Control of a switched reluctance motor engineering essay

The main objective of this chapter is to spot the light on the practical performance of some form of control on an actual switched reluctance motor in preference to merely theoretical method including simulation and modelling. Moreover, the design of the controller involves reducing the noise. The crucial motivation for this is to enhance new expertise, sensibly regarding circuit design and construction the use of a Programmable interface controller (PIC).

A switched reluctance motor (SRM) has been appeared since the nineteenth century, but the renewal of this motor has been to discover a high-power switched device [13]. The earlier motor was facing a controversial issue in their control where the power electronic switching was very expensive and has many drawbacks.

The Switched Reluctance Motor (SRM) is an electromagnetic, rotary machine in which torque is produced by the tendency of its movable part to move to a position where the inductance of the excited winding is maximized [12]. Furthermore, (SRM) has been proposed for variable speed applications [13]. In general a salient-pole synchronous machine without field excitation or permanent magnet is called a reluctance machine. From the general definition (SRM) is classified as a synchronous machine, but has different construction. These differences are both stator and rotor have salient poles. However, the stator has wound field coils but the rotor has no coils or permanent magnet. Moreover, the stator has higher number of poles or (tooth) than the rotor. While each pole in the rotor is excited by the opposite pole in the stator due to a sequence of current pulses which produce magnetic field on each stator poles. The Switched Reluctance Motor (SRM) can be more capable for variable speed than AC and DC motor. Since it is simple, robust, has a high efficiency and high power density [3, 10, 12].

Figure 1. 1: two- two poles SRM [12]

Over the past 30 years the power electronics growth has made the exploit of the characteristics of reluctance machines sufficiently well. Consequently, several successful products are now manufactured. The rotation of the motor depends on the angle between the rotor poles and the stator poles where the current is switched on or off to each poles in the stator where the position of the rotor is very significant. For the motoring principle example, two- two poles (SRM) where stator has two poles with two wound field coils connected in series and two poles in the rotor without magnets or windings and free to rotate as it shown in figure 1. 1. If the rotor poles edge is started to be aligned, the current is switched on. Consequently, the inductance is increased and the torque in the rotor is occurred to pull the rotor in clockwise direction. The direction of the rotation is addressed by the current. The current is switched off; when the rotor poles are fully aligned with the stator poles that make the rotor free to move. However, if the current is not switched off the torque at the fully aligned is become negative that produces an attraction between the poles where the negative torque and positive torque cancel each other [12]. The ideal current waveform is therefore a series of pulses synchronized with the rising inductance intervals. The cycle of torque production associated with one current pulse is called a stroke.[12] As a result, to increase the resolution more teeth can be add to the stator and the rotor.

From the instantaneous electromagnet torque equation which was derived by T. J. E. Miller(2001) [12] Te = i2/2 dL/dÎ¸ that shows the torque is proportional to the square of the current. Therefore, the current is always unipolar. However, at the end of each stoke the voltage must be reversed to return the flux linkage to zero. The power switching IGBT, GTO and MOSFET or any other switching devices can be used in the power electronic topologies [3]. These switches are used to open and close the exiting power in the stator winding.

1. 5. Applications of SRM

Since the SRM has a significant characteristic operation and design which shows many advantages and makes them suitable for various applications. R. Krishnan (2001) [10] shows the wide range of applications. For example, plotter drive, air-handler motor drive, hand fork lift/ pallet truck motor drive, door actuator and washers and dryers machine, those applications are low power applications where the drives are less than 3hp. Moreover, the medium power applications range is less than 300kw such as industrial general purpose drive, train air conditioning drive and mining drive. However, the SRM did not find much attention by the manufacturers in this range of power. The high power drives are still under study for drives up to 1000hp for fan and pump applications where the converter is very competitive. The high speed applications such as screw rotary compressor drives, centrifuge for medical applications, and aerospace applications the SRM is a perfect option for them due to the small size of the rotor and high power density. Some efforts of study are in Mild Hybrid Vehicles that is reported by (Watterson, P. A. ; et al) [17] in 2008.

