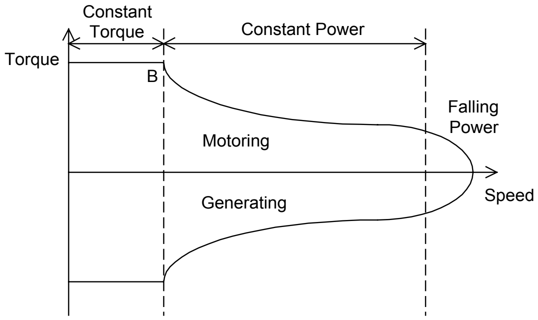


Fig. 6. Torque Speed Characteristics.

3. SPEED CONTROL OF SRM

The control of this motor is similar to that of the dc motor and therefore cascade control is used. Such a control scheme involves an outer speed loop and an inner current loop. The current loop is required to control the current level and it is faster than the speed loop. A current demand represents also a torque demand. Hence, when a certain speed is required, the speed error will demand a current demand. When this kind of motor attains a certain speed, the control strategy has to change. The control strategies are implemented in a control loop and the system switches from one to another at a particular speed, in order to optimise the system's performance.

At low speed, the back emf is small and therefore the current will build up quickly to dangerous levels if it is uncontrolled. This can be done by chopping the d.c. link voltage between $\pm V_d$ at a fixed frequency. The duty cycle is varied according to the current error. The switching scheme implemented was hard chopping, where the phase transistors are driven by the same pulse signal, which is at a higher frequency than the fundamental of the current waveform. Hard switching facilitates the board design but increases the current ripple.

At high speeds, the positive rate of change of current is limited due to the large back emf. Chopping cannot be used because this will lower even further the current rate of increase. Therefore, a single pulse is applied at the right time and both phase transistors are kept on. The pulse is applied when the inductance is at a constant minimum value.

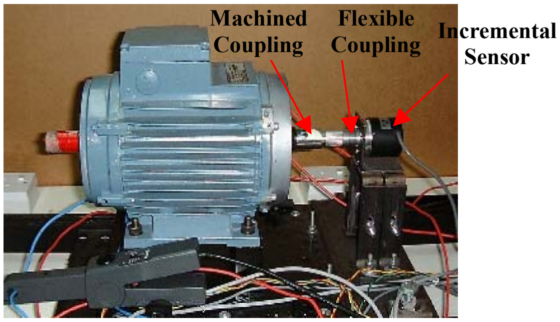


Fig. 7. Complete mechanical setup and incremental sensor.

4. PROJECT OVERVIEW

4.1 Position Sensing

An incremental sensor was used to detect the rotor position and the direction of rotation. The two signals A and B from the sensor were connected to a digital counter and to a logic circuit so as to detect the rotor position and direction respectively. The output of the incremental sensor was doubled.

4.2 Signal Conditioning

A Hall effect current transducer (CT) was used to sample the motor winding current. The current transducer used has an effective ratio of 1:1000. To read positive and negative currents, level shifting was required.

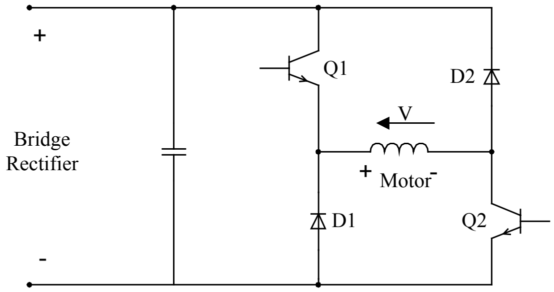


Fig. 8. Asymmetric half bridge inverter.

The current through the motor's winding is chopped at 6kHz, and therefore the output produced by the CT will also include the switching frequency. To filter the high frequency, the Sallen-Key topology for second order filters was used and the type of filter chosen is the *Butterworth*. This type of filter provides a good passband flatness.

The filter and the level shifter were combined in one board. The output of each CT is connected directly to this board through screened cables. When such cables were used, it was made sure that they were grounded from one side only so as to avoid an earth loop. The signals obtained from this board were then connected to the microprocessor board.

4.3 Protection circuitry

In any machine, the control circuitry is very important because this will ensure that the machine is operated safely. For instance, if the controller fails the current through the windings can raise to an alarming level. This can be prevented by using an adequate protection. The input to this board is taken from the filter board that was described in the last section. Once the current exceeds a preset high current value, the board issues a shut down signal to the power converter.

