An SR Drive for a Multi-Megawatt High-Speed Application

S.J. Watkins and J. Čorda
SCHOOL OF ELECTRONIC AND ELECTRICAL ENGINEERING
UNIVERSITY OF LEEDS
Leeds, LS2 9JT
United Kingdom
Phone: +44 (0)113 3432045
Fax: +44 (0)113 3432032
eensjwa@leeds.ac.uk

Keywords

switched reluctance drives, design, multilevel converters, simulation

Abstract

The paper gives an insight into the main features of an SR drive system from the perspective of a multi-megawatt drive application where the rated speed is typically above ten thousand rev/min and the operating voltage is in the range of several kV. The power electronic converter is based on a topology, which allows the application of multiple voltage levels to the machine's phase windings, while utilising lower voltage, fast switching IGBTs. The system's performance is illustrated by means of computer simulation which includes modelling of the electronics conduction and switching losses together with the copper and iron-loss in the machine.

Introduction

High power adjustable variable speed drives are being introduced extensively in the petrochemical industries for applications such as gas pipeline compressors [1] with power range varying up to 40 MW at compressor speeds up to 20000 rev/min. Traditionally, the inverter-fed synchronous motors have been used in high-power applications, because of reduced investment cost. However, the synchronous motor with the rotor winding based on the turbo-alternator technology has a major drawback due to speed limit around 7000 rev/min. In the last decade, the high-power inverter-fed cage induction motor (IM) drives, capable of running up to 20000 rev/min, have been introduced for gas pipeline compressors [2]. The inverter designs are based on multilevel topologies such as the diode-clamped inverter to cope with the high DC link voltages upwards of 7200 V. Even though these drives are well suited for this application, there is one area of concern. The heat generated in the rotor during high-power, high-speed running, with the consequent effects on lateral vibrations and stiffness of the cage, can be a major constraint in the design of the motor with a high torque/volume ratio. Other important issues for the petrochemical industry are high reliability with very low repair rates and fault-tolerance.

Switched Reluctance (SR) drives [3] have been gaining interest for use in variable-speed applications ranging from tens of watts (x-y plotters) to several hundred watts (mining industry) [4]. Their potential to important high-power applications such as gas pipeline compressor drive systems may extend the power range even further. The natural gas production and transportation industry is faced with the imminent requirement to widen the use of variable-speed electric drives in the gas injection and pipeline compressor systems [5-6]. This requirement is driven by a combination of environmental, technical and economic issues.

The SR drive is characterized by simple motor construction in which the rotor is free of conductors and permanent magnets, making it inherently suitable for high-speed applications. The SR drive also has an enhanced fault tolerance (‘shoot-through’ proof inverter with ability to work with reduced number of phases) and high efficiency over a wide range of operating speeds and powers [7].

The aim of this paper is to discuss the main features of an SR drive system from the perspective of high-speed multi-megawatt drive application. System’s performance is illustrated by means of computer simulation of an example 2 MW, 20000 rev/min, 4 kV switched reluctance drive system.

Power Electronics and Control

The basic requirements for the power electronic converter are: (i) operation from a 4 kV DC link and (ii) capability of switching up to 500 A at a maximum frequency of 1200 Hz (20000 rev/min, 4 rotor poles). A conventional asymmetric half-bridge converter is impractical because of voltage limitations in available power IGBT switches capable of operating at the necessary switching speed. For the considered example a two-level power converter [8], shown in Figure 1, is proposed. This permits a direct comparison with the two-level diode-clamped inverter used in an existing 2 MW induction motor driven gas compressor system. In addition to conventional full voltage application when all switches are in conduction, there are two switch states where only half the DC link is applied to the winding when either SW1 or SW4 is turned-off. There are also two complementary modes when de-fluxing with half the DC link voltage occurs with only SW2 or SW3 in conduction. The multilevel converter also has the added flexibility of freewheeling in common with the standard asymmetric half-bridge topology. The ability of the proposed topology to apply multiple voltage levels across the SRM phase winding increases the control flexibility for improving performance features such as torque ripple [9] and acoustic noise [10].