1. 6 Research area

Since the SRM has appeared and has disadvantages such as reduction of acoustic noise and torque ripple. According to the noise and vibration sources can be classified into four main categories: magnetic, mechanical, aerodynamic, and electronic. The classification was done by R. Krishnan (2001) [10] as it shows in figure 1. 2. Most researches are based on the design of the motor or in the controller to improve the motor performers and reduce the noise. Iqbal Husain (1994) [8] discusses the effect of the high ripple toque which causes vibration and acoustic noise. The case was in driving SRM for low speed and high performance applications by a new PWM strategy current control. The method was based on optimum profiling of the phase current during an extended overlapping conduction period of two phases. The result shows a smooth operation with minimum torque pulsations by controlling the current profiling. Moreover, other studies were in magnetic radial force as M. N. Anwar (2000) [1] shows the lower noise is occurred when the dominant mode frequencies is high. As a result the research has experimented a proposed design considerations to a 4-phase, 8/6 (1-repetition) and a 3-phase, 12/8 (2-repetition) 1. 0 kW SRM with low acoustic noise requirement. The results of the proposal design shows that the noise level has been reduced; however, a 3-phase SRM is noisier than a 4-phase SRM. There are other research was on reducing the noise by Adding extra winding to the phase winding to reduce magnetic stress during commutations with Two – stage power converter. Adding extra winding to the phase winding in 6/4 SRM with Two – stage power converter shows a significant improvement in the efficiency and reduce in the vibration and noise [16]. The electronic sources of noise occur by reason of the harmonics of voltage and current. The significant research is reported by (Lecointe J. P; et al) in (2004) [11]. The research was in adding an auxiliary winding to the model of a BDFRM (brushless doubly-fed reluctance machine) to shows that the additional winding has a benefit in reducing the noise in SRMs where a specially derived current is injected to create a suppression force. The BDFRM is used to analyse the equivalent circuit where the equivalent circuit of the model is similar to SRM. However, the process still needs to be complete using two current sources.

Figure 1. 2: sources of noise in electrical machines [10]

Advantages and disadvantages of 3 basic power electronic circuits

There are many power electronic topologies that is used for SRM depends on the machine phase configurations. R. Krishnan (2001) [10], figure 1. 3, has classified the power converters for switched reluctance machines. The simple three topologies are:

Figure 1. 3: Classification of power converters for SRM [10]

1. 7. 1. Single-Switch-per-Phase Circuits (Split dc supply converter)

The basic operation of this topology, figure 1. 4, is to split the reverse dc power supply into two capacitors. The phase voltage is half the dc voltage when the switch is on and negative half voltage when the switch is off. Consequently, this configuration is a disadvantage. Moreover, the maximum speed and the output power are half the rated while the current and the voltage are half. This topology is only used for low-cost application due to the high power losses. However, the advantages of this topology are: simple and less cost. [3, 10]

Figure 1. 4: Single-Switch-per-Phase Circuits (Split dc supply converter) [10]

1. 7. 2. Single-Switch-per-Phase Circuits (Bifilar type)

The basic operation of this topology uses a bifilar winding, figure 1. 5, with the motor winding to regenerate the stored energy to the supply that the phase winding is connected in series with the switch, and the diode is connected in series with the bifilar winding. The reflected energy is an advantage for this topology in some applications, where the transistor voltage is much higher than the supply voltage. However, the cost increases as the extra winding is added to the motor and the complex design of the power electronic. Moreover, the power density of the motor reduces because of the bifilar winding. [3, 10]

Figure 1. 5: Single-Switch-per-Phase Circuits (Bifilar type) [10]

1. 7. 3. Two-switch/phase Asymmetric Bridge Converter

From the half bridge topology that is illustrated in figure 1. 6. if both Q1 and Q2 are turned on the apply voltage at the winding is equal to the supply voltage. However, if both Q1 and Q2 are turned off the apply voltage at the winding is equal to a negative supply voltage where D1 and D2 to avoid the freewheel currents. The advantages of this topology that it can give a negative voltage to reduce the torque ripple refer to noise for a high performance SRM drive system and it can be used for generator or motor operations. The disadvantages more control is needed, more fault in the switching [3, 10, 12].

