COMPARISON OF CONVERTER TOPOLOGIES FOR A SWITCHED RELUCTANCE MOTOR

* Geun-Hie Rim (O), ** Wook Kang

* Power Electronics Research Lab. Korea Electrotechnology Research Institute
Chang-Won Gyong-Nam Ph. (0551) 80-1414

** Osan Technical Junior College Osan, Gyeongkee-Do

Abstract

The advent of inexpensive high power switching devices revived the interest in switched reluctance motor(hereafter referred to as SRM) drives. In the late 60's, the potential of SRM for traction application attracted researchers. Since then the progress in research of the SRM drive has been phenomenal.

In this paper, a review of the basic principle of operation of the SRM, currently available converter topologies, the controller requirements and some design considerations are included.

I. Introduction

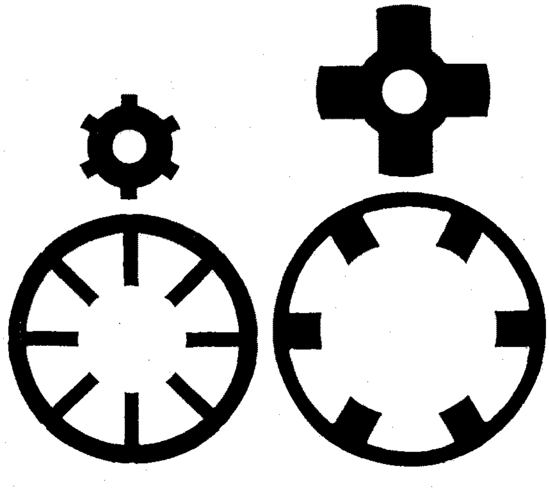
It is known that in comparing with the present variable speed induction drive, the SRM drive has simpler construction and better than or at least equal performance in terms of torque per unit volume, efficiency, and volt-ampere requirements. One of the distinct features of SRM is the absence of windings or permanent magnets in the rotor, which results in a mechanically and thermally robust and maintenance-free machine.

The SRMs are doubly salient machines with an unequal number of poles in the stator and rotor, for instance, 8/6 or 6/4 poles in the stators and rotors, respectively, for four or three phase machines. Such typical machines are illustrated in Figure 1.

II. Basic Principles of SRMs

A. Torque production

The operation of the machine is as follows. When a pair of the stator windings which are diagonally opposite in the stator across the rotor are excited, the rotor moves until it reaches aligned position with the axis of the excited phase. This position is referred to as aligned position and it corresponds to the maximum inductance. The unaligned position is reached when two diagonally-located rotor poles are half a rotor pole-pitch away from the excited phase. If the next phase is excited before the rotor is fully aligned with the currently excited phase then the rotor moves towards and produces one more work stroke. Similarly, by switching the phase current sequentially the rotor continues to move.



(a) 8/6 pole SRM structure (b) 6/4 pole SRM structure

Figure 1: SRM structures

Hence the movement of the rotor produces torque and hence mechanical power. The direction of rotation of the machine can be reversed by changing the switching sequence of the phase currents. Therefore this drive is capable of four quadrant operation.

In the case of a rotating machine, the relationship between the mechanical energy and torque is,

$$\delta W_m = T\delta\theta \tag{1}$$

where $\delta W_m, T$, and $\delta\theta$ are the incremental mechanical energy, electromagnetic torque, and the incremental mechanical angle, respectively. Hence

$$T = \frac{\delta W_m}{\delta\theta} \tag{2}$$

Assuming constant excitation and linear inductance, the incremental torque due to the rotor movement from θ_1 to θ_2 is,

$$\begin{aligned} \delta T &= \frac{\delta W_m}{\theta_2 - \theta_1} && (3) \\ &= \frac{L(\theta_2, i) - L(\theta_1, i)}{\theta_2 - \theta_1} \cdot \delta i && (4) \\ &= i \cdot \delta i \cdot \frac{\delta L(\theta, i)}{\delta\theta} && (5) \\ &= \frac{1}{2} i^2 \cdot \frac{\delta L(\theta, i)}{\delta\theta} && (6) \end{aligned}$$

where L is the self inductance of the circuit at the rotor position of θ. The torque equation (6) implies,

(i) The electromagnetic torque is proportional to the square of the winding current, which results in
  - The independence of torque with respect to the direction of current flow and hence one switch per phase winding requirement.
  - A good starting torque production.