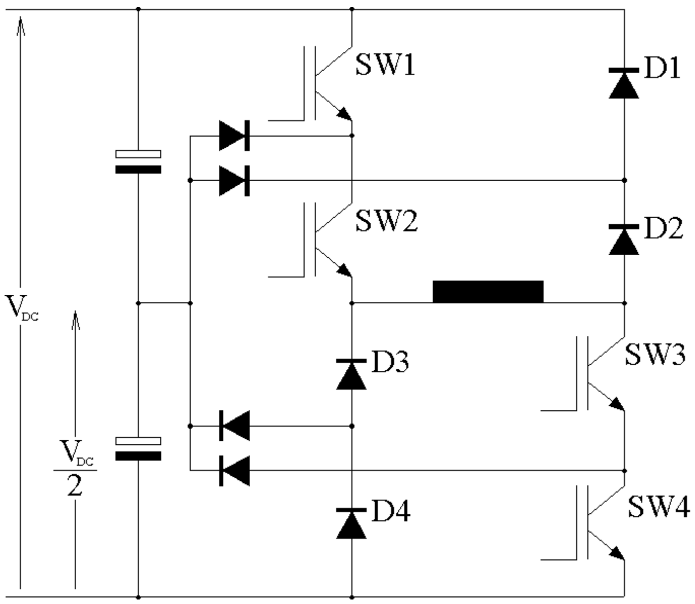


Figure 1: Two-level Diode-Clamped Asymmetric Half-Bridge Phase Limb

The devices modelled in the drive performance simulation are Eupec FF500R25KF1, 2500 V, 500 A IGBTs. The diode model used in the simulation uses the characteristics of the anti-parallel diode in the FF500R25KF1 module. The simulation uses the published non-linear conduction voltage versus current relationship to model the switch characteristics at a junction temperature of 125 ^{o}C. The switching transient energy is also computed from the published data as a function of voltage and current, and the total switching power loss is computed by summing every switching transient's energy during a complete phase energisation cycle and dividing by the phase cycle time.

The two basic control modes of the power converter can be implemented by pulse-width modulators and a hysteresis comparator. The control additionally requires a closed-loop controller that takes a speed demand and a measurement of the actual speed to generate a torque demand. The torque demand is then converted to the necessary firing angle and current reference level signals. Figure 2 illustrates the typical control blocks found in an SR motor controller. The control implementation is best achieved by using a DSP which has the necessary timer functions built-in as standard peripherals. The control algorithms are fairly straightforward to implement in software with the firing timing achieved typically by interrupt service routines in the timer modules. Commercial solutions for a basic SR controller are now available from Texas Instruments in the form of their TMS320C240 fixed-point DSP, which has the necessary hardware peripherals aimed specifically at brushless motion control applications.