Figure 1. 6: Two – Switched / Phase Asymmetric Bridge Converter [12]

1. 8 Speed and Position Controller

The switched-reluctance motor is basic control system form of a torque-controlled drive as compared in performance to a D. C motor (separately-excited). Commonly, controlled speed or even position is the most requirements. The SR motors speed increases if torque is still produced. As the D. C. drive the torque of SR motor controller is included within a speed regulating loop. The rotor position sensor, which is the encoder, is used as a feedback to derive the speed of the motor readily as it shown in figure 1. 7. From the figure it can be seen that an additional feedback is introduced to achieve the position control of the SRM [3].

Figure 1. 7: basic speed and position controller for SRM [3]

Aims and Objectives

The aims of the project are to design, build and test a power electronic circuit for Switched Reluctance motor (SRM) using Bifilar type.

The objectives are as following:

Understand the operation of two- two poles SRM to realise the behavior of the motor and their characteristic. We can know from their characteristic how to make the motor spin and the control techniques that is used for them.

Select and Design Power Electronic Circuit can help to active a high efficiency, low noise and low cost.

Test Power Electronic Circuit with Resistive Load: to find the advantages and disadvantages of the circuit when the resistive load is applied to the motor.

Design, Build and Test current limiting circuit where the current limitation can achieve low torque rebel. From the low torque rebel the noise can be decrease.

Rotate motor using direct feedback where the position of the rotor is important to detect the moment of switching on and off.

Study and understand PIC 18F 46K20.

Program PIC to control SR Motor by designing a simulation using the MATLAB or other programmes.

Chapter 2

Choosing power electronic component

2. Overview

Over the time motor control has a significant growth in the industrial control where digital signal processors together with external hardware and appropriate software are used widely. In order to control the motor the switching device should switch on and off according to the position of the motor rotor and the apply current to the stator winding. The aim of this chapter is to highlight the details of the components that were used in the controller design.

2. 1 Technical operation of Simple SRM

The simple SRM has 2 poles in the stator and 2 poles in the rotor, figure 1 which the stator iron core has square shape with two winding in the upper side opposite the poles. Both stator and rotor are salient poles where the free spinning rotor is placed between the stator poles. In order to spin the rotor, stator poles are energised by the winding when the rotor poles are unaligned with stator poles. The inductance increased and the torque is produced as the rotor approaches the aligned. At this point the stator winding is demagnetised allows the rotor free to spin. The time of the energised and de-energised of the motor windings depend on the rotor speed.

Figure 2. 1: (a) Simple SRM 2/2 poles with bifilar winding[12]

2. 3 Winding connections

The motor has a bifilar winding to build up the current in the stator quickly, figure 1, which facilitates the higher torque and magnetic flux densities occurring. As a result the stored energy regenerated to the supply that the phase winding is connected in series with the switch device. This leaded to three achievable connections, figure 2, for bifilar winding.

Figure 2. 2: Possible winding connections

The first connection shows the parallel connection that has a resistance connected in parallel to the motor windings to reduce the power losses when the switch is off. This connection has the main disadvantage due to the high loss.

The second connection shows series connection that two switching devises are used which increase the cost of the design. However, this topology is the most common one for SRM according to reduce the switching heat losses, protections and their control flexibility that is handling the phase current and the machine's acoustic noise.