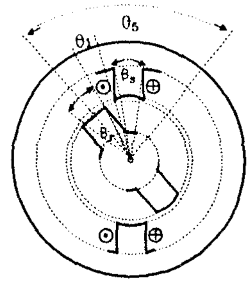
(ii) The torque is also directly proportional to the slope of the inductance and rotor position. Hence, a negative torque (generating mode) is made possible with unipolar current by operating the machine on the negative slope of the inductance and position.

B. Inductance variation and torque

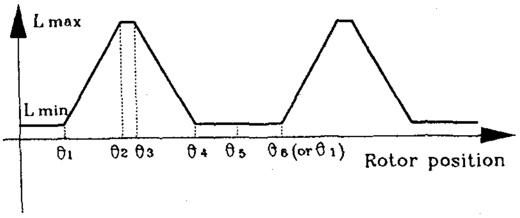
Neglecting the fringe effect and magnetic saturation, Figure 2 (b) shows the inductance variation of one-phase with respect to rotor position. Each rotor position at which the slope of inductance profile changes significantly is determined in terms of the stator and rotor pole-arcs and number of rotor poles. From Figures 2 (a) and (b), the various angles are derived as:

$$\begin{aligned} \theta_1 &= \frac{1}{2}\frac{2\pi}{N_r} - \frac{1}{2}(\beta_s + \beta_r) && (7) \\ \theta_2 &= \theta_1 + \beta_s && (8) \\ \theta_3 &= \theta_2 + (\beta_r - \beta_s) && (9) \\ \theta_4 &= \theta_3 + \beta_s && (10) \\ \theta_5 &= \theta_4 + \theta_1 && (11) \end{aligned}$$

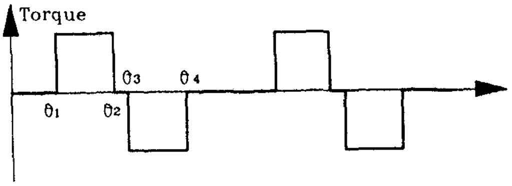
where β_s and β_r are pole arcs of the stator and rotor, respectively, as shown in Figure 2 (a).



(a) Rotor and stator position



(b) Inductance profile



(c) Torque production

Figure 2: Rotor position and torque

The number of cycles of inductance variation per revolution is proportional to the number of rotor poles, and its period is equal to the rotor pole pitch, θ_5 and is given by,

$$\begin{aligned} \theta_5 &= \frac{2\pi}{\text{No. of rotor poles}} && (12) \\ &= \frac{2\pi}{N_r} \text{ rad} && (13) \end{aligned}$$

The physical interpretation of inductance at each stator-rotor position is,

$0 - \theta_1$: The stator and rotor poles are not overlapping and the inductance stays at L_{min}.

$\theta_1 - \theta_2$: The rotor pole starts to overlap with the stator pole at θ_1 and the inductance increases until the poles are fully overlapped at θ_2 where the inductance has its maximum value L_{max}.

$\theta_2 - \theta_3$: The inductance remains constant at L_{max} until complete rotor-stator overlap is over. During this period no torque is produced. However, it is desired to have this flat inductance region to prevent significant negative-torque generation. The unequal rotor and stator pole arcs allow the flat-top inductance profile. Usually the stator pole arc is smaller than the rotor pole arc to get more winding space.

$\theta_3 - \theta_4$: The inductance decreases linearly until it reaches L_{min} and the poles are not overlapping anymore.

