CHAPTER 7
MAJOR SRM ISSUES

7.1 Construction

The switched reluctance motor is simple, low cost, fault-tolerant, and has a simple converter and control requirements. The motor is suitable for many variable-speed and servo-type applications and it is gaining increasing attention in the motor drive industry. The SRM is the simplest of all electrical machines. Only the stator has windings. The rotor contains no conductors or permanent magnets. It consists simply of steel laminations stacked onto a shaft. It is because of this simple mechanical construction that SRM carries the promise of low cost, which in turn has motivated a large amount of research on SRM in the last decade. The mechanical simplicity of the device, however, comes with some limitations. Like the brushless DC motor, SRM can not run directly from a DC bus or an AC line, but must always be electronically commutated. Also, the saliency of the stator and rotor, necessary for the machine to produce reluctance torque, causes strong non-linear magnetic characteristics, complicating the analysis and control of the SRM. SRM has some advantages along with potential low cost because they can be very reliable machines since each phase of the SRM is largely independent physically, magnetically and electrically from the other motor phases. Also, because of the lack of conductors or magnets on the rotor, very high speeds can be achieved.

Disadvantages of the SRM are that they are difficult to control, that they require a shaft position sensor to operate, they tend to be noisy, and they have more torque ripple than other types of motors.

7.2 Rotor Position Sensing

As mentioned above, rotor-mounted position sensors are a liability. Not only do they introduce cost to the motor, but they can also be a major source of poor performance and unreliability. Work world-wide has now produced a number of viable schemes for sensorless operation. They all require monitoring of the phase current and applied voltage (flux observation), then by using knowledge of the magnetic characteristics, the rotor position is determined. This information is then used to optimize performance. It is interesting that the most often touted negative issues of SRM performance may all be reduced by the merging of control means around real-time monitoring of the phase energisation in terms of flux-linkage and

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current coupled with knowledge of the machine being controlled (or possibly a self-learning control mechanism).

7.3 Torque Ripple

SRM has a significant torque ripple, especially when operated in single-pulse voltage control mode. This is the price to pay for high efficiency. For many applications where the machine is operating at fairly high speeds, this is not a problem since the mechanical time-constant is far longer than the fast rates of change of instantaneous torque produced by the motor. The human being can sense very low levels of torque perturbation and so minimizing not only the peak-to-peak levels, but also angular rates of change are high priorities. Effort can be put into both the machine design and the control strategies. Optimizing the individual phase torque-angle characteristic by salient pole shape profiling, longitudinal skewing of the rotor and angular phase current profiling can all help to minimize the inherent torque ripple. Significant work has already been carried-out by a number of institutions, notably Arkon University into ways of improving torque ripple performance (Hussain 2002), (Rodrigues et al 2001) and (Oscar et al 2002). Judging by the number of patents filed by TRW on an electric power-assisted steering system utilizing a variable reluctance machine, healthy interest in using SR for torque ripple sensitive applications is still prevalent.

One of the main disadvantages of SRM is its higher torque-ripple compared to other electrical machines. This work presents an adaptive fuzzy Logic Controller for the torque-ripple minimization in SRM. The method is not dependent upon the predetermined characteristics of the motor and can adapt to any change in the motor characteristics. Also, the controller is robust toward errors in rotor position feedback, avoids negative torque production during commutation, and minimizes torque-ripple up to the base speed of the motor.

One of the main disadvantages of the SRM is its higher torque ripple compared to other electrical machines. Various techniques have been proposed for torque-ripple minimization of SRM, such as current profiling, overlapping conduction of different phases, and linearized feedback control. Some of these methods use offline data collected from the machine during the static conditions, which change during the motor operation due to changes in the motor parameters. Some methods use a linear model of the machine, which may not be suitable for high-performance applications. Methods that use current profiling may produce high current peaks at
low $dL/d\theta$ regions. Also, most methods are highly dependent upon the rotor position. Any errors in the rotor position can lead to failure of the control. Most methods are limited to low-speed operation. In the regions where the change in inductance is small, the motor produces very small torque compared to regions where the change in inductance is large. This relationship becomes even more nonlinear, if the effects of saturation are included. Therefore, to maintain a constant torque, the current profile has to be adjusted continuously during phase conduction. The total torque of the machine is the sum of the torque produced by the independent motor phases. In order to have a continuous torque, smooth commutation from one phase to another is needed. The torque pulsation during the overlap period can be quite significant if the commutation process is not smooth. This effect becomes more significant, at higher speeds, when the commutation takes place over a large angle of the rotor, and the phases start to demagnetize before they reach the aligned position. If the phases are not demagnetized before the aligned position, the phases conduct in the generating region producing negative torque, thereby reducing the efficiency of the motor.

7.4 Acoustic Noise

SRM can produce excessive amounts of acoustic noise. It is shown in Figure 7.1. The operation of the motor where the salient poles tend to align to minimize reluctance in normal operation leads to high normal forces acting on the stator structure. **Harmonics** of these normal forces will resonance the natural frequency resonant modes of the stator structure producing acoustic noise. However, once the mechanism of noise production is understood, then steps can be taken to minimize the noise. The noise can be reduced by careful design on two fronts. First the mechanical design can be optimized to avoid significant resonances at common operating points over the speed range and the structure can generally be 'stiffened-up' to minimize movement.