The third connection is the most cost effective and easier to control for the simple SRM figure 2. Moreover, it is offering the zero voltage supply as a reference for all power switching that make it suitable for low- voltage systems. Simply this configuration operates as it shows in figure 2. 3, When the current of phase-A is turned off by removing the base drive signal to T1, the induced EMF in the winding is of such polarity that D1 is forward biased. This leads to the circulation of current through D1, the bifilar secondary winding, and the source, thus transferring energy from the machine winding to the source. The various timing waveforms of the circuit are shown in Figure 2. 3. During current turn-off, the applied voltage across the bifilar secondary winding is equal to the dc link voltage. The voltage reflected into the main winding is dependent upon the turns ratio of the windings. Considering the turns ratio between the main winding in series with the power switch and the auxiliary winding in series with the diode as a, the voltage across the power switch is VT 1 = Vdc + aVdc =(1 + a)Vdc This shows that the voltage across T1 can be very much greater than the source voltage. One switch per phase comes with a voltage penalty on the switch. The volt ampere (VA) capability of the switch will not be very different for one switch compared to two switches per phase circuit. [10]

Figure 2. 3: (a) Converter for an SRM with bifilar windings; (b) operational waveforms of bifilar converter. [10]

Thus, Figure 4 shows the primary plan for designing the current limiting circuit for the third connection of SRM and each block are explained next.

Figure 2. 4 basic configurations for current limiting

2. 4. Power switching component

Nowadays semiconductor and electronic switching devices offer a significant performance to control the electrical motors. Moreover, their size and cost make them more convenient to use in the motor control. The electronic devices has a significant role to control SRM where the switching on and off for the voltage is the major role to control the SRM with high performance. As a result, the main electronic devices that can be used are field effect transistors. There are two types of the field-effect transistor J-FET and MOSFET (see the appendix figure 3) [4]. The MOSFET has taken a widely role as a best choice to the simple SRM for many reasons that is discussed later in this chapter.

2. 4. 1 N-channel power MOSFET (STP36NF06)

Simply the MOSFET is a metal-oxide-semiconductor field effect transistor where the MSFET has a significant characteristic [2]. The characteristic of N-channel MOSFET shows a significant use in switching. The structures of the MOSFET are shown in figure 5 where the MOSFET consist of Si P material substrate, two N material substrate that one is the source and the other is drain, and between them there is an insulator Sio2 and at the top metal conductor which is known as a gate. The length (L) below the gate and between the source and the drain is known as a channel. Fundamentally, the MOSFET output current is proportional to the charge in the semiconductor material by the control electrode[15].

Figure 5 MSFET structures [6]

The MOSFET is used as a switching device to provide a high speed switching. The significant advantages of the field-effect transistor are:

Higher operation temperature.

Lower switching leakage.

High input impedance.

Low noise.

Lower power dissipation during switching.

In addition, The N-channel MOSFET has advantages such as ease to use for high frequency switching and simpler to control where the MOSFET gate drive do not require a continuous current to switch ON. When the MOSFET is needed to switch ON positive threshold voltage is needed to apply to the gate drive and Zero current to completely switch off. Moreover, the N-channel MOSFET has higher density integration and possible in rapid reduction in capacitances. [2]. MOSFET (STP36NF06) gate requires drive properly the later components are used to limit the current and the gate signal for the MOSFET. The gate drive is a power amplifier that accepts a low power input from a controller devices and generate the appropriate high current gate drive for a power MOSFET[4].

2. 5. Bipolar junction Transistor

Transistors are considered one of the main elements of semiconductors that have been discovered in modern times. Transistors are used in the amplifiers of electrical signals and electronic switching, which have helped a number of factors such as small size, ease in manufacturing, cost effective and consume less power to extend significantly.