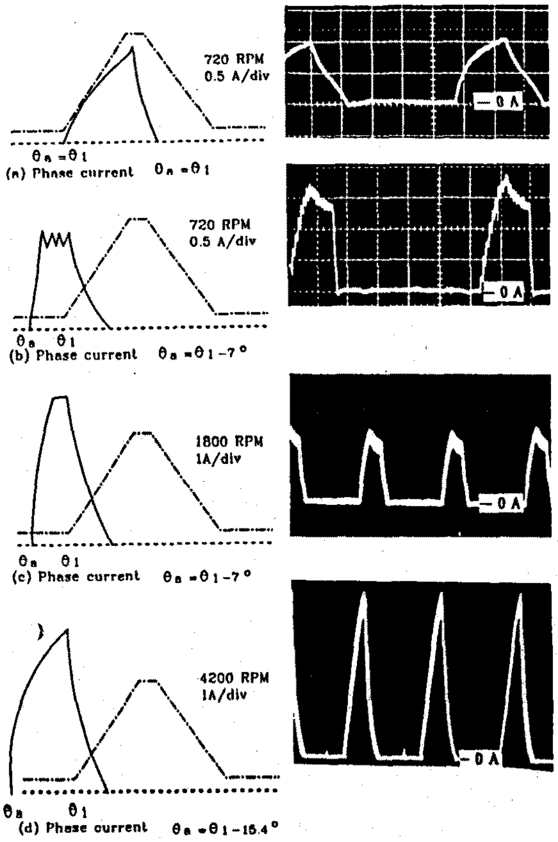
$\theta_4 - \theta_5$: The inductance remains at L_{min}.

Applying a constant current on the stator winding, the resultant torque is shown in Figure 2(c). Depending on the slope of the inductance and position, the machine produces either a positive (motoring mode), or a negative torque (generation mode) as seen from the torque equation (6). Note that due to the machine back emf and inductive circuit characteristics, the current is usually advanced. Typical current and their experimental waveforms using a four phase machine are shown in Figure 3. Figure 3(a) shows the effects of late commutation. The high rate of current rise and longer current rise-time explicable by the chopped current waveforms in Figure 3 (b) after advancing the turn-on timing 7° from θ_1 shown in Figure 2. At the base speed which is defined as the speed at which back emf is equal to the source voltage, a nearly flat-topped pulse current flows as shown in Figure 3(c) But at higher speed, enough advance in turn-on timing is required for the current to be built up. Compared to that of the base speed, more than two times of advanced angle is provided for the speed of 4200 rpms shown in Figure 3(d). Note that these two different advanced angle are almost of the same time duration, i.e. $7° = 0.65$ ms (@ 1800 rpm) and $15.4° = 0.61$ ms (@ 4200 rpm). An asymmetrical bridge converter shown in Figure 4 (a) is used in the current waveform measurements.

III. Review of the Topologies

Many SRM-converter topologies have been proposed to control the unidirectional phase currents. The cost minimization and performance maximization are the two important but sometimes conflicting requirements in selecting the converter topologies for SRM drives. That is, single switch per phase configurations are appropriate for low performance applications because of their use of minimum number of power devices and components, and resulting simplicity of the drive circuitry, whereas two switch per phase converters are needed for high performance drive system for them to have more freedom in controlling the phase currents in spite of the cost differential compared to the single switch per phase configuration.

It is well known that the SRM drives require only one switch per phase winding since the torque is independent of the direction of the winding current. However, in practice, some difficulties lie in the realization of single switch per phase configuration because of SRM's highly inductive circuitry.



(a) Phase current θa =θ1

(b) Phase current θa =θ1 -7°

(c) Phase current θa =θ1 -7°

(d) Phase current θa =θ1 -15.4°

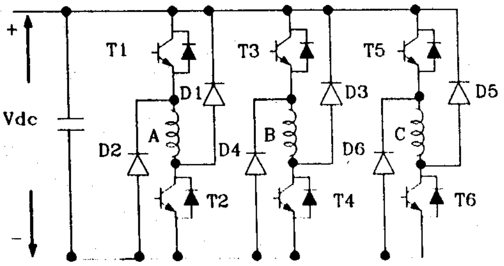
Figure 3: Typical current waveforms at different speed

Hence, provisions for diversion of current path are to be given before switching off the current. Otherwise, the converters experience high voltage-spikes, resulting in the failure of the switching devices. This factor is one of the major issues to be considered in the discussion of the SRM converter. The control complexities are the result of the SRM-converter topologies and hence the need for a clearer understanding of the converter topologies. But the inductance of the winding contributes to the device protection in case of a shoot through fault. Since each phase winding is connected in series with a switch or switches, it limits fast current rise. In this section, the presently available major topologies are reviewed in regard to the number of switches, operations, control flexibility, and device ratings, etc.