This board also includes a Watchdog circuit, the function of which is to ensure that the PWM is working properly. If the PWM fails, the watchdog circuit, will issue a shutdown signal to the power converter.

The protection board, includes other trips which are the manual trip, processor trip and a spare trip. For the processor trip, an optocoupler is available on the board, while the spare trip can be connected externally. All the above mentioned shutdown signals are 'ORed' together and transmitted to the shut down of the power converter through a current mirror and optocoupler. The optocoupler provides isolation and the current mirror helps in reducing the noise pick-up.

4.4 Steering Logic

The phases of the motor have to be turned on and off according to the rotor position. Furthermore, the PWM applied to a phase will vary according to which phase is 'on' or going to be turned 'off' or 'on'. As was explained at the beginning, a phase is turned on before the previous phase is turned off i.e. the *advance angle*. The PWM applied to the phase that will be turned off should have a low duty cycle whilst a duty cycle of 100% must be applied to the next phase. The microprocessor used can output two PWMs at the same time and can be controlled independently. The PWM is applied to the right phase and moment by using steering logic. The resulting logic outputs drive a current mirror- optocoupler setup, which are connected to the power converter.

4.5 Power Converter

The performance and cost of a SRM drive is highly affected by the power converter. The power converter that was chosen for this project falls under the hard switching converters and is called the *Classic Bridge converter*. Figure 8 shows this converter. This circuit is widely used and it is also called the *Asymmetric half bridge*. This circuit consists of two freewheeling diodes and two power switches. The motor's winding is energised, and current starts to rise as soon as transistors Q_1 and Q_2 are turned 'on'. When the current reaches the reference value, the converter is controlled to remain at that value by the PWM. At the moment of phase commutation, the phase starts to demagnetise through the two diodes and energy will return back to the dc link voltage. For this project the asymmetric half bridge was modified to an H-bridge. This decision was made because an H-bridge offers more flexibility.

4.6 The Microcontroller

The microprocessor chosen for this project is the PIC 16F877. This processor was chosen due to its low cost and it offers various facilities. Some examples include Pulse Width Modulation (PWM) generation, analogue-to-digital conversion, three digital ports that are eight bits wide and two other ports, which can handle both analogue and digital data. It also includes protection facilities, such as watchdog timer and brown-out detection circuitry. Other specifications and facilities of the PIC 16F877 can be found in its data sheet [9].

Figure 9 shows how the boards described in this section were connected together.

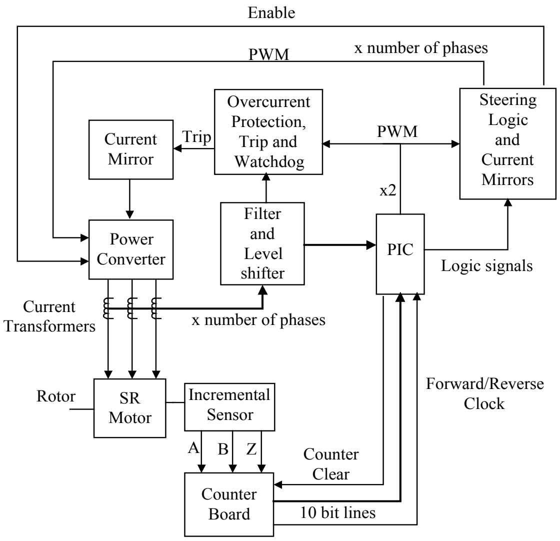


Fig. 9. Connection of sub systems.

5. RESULTS

Figure 10 shows the complete experimental set up. On the left-hand side, one can see the SRM and power converters while on the right hand side there is the controller circuitry.

5.1 Position loop

The position loop code was implemented on the PIC micro-controller and the system could read the absolute rotor position. According to the position, the processor turned the phases 'on' and 'off'.

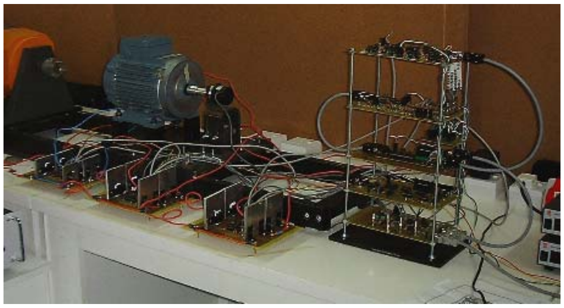


Figure 10 - Complete Setup.