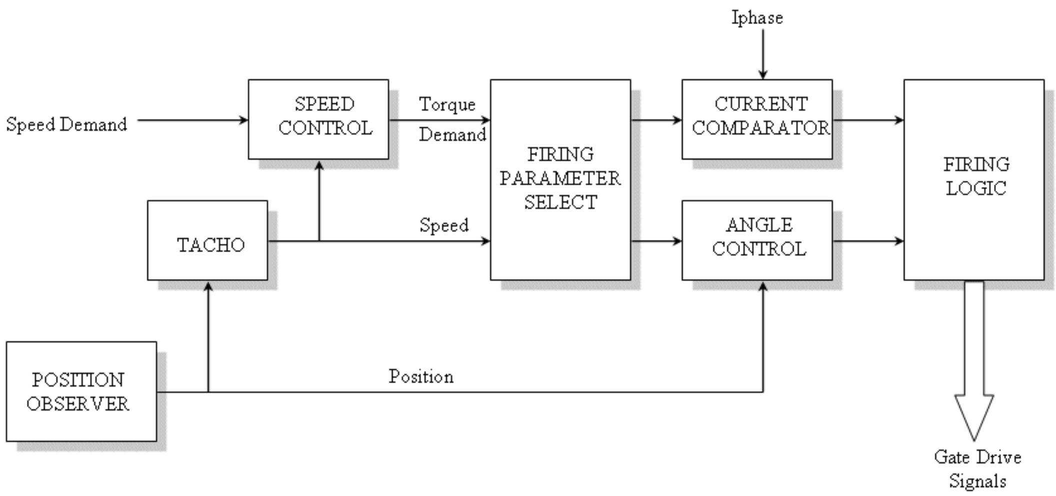


Figure 2: Typical SR Controller Block Diagram

There will be a specific requirement for operation without an integral rotor position sensor for producing the rotor position signal. The compressor application is likely to pose problems in trying to use conventional position sensors such as optical or magnetic head sensors. It would also be potential source of unreliability and would add additional lead-out issues in a hermetically sealed machine. The obvious solution is use a sensorless control algorithm which observers the rotor position with respect to each phase by monitoring the voltage and current appearing on the terminals of each phase winding. The algorithm uses the fact that in an SR machine the flux-linkage versus current characteristic is dependent on the rotor position. There are a number of techniques that have been developed which either employ diagnostic signals in an inert phase, or deduce the position from the actual phase waveforms [11]. The compressor is likely to operate almost exclusively in the high-speed, single-pulse, operating mode and so a non-intrusive position computation method will be preferred. For starting and very low-speed operation, a diagnostic method would still be required.

Vibrations and acoustic noise are important issues in compressor applications where torque ripple and normal forces acting on the stator poles plays an important part. In general, high-speed rotor vibrations due to torque ripple are not the major problem, but it is the normal force induced vibrations on the stator that need to be controlled. Besides good mechanical and electromagnetic design of the machine, incorporating specific reduction techniques within the control can reduce vibrations and associated acoustic noise. At low speeds, introducing a profile in the phase current waveform shape, rather than a fixed 'flat-topped' chopping current, will reduce the harmonic content of the normal forces. Current profiling is also beneficial in reducing the peak-to-peak torque ripple. The use of freewheel chopping mode also reduces harmonics associated with the chopping switching frequency. Multilevel power converters have the added advantage of intermediary voltage levels [8] for fluxing and de-fluxing the machine, and these can be used in conjunction with freewheeling to help to profile the current at all speeds at a reduced power device switching frequency.

The Machine

The SRM design example is based on the frame size, class of insulation and cooling arrangement of the equivalent induction motor (IM) rated with 1870 kW and 16789 rev/min, which is currently used in high-power gas-compressor system.

In terms of cooling, the SRM offers a significant advantage over the IM because the bulk of losses occur in the stator and there are no conductors on the rotor. When applying internal pressurisation, as in the cooling arrangement of IM, the space between adjacent coil sides of SRM allows the pressurised cooling medium to stream directly over the coils. Therefore an increased airgap for allowing the flow of pressurised cooling medium between the stator and rotor, which is introduced in the equivalent IM, is unnecessary in the SRM.

A 3-phase SR topology is chosen from the point of view of suitability for direct comparison between the SR drive and a 3-phase equivalent IM drive. An SRM topology with 6 stator and 4 rotor poles was chosen on the basis of minimisation of the switching frequency in respect of the core losses at high-speed operation. Also because of core losses, the low-loss laminated steel M43 is adopted for modelling of the magnetic circuit.

The magnetic circuit is shown in figure 3a. The main dimensions of the magnetic circuit are as follows:

- The stator core diameter of 570 mm is taken of the equivalent IM.

- The SRM core length of 585 mm together with coil overhang of 80 mm on each side gives the total stator length of 745 mm. In comparison with the equivalent IM, the SR motor would allow the use of a shorter frame size for around 140 mm.