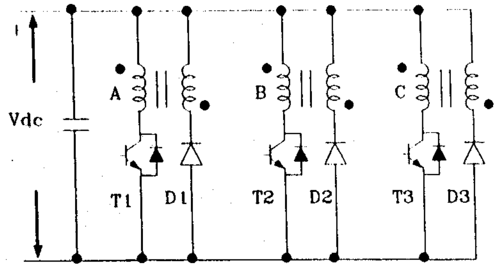
A. Converter configurations and operations

Many converter topologies have been used in various applications. The configurations are classified as in the following:

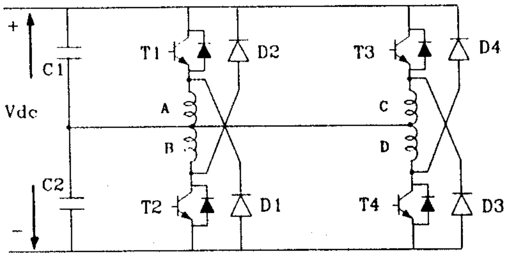
(i) Asymmetric bridge converter.
(ii) Bifilar-winding configuration.
(iii) Split dc supply converter.
(iv) C-dump configuration.
(v) R-dump configuration.
(vi) Switch-shared configuration.



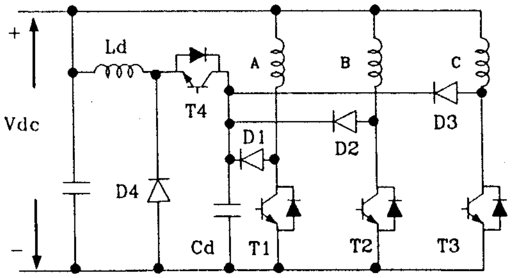
(a) Asymmetric bridge converter



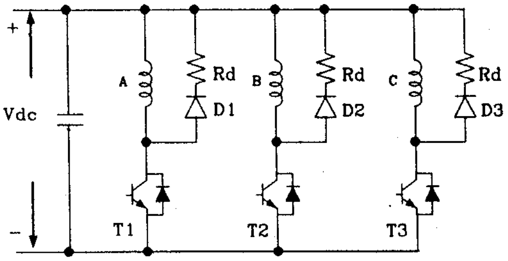
(b) Bifilar winding machine configuration



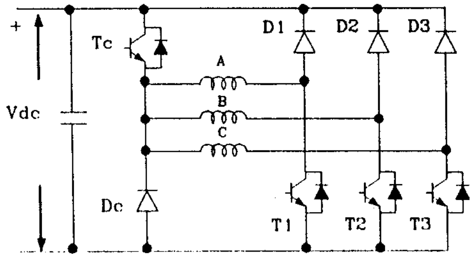
(c) Split source converter



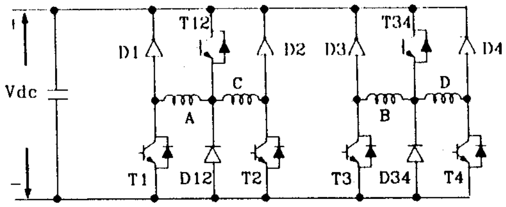
(d) C-dump configuration



(e) R-dump configuration



(f) q+1 switch topology



(g) 1.5q switch topology

Figure 4: SRM Converter topologies

In spite of the different configurations, they have the following common features:

(i) Series connection of the switches and the phase winding, resulting in the immunity to shoot through faults.

(ii) Independent operation of each phase, resulting in the operation of healthy phase even in the presence of some phase failures.

(iii) Energy return paths when the switches are turned off to prevent the high voltage spikes.