Figure 2. 6 (a) transistor structures (b) npn and pnp structures

2. 5. 1. ZTX 653 NPN transistor

The NPN transistor is a type of bipolar transistors known as a medium power transistor. The NPN ZTX 653 transistor has interesting features that make it suitable for the push pull topology and amplifier topology (pre totem pole connections). The features of NPN ZTX 653 transistor are [6]

* 100 Volt VCEO

* 2 Amp continuous current

* Low saturation voltage

* Ptot= 1 Watt

5. 5. 2. ZTX 753 PNP transistor

The PNP transistor is another type of bipolar transistors that is used in the push pull topology. The PNP ZTX 753 transistor is suitable to employ in the push pull topology (Totem Pole) according to their features. Their features are [6]

* 100 Volt VCEO

* 2 Amp continuous current

* Low saturation voltage

* Ptot= 1 Watt

Figure 2. 7: npn and pnp characters

2. 5. 3 Gate drivers (Totem Pole)

This type of connection is known as a discrete drivers or push pull drives which is in common use today. Figure 2. 8 shows the complimentary arrangement pair bipolar NPN and PNP emitter configuration. Moreover, the N-channel and P-channel MOSFT can be employing for totem pole connection. However, the N-channel and P-channel MOSFT driver suffers from shoot through current, caused by the threshold voltage overlap during ON and OFF transitions, resulting in increased drive power requirements [9].

Figure 2. 8: push pull configuration

The bipolar Totem Pole, figure 2. 8, is non-inverting and offers no voltage gain to improve the pre-driver rise or fall times. It does provide current gain to reduce the driver impedance to speed the charge and discharge of the device capacitances. Once the input capacitances are charged and the power device has been switched, the driver does not require holding current. It has medium speed and does not perform well at higher conversion frequencies [9].

This circuit uses a complementary pair of transistors similar betas and power rating one is an npn power Darlington, and the other is a pnp power Darlington. When a high voltage (e. g., +15 V) is applied to the input, the upper transistor (npn) conducts, allowing current to pass from the positive supply through the motor and into ground. If a low voltage (0 V) is applied to the input, the lower transistor (pnp) conducts, allowing current to pass through the MOSFET gate from ground into the negative supply terminal.[14]

2. 5. 4. Common emitter amplifier (inverter)

This configuration is a simple electronic circuit that is used to boost and invert the low signal. Figure 2. 9 shows the circuit that contain a high resistance value with NPN transistor. The low signal is switch on and off the transistor where the resistance is limiting the current that apply to the transistor. This topology is used to boost and invert the output of signal processing unit to appropriate the signal that can switch the MOSFET as it will be discussed in the following point.

Figure 2. 9 common emitter configuration

2. 6. Current control and limiting

The winding current is controlled inorder to be not more than 8A. When the MOSFET is switched ON without any current limiting circuit, the current shoots up without any control. As a result, the technique for current limiting is arranged as follows

When the winding current is less than 8A the MOSFET switches ON.

When the winding current is exceeds 8A the MOSFET switches OFF.

Therefore for appropriate current control, square wave signal is applied to the gate of the MOSFET. The frequency of input signal at the gate of the MOSFET is take into account to make the MOSFET switch properly with regard to the above current control arrangement. In order to do that feedback from the source of the MOSFET is carried to non-inverting terminal of the comparator. Figure 10 shows the operational waveform of the MOSFET. It can be seen that, the MOSFET needs to switch off when the voltage at inverting input of the comparator reaches 0. 8V and switch on when the voltage is zero. Moreover, the reference voltage is 0. 8 volt from the voltage divider law when a 0. 1Î© resistance is connected to the source of the MOSFET. The 555 timer can offer the control of MOSFET’s switching frequency.

Figure 2. 10: the expected waveforms from the design.

2. 6. 1 Timer NE555P

The 555 timer IC is an incredibly useful precision timer that can act as either a timer or an oscillator. In timer mode is known as monostable mode – the 555 simply acts as a “ one-shot” timer; when a trigger voltage is applied to its trigger lead, the chip’s output goes from low to high for a duration set by an external RC circuit. In oscillator mode is known as astable mode – the 555 acts as a rectangular-wave generator whose output waveform (low duration, high duration, frequency, etc.) can be adjusted by means of two external RC charge/discharge circuits.[14] In this project the monstable circuit is highlighted due to it has one stable state.