- The SRM rotor diameter of 300 mm is determined on the basis of the same rotor mass for both SRM and the equivalent IM.

- As already mentioned in considering the cooling arrangement with internal pressurisation, the winding configuration in SRM allows minimisation of the radial airgap between the stator and the rotor poles. The airgap size of 1.25 mm is considered mechanically safe and sufficiently large with respect to small eccentricities caused by manufacturing tolerances.

The masses of the stator and the rotor laminated core stacks are of 548 and 164 kg, respectively.

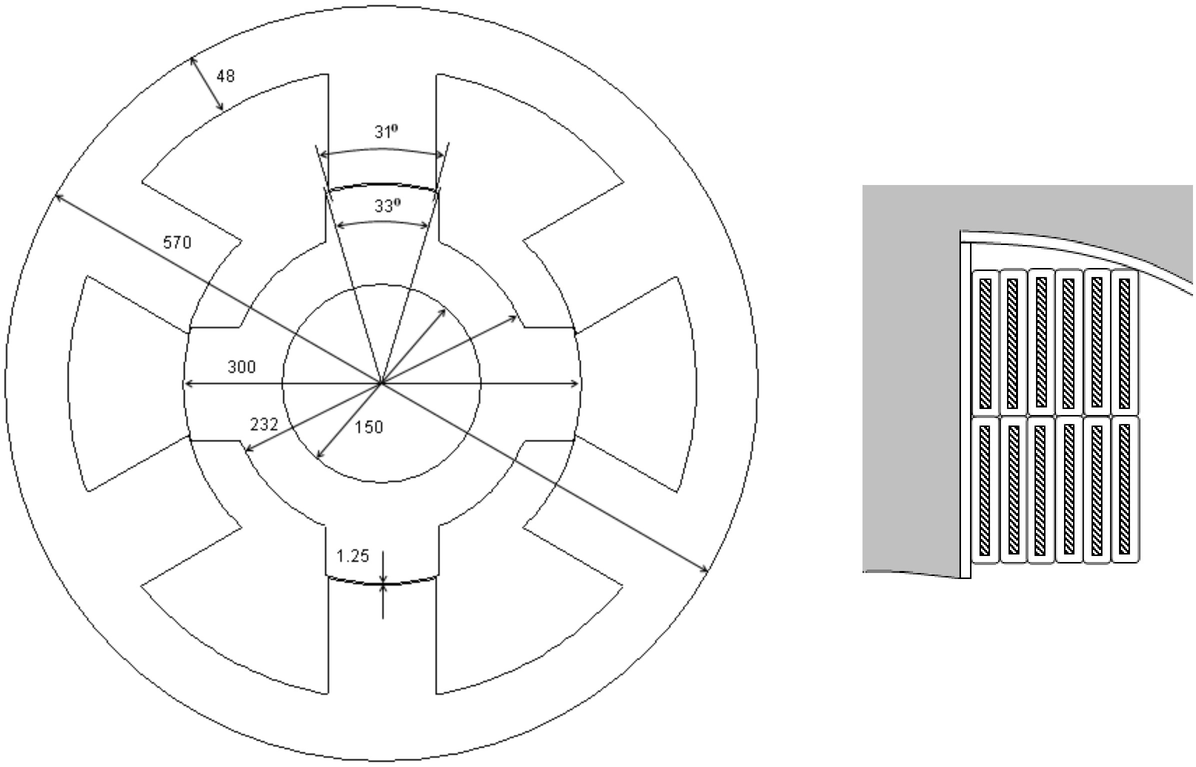
In the winding design it is assumed that the power electronic converter supplies the machine’s phases with voltage pulses of 4 kV.