A.1 Asymmetric bridge converter

The converter, as shown in Figure 4(a), requires two switches and two freewheeling diodes per phase. There are three stages of operation for this configuration. The first stage occurs when both switches are turned on. The source voltage, V_{dc} is applied across the phase winding to build up the current. In the second stage, one or two switches are turned off while current is flowing in the winding, the current freewheels through one diode and one switch or it flows back to the source through the two freewheeling diodes to reduce the current magnitude, depending on the control strategy. The last stage is performed when both switches, T_1 and T_2 are turned off to commutate, forcing the current to flow against the source voltage through diodes, D_1 and D_2. The energy stored in the winding is depleted at this stage and recovered. Among the currently known SRM drive topologies, this has the maximum freedom in the control capability and has no constraints on the number of phase windings.

A.2 Bifilar-winding configuration

Figure 4(b) shows a simple converter for an SRM with bifilar stator windings. Current increases in the main winding when the switch, T_1, is turned on and the stored energy in the winding is transferred to the source through the auxiliary winding and diode when the switch is turned off. The simplicity of the converter is achieved with the bifilar wound machine which has a poor winding space factor, additional copper, more terminals in the machine. The high voltage spikes resulted from the imperfect coupling and winding turns ratio may be more than twice the source voltage when the switch is turned off. Therefore the voltage rating of the switching devices is more than twice that of the SRM winding.

A.3 Split source converter

This also meets the minimum switching device requirement and is shown in Figure 4(c). Phase A is energized by turning on T_1. The current circulates through T_1, C_1 and phase-winding A. If T_1 is off, the current continues to flow through phase winding A, D_1 and C_2. Note that C_2 is at $\frac{1}{2}V_{dc}$. Hence the stored energy in the winding is depleted fast.

A.4 C-dump configuration

C-dump configuration shown in Figure 4(d) requires one more switch and diode than the number of machine phases and additionally a capacitor and an inductor. When T_1 is switched off while A-phase winding current flows, the current commutates to D_1 and begins to charge the dump capacitor C_d. The rising voltage across the capacitor reduces the decaying time of the phase current. The trapped energy is recovered with the step-down chopper made up of T4, D4 and the inductor L_d. The configuration has the disadvantages of relatively high voltage rating of the power devices and energy recovery losses and increased capacitor use.

A.5 R-dump configuration

Figure 4(e) shows a converter configuration with one switch and one diode per phase. When T_1 is switched off, the winding current freewheels through D_1 and an external resistor R_d. Compared to the other source-recharging type converters, this configuration is disadvantageous in that it takes longer time to extinguish the winding current at commutation possibly causing negative torque and further it dissipates a part of the winding energy in the resistor, reducing the overall efficiency.

A.6 Switch-shared configuration

This configuration is categorized into the following two types.

q+1 switch topology: q is the number of phases. Figure 4 (f) shows a converter circuit in which one end of all phase winding is connected to one common midpoint between a switch and a diode. Other ends of the windings are connected separately at the similar points. To excite phase-A winding T_c and T_1 are turned on. When the phase A is enabled the common switch, T_c remains turned on and the phase switch T_1 is switched on and off for current control, or keep the phase switch, T_1 on , and switch on and off the common switch, T_c for freewheeling control. Only after completing the depletion of the energy stored in the phase winding, the next phase can be energized. The converter is fit for SRMs which do not have inductance overlap because it can control only one phase current at a time. Therefore it is suitable for SRMs with low number of phases and not for high performance applications where multiple phase energizations may be required.

1.5q switch topology: A power converter circuit for an even number of phase machine is shown in Figure 4(g). Top switch, T_{12} is shared by two phases. Note that it is shared by phase A and phase C, and T_{34} is shared by phase B and phase D so that each phase has enough time to deplete the winding energy. The top switch controls one phase current at a time since there are no overlap current in phases A and C (or phases B and D). The peak current through the switches are equal but the rms currents are different. Hence the switching and conduction losses are not evenly distributed, but the converter has almost the same flexibility in control as an asymmetric bridge converter.

Table 1 summarizes the key features of the SRM converter topologies. The merits and demerits are also included.