![Figure 7.1 Vibrations with acoustic Noise](image)

[Courtesy: Switched Reluctance Motor by R. KrishnanJ]

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Next, the phase energisation can be modulated to reduce the frequency components of the normal forces which cause the most sympathetic vibrations in the motor structure. Control techniques understood to be beneficial are forms of current profiling during the phase energization. In its simplest form, this can be a short period of freewheeling which, if selected correctly, can reduce the higher harmonics of the normal force when the machine is operating in the single-pulse voltage control mode. More complicated control measures entail angular profiling of the individual phase currents to minimize the less desirable force and torque harmonics using power converter switching frequencies above the human ear audible level.

7.5 SRM Working Principle

- Energizing one or more stator coils cause the rotor to step forward (or reverse) to a position that forms a path of least reluctance with the magnetized stator teeth.
- It is to be noted that when there is no current in the stator coils, the rotor is completely free to rotate. In Figure 7.2, AA’, BB’, CC’ are the diametrically connected stator coils. S1, S2, S3 are the MOSFET used for switching.

![Figure 7.2 Simplified switching circuit](image)

7.6 Electronic Control Circuit

The motor is excited by a sequence of D.C. pulses applied at each phase. It is shown in Figures 7.3 and 7.4. The rotor position with angle is tabulated in Table 7.1.

* The individual phases are consequently excited, forcing the motor to rotate.
- The current pulses need to be applied to the respective phase at the EXACT rotor position relative to the excited phase.

![Control circuit](image)

**Figure 7.3 Control circuit**

**Table 7.1 Rotor position with angle**

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>ANGLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>0</td>
<td>0</td>
<td>0°</td>
</tr>
<tr>
<td>0</td>
<td>+</td>
<td>0</td>
<td>30°</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>+</td>
<td>60°</td>
</tr>
</tbody>
</table>

When S1 is closed, AA’ is excited and the rotor gets rotated by 30°

![Rotor position at 30°](image)
7.7 Motor Characteristics

The basic operating principle of the SRM is when the current is passed through one of the stator windings; torque is generated by the tendency of the rotor to align with the excited stator pole. The direction of torque generated is a function of the rotor position with respect to the energized phase and is independent of the direction of current flow through the phase winding. Continuous torque can be produced by synchronizing each phase’s excitation with the rotor position. By varying

When S2 is closed, BB’ is excited and the rotor gets rotated by 60°

Rotor position at 60°

When S3 is closed, CC’ is excited and the rotor gets rotated by 90°

Rotor position at 90°

Figure 7.4 Rotor position at various angles

[Courtesy: Switched Reluctance Motor by R. Krishnan]
the number of phases, the number of stator poles and the number of rotor poles, many
different SRM geometries can be realized. It is shown in Figure 7.5.

![Figure 7.5 various types of SRM](Courtesy: Switched Reluctance Motor by R. Krishnan)

The number of phases is not necessarily equal to half the number
of rotor poles. Generally, increasing the number of SRM phases reduces the torque
ripple, but at the expense of requiring more electronics with which to operate the
SRM. At least two phases are required to guarantee starting, and at least three phases
are required to insure the starting direction. The number of rotor poles and stator poles
must also differ to insure starting.
7.7.1 Torque-Speed Characteristics

Like other motors, torque is limited by maximum allowed current, and speed by the available bus voltage. With increasing shaft speed, a current limit region persists until the rotor reaches a speed where the back-emf of the motor is such that the given DC bus voltage limitation, we can no more current is received in the winding—thus no more torque from the motor.

At this point it is called as the base speed and beyond it, the shaft output power remains constant and is at its maximum. At still higher speeds, the back-EMF increases and the shaft output power begins to drop. This region is characterized by the product of torque and the square of speed remaining constant. The Torque-Speed Characteristics curve is shown in Figure 7.6.

![Torque-Speed Characteristics of SRM](image)

Figure 7.6 Torque-Speed Characteristics of SRM

7.8 Advantages of SRM

- The rotor does not have any windings, commutators, brushes or cages.
- The torque-inertia ratio is high.
- It provides high reliability, wide-speed range at constant power, low manufacturing cost, fast dynamic response, ruggedness and fault tolerance.
- No shoot-through and crossovers in the converter.
- The maximum permissible rotor temperature is higher since there is no permanent magnet.
- **Open-circuit** voltage and short-circuit current at faults are zero or very small.

7.9 Disadvantages of SRM

- Doubly-salient structure causes vibration and acoustic noise.
- High **torque-ripple**.
7.10 Applications of SRM

> Washing machine.
> Vacuum, blower.
> Motorcycle.
> Automotive cruise control drives
> Conventional automotive actuators.
> Aerospace starter/generators.
> High-speed adjustable speed fluid pumps.
> Robotic prime movers.