Each phase winding consists of two coils connected in series so as to produce supporting magnetic polarity in the two diametrically opposite stator poles. Each coil contains 12 turns of rectangular copper conductors, 2 mm × 27 mm. The conductor thickness of 2 mm is appropriate with respect to the skin effect at the pulse frequency corresponding to a speed of 16789 rev/min. For simulation purposes, the estimated conductor length and copper mass per coil are 19 m and 9.2 kg. The DC value of phase resistance (2 coils connected in series) at 20°C is 12.8×10^{-3} Ω. The estimated phase resistance

ISBN : 90-75815-07-7

used in the model is $21.4\times10^{-3}\ \Omega$, which takes account of a temperature rise of 115 °C and an allowance for skin-effect.

The turns within the coil can be arranged as shown in the Figure 3b of the coil cross-sectional area. With the available rectangular cross-sectional area per coil side of 44 mm × 70 mm, this coil arrangement allows an insulation thickness of up to 2 mm around each conductor (total of 4 mm between conductors), 3 mm between the coil and the core and 3 mm free space between nearest points of adjacent phase coils. This arrangement would be considered adequate with respect to applying voltage pulses of 4 kV to the phase windings.



(a) Lamination Details (b) Coil Construction

Figure 3: Machine design

Simulated Performance

In order to simulate on a computer the SR drive's steady-state performance, the system's magnetic and electric equations must be solved. Because of the highly non-linear electromagnetic characteristics, a look-up table of electromagnetic data (flux-linkage/position/current) representing the phase magnetisation characteristics is used in simulation to reduce overall computation time. The block diagram of the simulator is shown in Figure 4.