B. Device ratings

B.1 Selection of switching devices

The selection of switching devices takes an important place in designing a converter. The following factors are the key issues to be considered:

(i) Power level.

(ii) Source and transient voltage.

(iii) Peak and continuous current.

(iv) Switching frequency or switching speed.

(v) Cost.

(vi) Simplicity of driving circuit.

In the SRM drives, forced commutated converters are required. Therefore the converters consist of the switching devices such as GTOs, BJTs, IGBTs, and MOSFETs. For low power range converters, the MOSFETs and IGBTs are the attractive candidates. Judging from the peak and continuous current ratings, MOSFETs are the most suitable devices for the SRM converters.

B.2 Current rating of the switching devices

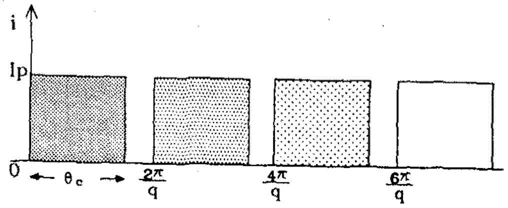
Depending on the control strategies and converter topologies, the current rating is varying. The peak current rating and the continuous current ratings should be defined first in any case. From the given specifications, the peak current, I_{peak} is defined as the following.

$$I_{peak} = \frac{P_o}{\eta_s D V_{dc}} \qquad (14)$$

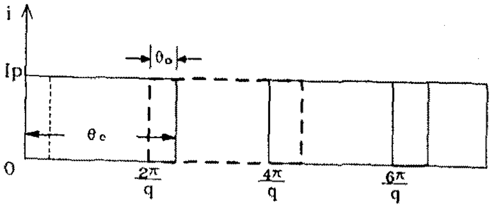
where P_o is the peak output, D is the duty ratio, V_{dc} is the dc source voltage, and η_s is the efficiency of the system. The continuous current rating is equal to or less than the peak current of the winding. Assuming the continuous current equal to the rms current per phase, the rms current is determined from a flat-topped current. Allowing no overlap current and no phase-shared switch, from Figure 5 (a) the rms current is given as,

$$\begin{aligned} I_{rms} &= \sqrt{\frac{1}{2\pi}\int_0^{\theta_c} I_p^2 d\theta} && (15) \\ &= \sqrt{\frac{\theta_c}{2\pi}} I_p && (16) \end{aligned}$$

if $\theta_c = \frac{2\pi}{q}$ then $I_{rms} = \frac{I_p}{\sqrt{q}}$ where q is the number of phases, θ_c is the conduction angle for each phase, and I_p is the peak current value.



(a) Flat-topped current without overlap current



(b) Flat-topped current with overlap

Figure 5: Rms current calculations using a flat-topped current

Configuration	Merits	Demerits	Misc.
Asymmetric bridge converter	- High efficiency - Fast regeneration - High control capability	- High count of devices - High voltage drop (across the devices)	- Good for lower No. of phases
Bifilar winding converter	- Fast regeneration - Low count of devices	- Poor thermal management - Low power density - High voltage ratings of devices - Extra copper & connections	- Good for low voltage low power level
Split source converter	- Low count of devices - Fast regeneration - Relatively high efficiency	- Phase dependence - Extra capacitor - Even No. of phases - Low reliability	
C-dump configuration	- Low count of devices - Relatively high efficiency	- One Extra switch - Extra inductor - High count of components	
R-dump configuration	- Simplicity - Low count of devices	- Low efficiency - Slow current decay - Limited conduction angle - High voltage rating of machine	- Low performance applications - Low power level
q+1 switch Topology	- High efficiency - Fast regeneration - Low count of devices - Simplicity	- Limited conduction angle - Extra switch - Not even power dissipation of devices - Limited conduction angle - High voltage rating of switch	- Low performance applications
1.5q switch Topology	- Fast regeneration - Relatively low count of devices	- Even No. of phases - Uneven power dissipation of devices	

