CHAPTER 3

SWITCHED RELUCTANCE MOTOR TOPOLOGIES

3.1 Switched Reluctance Motor

Switched reluctance motor is an electrical rotating machine in which torque is obtained by the tendency of its rotor to move into a position where the reluctance of a magnetic circuit is minimized.

Figure 3.1 Switched Reluctance Motor

It means the inductance of the exciting winding is maximized. External circuit is provided for detecting the angular position of the rotor and energizing the phase windings with respect to rotor position. This type of motor is known as a switched reluctance machine. It is shown in Figure 3.1. It is operated as both motor and generator.

3.2 Principle of operation

If an iron rotor with poles, but without any conductors, is fitted to a multiphase stator, a switched reluctance motor is capable of synchronizing with the stator field results. When a stator coil pole pair is energized, the rotor will move to the lowest magnetic reluctance path. It is shown in Figure 3.2. A switched reluctance motor is also known as a variable reluctance motor. The reluctance of the rotor to stator flux path varies with the position of the rotor.
Figure 3.2 Reluctance is a function of rotor position in a variable reluctance motor

[Courtesy: Switched Reluctance Motor by R. Krishnan]

Sequential switching of the stator phases moves the rotor from one position to the next. This is an over-simplified rotor and the waveforms illustrate operation.

The other coil connections are successively pulled to ground, one at a time, in a wave drive pattern. This attracts the rotor to the clockwise rotating magnetic field in 60° increments.

Figure 3.3 Variable reluctance motor over-simplified operation

[Courtesy: Switched Reluctance Motor by R. Krishnan]

If one end of each 3-phase winding of the switched reluctance motor is brought out, various waveforms may drive variable reluctance motors. Wave drive (a) is simple, requiring only a single-ended unipolar switch. That is, one which only switches in one direction. More torque is provided by the bipolar drive (b), but it requires a bipolar switch.
Figure 3.4 Variable reluctance motor drive waveforms: (a) unipolar wave drive, (b) bipolar full Step (c) sine wave (d) bipolar 6-step (Courtesy: Switched Reluctance Motor by R. Krishnan)

Figure 3.4 is a representation of the drive waveforms. The power driver must pull alternately high and low. Waveforms (a and b) are applicable to the stepper motor version of the variable reluctance motor. For smooth vibration-free operation, the 6-step approximation of a sine wave (c) is desirable and is easy to generate. Sine wave drive (d) may be generated by a pulse width modulator (PWM), or drawn from the power line.

Doubling the number of stator poles decreases the rotating speed and increases torque. This might eliminate a gear reduction drive. A variable reluctance motor move in discrete steps, with respect to the energy status of the coils. If smooth rotation is the goal, there is an electronic driven version of the switched reluctance motor. Variable reluctance motors or steppers actually use rotors like those in Figure 3.4.

3.3 Electronic driven Variable Reluctance Motor

Variable reluctance motors are poor performers when direct power line driven. However, microprocessors and solid state power drive make this motor an economical high performance solution in some high volume applications. Though difficult to control, this motor is easy to spin.

Sequential switching of the field coils creates a rotating magnetic field which drags the irregularly shaped rotor around with it as it seeks out the lowest magnetic
reluctance path. The relationship between torque and stator current is highly nonlinear and difficult to control.

Figure 3.5 Electronic driven variable reluctance motor

(Courtesy: Switched Reluctance Motor by R. Krishnan)

An electronic driven variable reluctance motor resembles a brushless DC motor without a permanent magnet rotor. It is shown in Figure 3.5. This makes the motor simple and inexpensive. However, this is offset by the cost of the electronic control, which is not nearly as simple as that for a brushless DC motor. Variable reluctance motor is simple than an induction motor due to control the speed. Electron reluctance control solves this problem and makes it practical to drive the motor well above and below the power line frequency. A variable reluctance motor driven by a servo, an electronic feedback system, controls torque and speed, minimizing ripple torque. It is shown in Figure 3.6.

Figure 3.6 Block diagram of Electronic driven variable reluctance motor

A variable reluctance motor is optimized for continuous high speed rotation with minimum ripple torque. It is necessary to measure the rotor position with a rotary position sensor like an optical or magnetic encoder, or derive this from monitoring the stator back EMF. A microprocessor performs complex calculations for switching the
windings at the proper time with solid state devices. This must be done precisely to minimize audible noise and ripple torque. For lowest ripple torque, winding current must be monitored and controlled. The strict drive requirements make this motor only practical for high volume applications like energy efficient vacuum cleaner motors, fan motors, or pump motors. One such vacuum cleaner uses a compact high efficiency electronic driven 100,000 rpm fan motor. The simplicity of the motor compensates for the drive electronics cost. No brushes, no commutator, no rotor windings, no permanent magnets, simplifies motor manufacture. The efficiency of this electronic driven motor can be high. But it requires considerable optimization, using specialized design techniques, which are only justified for large manufacturing volumes.