 ISBN : 90-75815-07-7

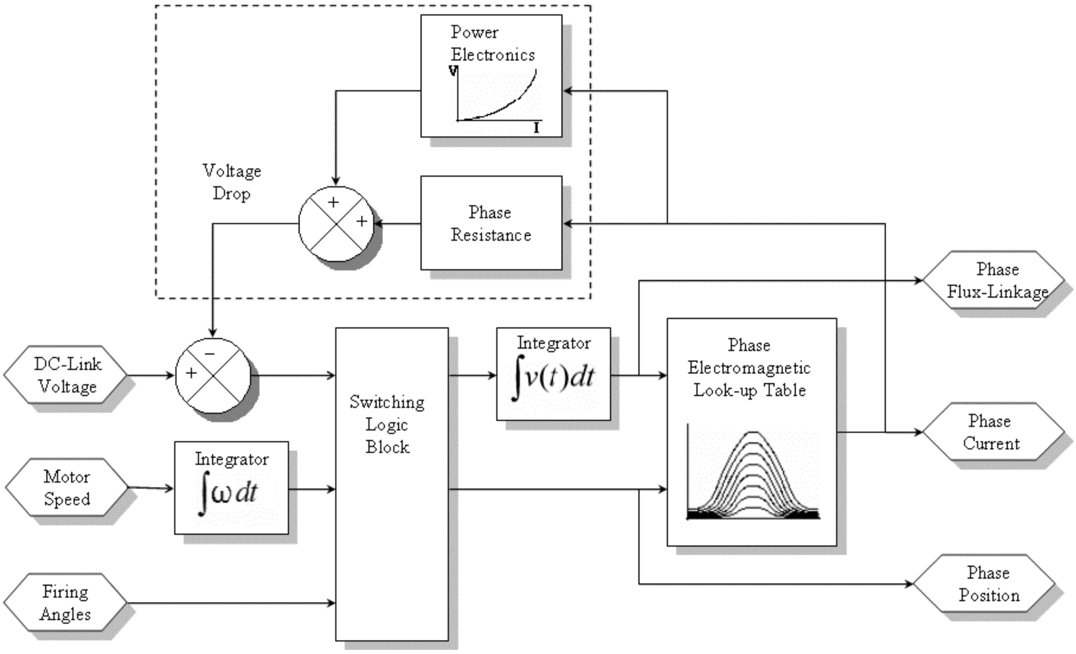


Figure 4: Block Diagram of SR Drive Computer Simulator

Four operating points where selected for a complete loss breakdown simulation. The original induction moor base speed rated point is around 16790 rev/min, 1064 Nm. The original inverter drive was also specified to operate at 105% overload speed at the peak power of 2 MW. The peak torque is 1140 Nm for 2 MW at rated speed. Two operating points were simulated at a much lower speed of 10000 rpm for typical running and peak acceleration torque. The results are listed in Table I. The ac input stage losses include the transformer (98% efficient), harmonic filter (99% efficient) and 12-pulse bridge rectifier. The rectifier losses are estimated for the simulated mean dc-link current using the Semikron power dissipation data on thyristor bridge modules. The simulated current waveforms for all four operating points are shown in Figures 5 – 8. The inductance waveform in the figures is only shown symbolically to indicate the minimum and maximum inductance positions, and in the real simulation the effects of magnetic saturation are taken into account through the electromagnetic look-up table.

The core losses are computed as function of speed and the voltage across the winding. On the basis of the frequency and estimated flux-density, which are specific for each bulk element of the magnetic core [12], the total core loss is obtained by adding the estimated core loss of each individual volume.

The simulated performance at 16790 rev/min reveals a motor efficiency of 97.1% and a power electronics efficiency of 99.2%. This compares well with the IM drive system operating at its rated power point which has typical motor and inverter efficiencies of 97% and 98% respectively. The results show that the SR motor drive is slightly more efficient in both the machine and the power converter. Also, the loss breakdown in the SR machine indicates that the majority of losses in the machine occur in the stator (29200 W) compared to 27400 kW in the IM stator, and the rotor loss (5500 W) is 40% less than in the IM motor (9600 W).

Table I: Simulation Results Loss Breakdown

SR Drive Simulated Performance	**Rated Operating Point**	**Overload Speed Point**	**Low-Speed Max. Torque Point**	**Low-Speed Typical Point**
Mechanical Output				
Machine Speed	16790 rpm	17600 rpm	10000 rpm	10000 rpm
Machine Torque	1069 Nm	1090 Nm	1147 Nm	453 Nm
Total Output Power	**1880 kW**	**2008 kW**	**1201 kW**	**475 kW**
Electrical Input				
DC-Link Voltage	4000 V	4000 V	4000 V	4000 V
DC-Link Current	487 A	523 A	307 A	122 A
DC-Link Power	**1949 kW**	**2086 kW**	**1228 kW**	**490 kW**
Total AC Input Power	**2009 kW**	**2150 kW**	**1266 kW**	**505 kW**
DC-Link Efficiency	**96.5%**	**96.3%**	**97.8%**	**96.9%**
Overall Drive Efficiency	**93.6%**	**93.4%**	**94.9%**	**94.1%**
Drive Loss Breakdown				
Input Stage				
Transformer Loss	40 kW	43 kW	26 kW	10 kW
Harmonic Filter Loss	20 kW	21 kW	12 kW	5 kW
Total Losses	**60 kW**	**64 kW**	**38 kW**	**15 kW**
Input Stage Efficiency	**97.0%**	**97.0%**	**97.0%**	**97.0%**
Power Converter				
Bridge Rectifier Loss	2.8 kW	3.0 kW	1.6 kW	0.6 kW
Single IGBT Conduction Loss	0.54 kW	0.59 kW	0.36 kW	0.12 kW
Single IGBT Switching Loss	0.50 kW	0.51 kW	0.57 kW	0.27 kW
Single Diode Loss	0.08 kW	0.08 kW	0.09 kW	0.05 kW
Total Losses	**15.6 kW**	**16.7 kW**	**13.3 kW**	**5.7 kW**
Power Converter Efficiency	**99.2%**	**99.2%**	**98.9%**	**98.8%**
SR Machine				
Stator Copper Loss	6.8 kW	7.5 kW	4.5 kW	1.1 kW
Stator Iron Loss	22.4 kW	26.0 kW	4.8 kW	3.3 kW
Rotor Iron Loss	5.5 kW	6.4 kW	1.2 kW	0.8 kW
Friction & Windage Losses	21.0 kW	24.0 kW	4.4 kW	4.4 kW
Total Losses	**55.7 kW**	**63.9 kW**	**14.9 kW**	**9.6 kW**
Machine Efficiency	**97.1%**	**96.9%**	**98.8%**	**98.0%**
Total System Losses	**131.3 kW**	**144.6 kW**	**66.2 kW**	**30.3 kW**