5.2 Current loop

To control the current through the motor's windings a proportional (P) controller was used for the initial experimental control. Eventually this will be replaced by proportional integral (PI) controller. Prior to connection all of the phases to their respective power converters, the P control strategy was applied on one of the motor's phases and the result is shown in figure 11a.

The controller was designed for a reference current of 5A. The bus voltage was 100V and the resulting output current was 4A. Since the integral action is missing then the steady state error was not reduced to nil.

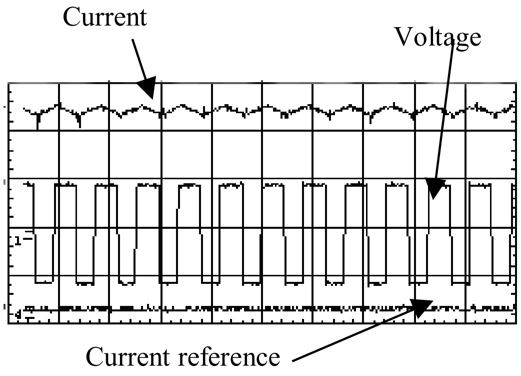


Fig. 11. P controller.

5.3 Speed Loop

At the time of writing, a very basic speed loop was designed. Like the current control loop described above, eventually a PI controller for the speed loop shall also be designed. To observe the current waveforms through each phase, current probes were connected to each phase. The output of these probes was connected to a four-channel oscilloscope. The speed was measured by a manual tachometer. Figure 11b shows the three phases being switched on and off together. The current through phase A is represented by channel 2. The current through B by channel 3 while that through C by channel 4. Channel 1 shows the PWM that is applied across phase C.

The waveforms in figure 12a were obtained at a DC voltage of 40V and a speed of 84 RPM and a peak current of 1.4A on each phase was obtained.

After a dwell angle of 30^0, the PWM is set to a duty cycle of 0.1 on the active phase and at the same time the next active phase is enabled by a 0.9 duty cycle. The waveforms in figure 11b shows how the current waveform is controlled.

Using the same scale and notation for each phase, the motor was rotated at a lower voltage i.e. at 20V. The waveforms obtained are shown in figure 12b. The motor was crawling at a speed of 44 RPM. As it can be noted, the period of the current pulses is wider than the previous case. Figure 12c shows the motor tested at 70V. The speed was measured to be 168 RPM. As the voltage increases, both the current through the windings and the speed increase. Furthermore, the period of the current pulses gets smaller, i.e. the phases are being turned on and off at a faster rate.

6. FUTURE WORK

The main aim of this project was to show that the SRM can easily be controlled by a low cost micro-controller, such as the PIC 16F877. The next stage of this project will be that of implementing an improved current controller and also to close the speed loop. Further, the SRM drive will then be used for research in three main areas:

1. Sensorless speed control of SRM
2. High performance control of the SRM for electric drives
3. Wind turbine drive SRM for grid-connected applications

7. SR MOTOR DATA

Three Phase 6/4 SRM
230V, 14 A, 1.5 kW
1500 RPM

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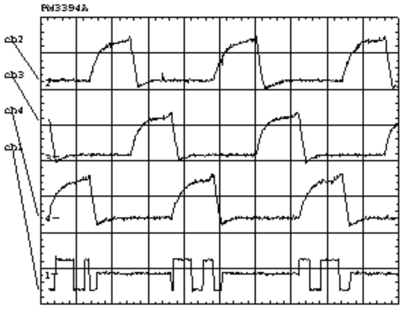
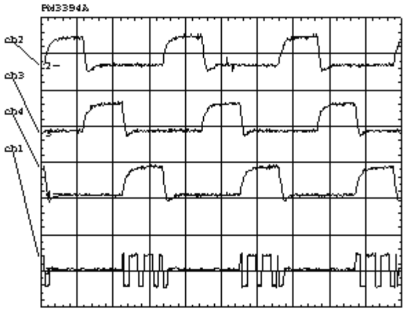
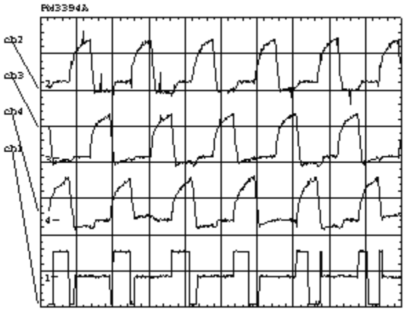


(a) 84 r.p.m.



(b) 44 r.p.m.



(c) 168 r.p.m.

Fig. 12. Waveforms at different speeds

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