3.4 Electrical Theory behind SRM

The motor is doubly salient with phase coils mounted around diametrically opposite stator poles. Energisation of a phase will lead to the rotor moving into alignment with the stator poles, thus minimizing the reluctance of the magnetic path. This is the same principle of operation as the variable reluctance stepper motor.

![Graphical explanation of Electrical theory behind SRM](image)

Figure 3.7 Graphical explanation of Electrical theory behind SRM

[Courtesy: Switched Reluctance Motor by R. Krishnan]

Rotor position information is used to control phase energisation in an optimal way to achieve smooth and continuous torque and high efficiency.
The theoretical equations governing the torque production mechanism have been published countless times in the literature. Simple graphical explanation is shown in Figure 3.7. The current waveforms are superimposed on the angular unsaturated phase inductance. The maximum inductance corresponds to the minimum reluctance pole-aligned position. Positive torque is only produced at angles when the inductance gradient is positive.

At low speeds, the phase current has to be constrained to protect the electronics because of the high available volt-seconds. This is typically achieved by hysteresis current chopping as illustrated.

At higher speeds, the current is naturally constrained, and single-pulse voltage control is normally employed with angle advance prior to the unaligned position to optimize performance.

Figure 3.8 Graphical explanation of Energy conversion of SRM

The energy conversion mechanism is illustrated by the co-energy trajectory. It is shown in Figure 3.8. The $W_{\text{con}}$ area represents the energy converted into mechanical energy (or converted in the case of a generator).

$W_{\text{ret}}$ is the surplus energy returned to the power supply rails. Minimizing $W_{\text{ret}}$ by good magnetic design and optimal phase energisation control are the key features of a switched reluctance motor system.

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3.5 Machine Topologies

Switched reluctance machines can offer a wide variety of aspect ratios and salient pole topologies. This means that each application is likely to be better suited to a specific switched reluctance motor topology. Therefore, it is difficult to give an overview of which topology offers what advantage or disadvantage without resorting to sweeping statements.

3.5.1 Single-Phase Motor

This is the simplest switched reluctance motor with fewest connections between machine and electronics. The disadvantages lie in very high torque ripple and inability to start at all angular positions. May be attractive for very high speed applications, but starting problems may preclude their use. It is shown in Figure 3.9.

Figure 3.9 Single phase

3.5.2 Two-Phase Motor

Problems of starting compared with single phase machines can be overcome by stepping the air-gap, or providing asymmetry in the rotor poles. This machine may be of interest where the cost of winding connections is important, but again high torque ripple may be detrimental. It is shown in Figure 3.10.
3.5.3 Three-Phase Motor

If the number of phases of SRM increases, then torque ripples decrease. Hence this has been the most popular topology in its 6/4 form. It is shown in Figure 3.11. Alternative 3-phase machines with doubled-up pole numbers can offer a better solution for lower speed applications.

3.5.4 Four-Phase Motor

The large number of power devices and connections will probably limit four-phase to a limited application field for reducing torque ripple. Five- and six-phase motors can offer better torque ripple reduction compared with four-phase and three-phase. It is shown in Figure 3.12.
3.6 Power Electronics

Unipolar current is present in a conventional SRM. It can be driven bipolar especially if foil pitched winding where torque is produced by the change in mutual reluctance rather than self-reluctance. Single-ended converters can be used but the favorite is the two-transistor forward converter topology (asymmetric half-bridge) which has two power switches connected to either end of the power rails and in series with a winding for fluxing the machine and two diodes forming a return path. In the past, there has been some debate about VA ratings when comparing other motor topologies, but nowadays with modern majority carrier devices such as IGBTs, this argument is largely irrelevant especially when compromises are made with respect to torque ripple and acoustic noise.
It is shown in Figure 3.6. Similar rated drive electronics will more than likely have the same size devices. There is a cost disadvantage over a MOSFET inverter since the inherent MOSFET anti-parallel diode cannot be used.

3.7 Commutation Control

Voltage or current control, chopping or PWM, depends on speed (available Volt-seconds) and any servo performance criteria. The control electronics will now be performed digitally, and cost versus performance will be the main factor in selecting the most suitable circuit. ASIC have been mooted as the best option for very high volume drives, but microcontrollers, and more recently DSP, are proving to be the most popular control devices because of their flexibility. Current feedback is required for low speed operation, and PWM is now finding favor because of acoustic noise issues. Rotor position feedback is required in some form, and traditionally this is done with a rotor mounted sensor. This is a major cost and reliability issue and so a large amount of R and D effort has been placed in eliminating this sensor.