Table 1: Comparison of the topologies

The top switches in the q+1 and 1.5q switch converter topologies have the rms current as in the following:

$$I_{rms} = \sqrt{\frac{1}{2\pi}\left[\int_0^{\theta_c} I_p{}^2 d\theta + \int_{\frac{2\pi}{q}}^{\frac{2\pi}{q}+\theta_c} I_p{}^2 d\theta\right]} \quad (17)$$

$$= \sqrt{\frac{\theta_c}{\pi}} I_p \quad (18)$$

If $\theta_c = \frac{4\pi}{q}$, then

$$I_{rms} = \frac{\sqrt{2}}{\sqrt{q}} I_p \quad (19)$$

When there are overlap currents through the switches of the asymmetric bridge converter or through the switches in the similar conditions, the rms current is given,

$$I_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{\frac{2\pi+\theta_o}{q}} I_p{}^2 d\theta} \quad (20)$$

Configuration	Device				Motor winding rating	Control capability
	No. of		Ratings			
	SW.	Diode	Voltage	Current		
Asymmetric bridge converter	2 q	2 q	> Vdc	$\frac{Ip}{\sqrt{q}}$	Vdc	Very flexible
Bifilar winding converter	q	q	> 2Vdc	$\frac{Ip}{\sqrt{q}}$	Vdc	No freewheeling control
Split source converter	q	q	> Vdc	$\frac{Ip}{\sqrt{q}}$	$\frac{1}{2}$ Vdc	No freewheeling control
C-dump configuration	q+1	q+1	>2Vdc	$\frac{Ip}{\sqrt{q}}$	Vdc	No freewheeling control
R-dump configuration	q	q	>2Vdc	$\frac{Ip}{\sqrt{q}}$	Vdc	No regeneration No overlap current
q+1 switch Topology	q+1	q+1	> Vdc	$\frac{Ip}{\sqrt{q}}$ Ip	Vdc	No overlap current control Tc
1.5q switch Topology	$\frac{3}{2}$q	$\frac{3}{2}$q	> Vdc	$\frac{Ip}{\sqrt{q}}$ $2\frac{Ip}{\sqrt{q}}$	Vdc	Very flexible T12, T34

Table 2: Device ratings

$$= \sqrt{\frac{1}{q}+\frac{\theta_o}{2\pi}}\, I_p \qquad (21)$$

where θ_o is the overlap angle. The switch T_c in Figure 4(f) is a particular case and its rms current is given from Figure 5(b) as,

$$I_{rms} = q\sqrt{\frac{1}{2\pi}\int_0^{\theta_c} I_p{}^2 d\theta} \qquad (22)$$

$$= q\sqrt{\frac{\theta_c}{2\pi}}\, I_p \qquad (23)$$

In practice the rms current is less than the calculated value, since the current is usually chopped to control the magnitude and the duty ratio is less than unity. When the switches are turned off while the current is flowing, the freewheeling diodes take over the current, resulting in the reduction of the switch rms currents.

B.3 Voltage rating of the switches

The voltage rating of the switching devices is dependent on the source voltage and the converter topologies involved. As discussed earlier, the voltage rating of devices in a bifilar winding machine is the worst case, where the minimum voltage rating is at least twice of the winding voltage for the turns-ratio of 1:1. Other topologies, even the split source configuration, need the device voltage rating of $V_{dc} + \Delta V$, where V_{dc} is the dc link voltage and ΔV is a voltage margin to allow the increased voltage dc link voltage at commutation and the voltage spikes at turn off due to the circuit stray-inductance.

B.4 Freewheeling diodes

If the phase switches are turned on, the freewheeling diodes are reverse-biased by the source voltage. Hence, the minimum reverse voltage blocking capability is equal to the switch forward-blocking voltage. In the SRM drives, fast-recovering diodes must be used in conjunction with the switches because fast forward and reverse recovery are required to ensure fast current transfer at turn-off and fast blocking of diodes at turn-on of the switches. When phase switches are off, the freewheeling diodes conduct. The peak current rating of the diodes is the same as the peak current of the drive. But the rms current rating is not obvious because it is a function of the duty ratio and the machine inductance.

The device ratings and control capability for each topology are included in Table 2.