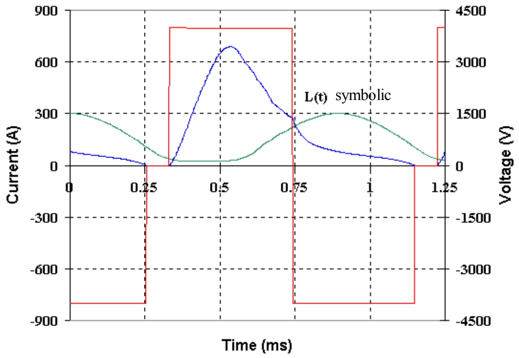


Figure 5: Simulated Waveforms at 16780 rev/min, 1066 Nm

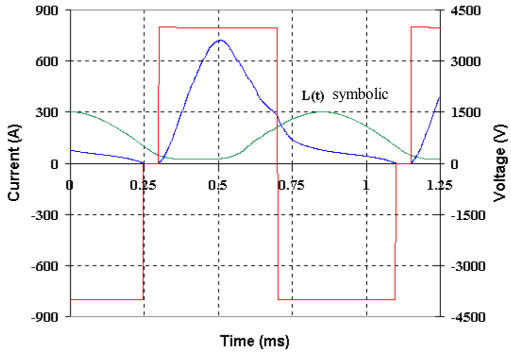


Figure 6: Simulated Waveforms at 17600 rev/min, 1087 Nm

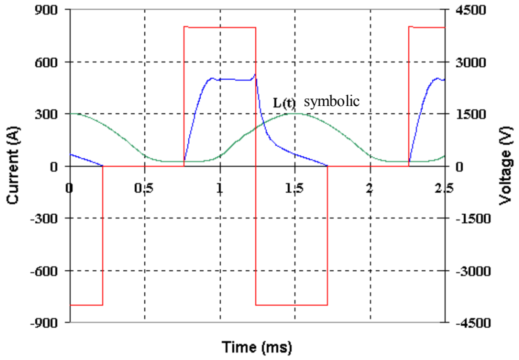


Figure 7: Simulated Waveforms at 10000 rev/min, 1140 Nm

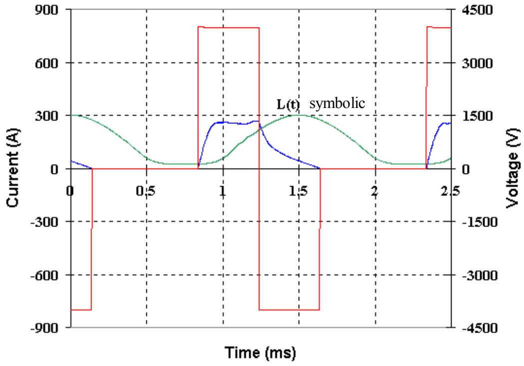


Figure 8: Simulated Waveforms at 10000 rev/min, 540 Nm

Conclusions

The paper has reviewed the switched reluctance motor technology for a high-power high-speed application in the light its basic electromagnetic, power electronic and control features together with its operating characteristics. Like the three-phase cage-induction motor, the SR motor is also a brushless machine, but with the additional advantages arising from the absence of conductors on the rotor and a very simple winding arrangement on the stator. Consequently, the SR machine is simpler to manufacture and offers possibilities for efficient cooling. Its power electronic converter can consist of an equal or less number of main power switches than the inverter used in the three-phase induction motor drive, and has additional advantages in terms of fault tolerant operation. There are no restrictions to high-power, high-voltage applications since the converter can be implemented using a number of multilevel topologies and the latest commercially available IGBT modules. The disadvantages in performance, associated with rotor position sensing, vibration and torque ripple, can be addressed using advanced control techniques implemented within a modern digital controller.