Figure 2. 11 (a) monostable configuration of timer 555 (b) monostable operations[14]

In the monostable configuration, figure 2. 11(before a trigger pulse is applied) the 555’s output is low, while the discharge transistor in on, shorting pin 7 to ground and keeping C discharged. Also, pin 2 is normally held high by the 10-k pull-up resistor. Now, when a negative-going trigger pulse (less than 1â„ 3VCC) is applied to pin 2, comparator 2 is forced high, which sets the flip-flop’s Q_ to low, making the output high (due to the inverting buffer), while turning off the discharge transistor. This allows C to charge up via R1 from 0 V toward VCC. However, when the voltage across the capacitor reaches 2â„ 3VCC, comparator 1’s output goes high, resetting the flip-flop and making the output low, while turning on the discharge transistor, allowing the capacitor to quickly discharge toward 0 V. The output will be held in this stable state (low) until another trigger is applied [14].

According to the operation of the monstable the pulse width can be modified by changing the value of R1 and C.

T= 1. 11 R1C

Thus, to obtain capable functioning of the circuit the variable resistance R1 with a maximum value 100KÎ© and the threshold capacitance C value is 100nf are chosen.

The timer input is the output of the comparator where the two values of the voltage are compared to make the output of the timer based on these two values. The two voltages are one is 5V and the other is the feedback from the MOSFET’s source.

2. 6. 2. (LM393) Comparator

The comparator is used to compare the voltage between the source voltage and the feedback from the MOSFET. This is important to control the current by triggering the timer to limit the current as it is mentioned before. LM393 has several advantages for timer input which are

Higher accuracy in comparators.

High voltage range (2. 0V to 36V)

Biasing with lower input current.

Lower input offset current ±5 nA

Figure 2. 12 LM393 connections to the circuit

In order to establish the reference voltage variable resistance is required in the voltage dividers law. The operation of the comparator is simply as follows

If IN+ > IN- the comparator output = V8.

If IN+ < IN- the comparator output = V4.

From the previous operation it can be seen that the comparator send the signal to trigger the input of the timer and the timer acts upon the applied signal therefore the MOSFET switches on and off with regard to the timer output. However, the output of the timer switches on the MOSFET when the current is high which will be disastrous to the motor. To avoid this not to happen, a design of logic gates are incorporated in the current limiting topology of the SRM.

2. 6. 3. Logic gate design (SN74LS00N)

Logic gate is designed according to the output of the timer which gives the positive pulses when the current exceeds to 8A and no pulse when the current is less than 8A. With the purpose of switch (totem pole) the gate of the MOSFET turns on and off at required instants of time using an external Drive Signal. Figure 2. 13 shows the technique of the combination between the Drive Signal and the timer output to control the MOSFET. SN74LS00N has four NAND gates that can be used to reduce the number of IC’s in PCB connection. The logic gate is connected to the timer output which will be inverted with a common emitter configuration to switch on the MOSFET when the timer output is low (Itimer <8A), (table 1).

Figure 2. 13: (a) SN74LS00N chip (b) logic circuit connection (c) NAND gate logic signal.

The MOSFET behaviour that is need according to the timer output is shown in table 1. To do that the NOT gate, OR gate and AND gate are needed before the pre totem pole connections (common ammeter topology).

Current condition

Timer(A)

Drive Signal(B)

Output of the logic gate (C)

MOSFET gate signal (Output after totem pole)

I > 8A

MOSFET must be off

1

0

1

0

1

1

1

0

I < 8A

MOSFET can be on

0

0

1

0

0

1

0

1

Table 2. 1 digital signal behaviour

Boolean algebra

From the logic gate output we can get the function:

(1)

This function can be simplified

(2)

Figure 2. 14 (a) logic gate from equation 2 (b) table shows the equavelant NAND gates [7](c) the final simblified gates using the table (b)

2. 7 Curant limiting circuit simulation

Curent limiting circuit , figure 2. 15 , is the simulation circuit and the combination of each part that discussed previously.

Figure 2. 15: current limiting circuit