IV. Conclusions

This paper has briefly described the basic operation of the switched reluctance motor. The presently available major topologies were reviwed in regard to the counts of devices, operations, control flexibility, and device ratings. The merits and demerits of each topology, the selection and ratings of the converter devices were also included.

It must be realized that the cost minimization and performance maximization are the two important but sometimes conflicting requirements in selecting the converter topologies for SRM drives. That is, single switch per phase configurations are appropriate for low performance applications because of their use of minimum number of power devices and components, and resulting simplicity of the drive circuitry, whereas two switch per phase converters are needed for high performance drive system for them to have more freedom in controlling the phase currents in spite of the cost differential compared to the single switch per phase configuration.

References

[1] T.J.E.Miller and et al., "Design of a Synchronous Reluctance Motor Drive", IEEE IAS Conference Record, Oct. 1989, pp 122-127

[2] R. Krishnan and et al., "A Design Procedure for Axial Field Switched Reluctance Motors", IEEE IAS Conference Record, Oct. 1990, pp 858-863

[3] P.N. Materu and R. Krishnan, "Steady-State Analysis of the Variable-Speed Switched-Reluctance Motor Drive", IEEE Trans. on Industrial Electronics 1989, pp 523-529

[4] P.N. Materu and R. Krishnan, "Analytical Prediction of SRM Inductance Profile and Steady-State Average Torque", IEEE IAS Conference Record, Oct. 1990, pp 214-223

[5] P.J. Lawrenson and et al., "Variable-Speed Switched Reluctance Motors", IEE Proc. Vol.127, Pt.B No.4, Jul. 1980, pp 253-265

[6] J.M. Stephenson and J. Corda, "Computation of Torque and Current in Doubly Salient Reluctance Motors from Nonlinear Magnetisation Data", IEE Proc., Vol.126 No.5, May 1979 pp 393-396

[7] W.F. Ray and R.M. Davis, "Inverter Drive for Doubly Salient Reluctance Motor: Its Fundamental Behavior, Linear Analysis and Cost Implications", Electric Power Applications, Vol.2, No.6, Dec.1979, pp 185-193

[8] T.J.E.Miller, "Converter Volt-Ampere Requirements of Switched Reluctance Motor Drive", IEEE IAS Conference Record, Oct. 1984, pp 813-819

[9] R. Krishnan and P. Materu, "Analysis and Design of a New Converter Topology For Switched Reluctance Motor Drives", IEEE IAS Conference Record, Oct. 1989, pp 1181-1185

[10] C. Pollock and B.W. Williams, "A Unipolar Converter for A Switched Reluctance Motor", IEEE IAS Conference Record, Oct. 1988, pp 44-49

[11] J.T. Bass and T.J.E. Miller, "Development of a Unipolar Converter for Variable Reluctance Motor Drives", IEEE IAS Conference Record, Oct. 1985, pp 1062-1074

[12] C. Pollock and B.W. Williams, "Power Converter Circuits for Switched Reluctance Motors with the Minimum Number of Switches", IEE Proc., Vol.137, Pt.B No.6, Nov. 1990

[13] R. Krishnan and P. Materu, "Analysis and Design of a Low Cost Converter for Switched Reluctance Motor Drives", IEEE IAS Conference Record, Oct. 1989, pp 561-567

[14] R. Krishnan and et al., "A Low Cost SRM Analog Controller", Electronic Motortechnics Feb./Mar. 1990, pp 19-23

[15] R.M. Davis and I. Al-Bahadly, "Experimental Evaluation of Mutual Inductances in a Switched Reluctance Motor", IEE Proceeding Pt.B, 1991 pp 243-248

[16] T.J.E. Miller and et al., "Four Quadrant Brushless Reluctance Motor Drive", IEEE IAS Conf. Record, 1988, pp 273-276

[17] S.R. MacMinn and W.D. Jones "A Very High Speed Switched Reluctance Starter-Generator for Aircraft Engine Applications", NAECON Proc. May 1989

[18] P.N. Materu, "Design and Steady-state Analysis of the Switched Reluctance Motor Drives", Ph.D Dissertation, Dept of Electrical Engineering, VPI & SU, Blacksburg, VA 24061, Jul. 1989.