An SR drive is definitely a strong contender with the inverter-fed induction motor drive for application in the high-power gas compressor system. The predicted performance of a 2 MW, 16800 rev/min, SR drive has shown that it is technically feasible to produce a system capable of meeting the gas compressor's performance requirements. The loss breakdown for the machine has illustrated the beneficial features of the simple rotor construction with its lower losses compared to the induction machine. This offers the potential for even higher operating speeds than are presently used with the accompanying benefits of higher power densities.

Reference:

[1]. Lockley, B., “Adjustable speed drives in the petrochemical industry”, Conference Record of IAS ’02, IEEE Industry Applications Society Annual Conference, Pittsburgh, PA, USA, October 2002, Vol. 2, pp. 1240 – 1243.

[2]. Kleiner, F., de Wit, B. and Ponick, B., “Choosing Electric Turbocompressor Drives”, IEEE Industry Applications Magazine, July/August 2001, pp. 45 - 52

[3]. Lawrenson, P.J., Stephenson, J.M., Blenkinsop, P.T., Čorda, J. and Fulton, N.N., “Variable-speed switched reluctance motors”, IEE Proceedings, Part B, Electric Power Applications, Vol.127, No.4, July 1980, pp. 253 - 265

[4]. Kline, J.A. Sr., "Opportunities for switched reluctance motor-drives", Record of 1999 Annual Pulp and Paper Industry Technical Conference, Seattle, WA, USA, June 1999, pp. 42 - 47.

[5]. Odegard, B., Stulz, C.A. and Steimer, P.K., “High-speed, variable-speed drive system in megawatt power range”, IEEE Industry Applications Magazine, May/June 1996, pp. 43 - 50

[6]. Ahrens, M., Bikle, U., Prenner, H. and Gottkehaskamp, R., Electrical design of high-speed induction motors of up to 15 MW and 20000 RPM”, Proceedings of PEMD ’02, IEE International Conference on Power Electronics, Machines and Drives, Bath, UK, April 2002, pp. 381 – 386.

[7]. MacMinn, S.R. and Jones, W.D., “A very high speed switched-reluctance starter-generator for aircraft engine applications”, Proceedings of NAECON'89, National Aerospace Electronics Conference, Dayton, OH, USA, May 1989, pp. 1758 - 1764.

[8]. Watkins, S.J., Čorda, J. and Zhang, L., “Multilevel asymmetric power converters for switched reluctance motors”, Proceedings of PEMD ’02, IEE International Conference on Power Electronics, Machines and Drives, Bath, UK, April 2002, pp. 195 – 200.

[9]. Lovatt, H.C. and Stephenson, J.M., “Computer-optimised current waveforms for switched-reluctance motors”, IEE Proceedings - Electric Power Applications, Vol. 141, No. 2, March 1994, pp. 45 - 51.

[10]. Pollock, C. and Wu, C.Y., “Acoustic noise cancellation techniques for switched reluctance drives”, Conference Record of IAS '95, IEEE Industry Applications Society 30th Annual Meeting, Orlando, Florida, USA, October 1995, Vol. 1, pp. 448 - 455.

[11]. Ray, W.F. and Al-Bahadly, I.H., “Sensorless methods for determining the rotor position of switched reluctance motors”, Proceedings of EPE '93, 5th European Conference on Power Electronics and Applications, Brighton, UK, IEE Conference Publication No. 377, September, 1993, Vol. 6, pp. 7 – 13.

[12]. Čorda, J., “Switched reluctance machine as a variable-speed drive”, PhD Thesis, Department of Electrical and Electronic Engineering, University of Leeds, May, 1979.