

A Review of Various Converter Topologies for SRM Drives

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ABSTRACT

The switched reluctance motor (SRM) driver is receiving increasing attention from various researchers as well as industry as a viable for adjustable speed and servo applications. Combining the unique features of an SRM with simple and efficient power converter that in use, a superior motor drive system emerges which may be preferable for many applications compared to other AC or DC motor driver systems. Although a number of converters have emerged over the years for SRM drives, but every single driver has its own advantages and drawbacks and there has always been a trade-off between gaining something of the advantages and losing some when a new driver is offered. This paper presents a review of various research about SRM driver converters, for power quality and torque improvement, in last 20 years, in the area of modeling, simulation, static, dynamic analysis, different control schemes like power factor correction, quasi resonant switching, various demagnetization techniques for field current etc.

INDEX TERMS-Switched reluctance motor, power factor correction, quasi resonant switching, zero voltage switching, static analysis, dynamic analysis, mmf (magneto motive force), CCM (continuous conduction mode), DC (discontinuous conduction).

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INTRODUCTION

SWITCHED reluctance machine (SRM) exhibits several advantages when compared to other machine types, such as rigid structure, simple construction, absence of permanent magnet, brush less, less maintenance, low cost, high efficiency, simple converter circuit and switching control, freedom from shoot-through fault, etc. [1, 2, 3, 4, 5, 6, 7, 8]. Among the advantages of the reluctance motor are the simple construction and the absence of permanent magnets, which eliminates cost in both raw material and manufacturing processes. The absence of rotor windings and low rotor losses help to make the machine robust and suitable for high-temperature applications as well as high speed applications. Under almost all electrical fault conditions the reluctance motor is inert and completely safe. Therefore, it has increasingly attracted much research interest.

On the negative side, the SR motor tends to have more torque ripple and a higher noise level than other motors. SR motor cannot be controlled by conventional AC inverter; however to some extends this is an advantage, because the SR controller is arguably simpler and required less protection. However, the SRM suffers from some disadvantages: undesired acoustic noise, torque ripple, and current tracking control characteristics chiefly determined by the position-varied inductance and back EMF [3].

During the past, many researchers have investigated methods to improve the operating performance of the SRM drive and to promote its use in high-performance industry applications. Applications can be roughly categorised into: (i) simulation environment establishment (ii) converter circuit improvement (iii) advancing commutation for current switching control to pursue larger average torque, smaller torque ripple or higher

Conversion efficiency; (iv) DC-link voltage boosting to enhance high-speed driving capability; and (v) other issues such as motor design, acoustic noise reduction, small-signal dynamic modelling, sophisticated speed and position control methods, etc.

TORQUE PERFORMANCE

The combination of an SR motor and an appropriately controlled converter provides many of the desired characteristics of an efficient drive system. The output power of an SRM is higher than that of a comparable induction motor and the torque inertia ratio is also higher due to the absence of rotor windings. The primary disadvantage of an SRM is the higher torque ripple compared with conventional machines, which contributes to acoustic noise and vibration. The origin of torque pulsations in an SRM is due to the highly nonlinear and discrete nature of torque production mechanism. The total torque in an SRM is the sum of torques generated by each of the stator phase, which are controlled independently. Torque

pulsations are the most significant at the commutation instants when torque production mechanism is being transferred from one active phase to another. The resonant vibrations of the stator are the dominant source of acoustic noise in an SRM.

There are essentially two primary approaches for reducing the torque pulsations: One method is to improve the magnetic design of the motor, while the other is to use advanced electronic control [9]. Machine designers are able to reduce the torque pulsations by changing the stator and rotor pole structures, but only at the expense of motor performance. The electronic approach is based on selecting an optimum combination of the operating parameters, which include supply voltage, turn on and turn off angles, current level and shaft load. The minimization of torque ripple does lead to a reduction of the average torque, since the capabilities of the motor are not being fully utilized at every rotor position.

The effect of different lamination shapes on vibration is analyzed [10], considering five different shapes; the effects of a smooth frame were examined for each case. The resonant frequencies and mode shapes of the five models were compared with each other. Criteria for low-vibration designs were discussed for SRMs of different phase numbers. The implications of employing SR machines in actuator application and an assessment on the torque control quality with series of dynamic tests are explained in [11].

An approach to minimize torque ripple and produce ripple-free torque in SRM's by using simple position and current feedback structure, has been addressed in [12]. A complete parameterization of position-dependent voltage and current profiles that result in (nominal) ripple-free operation of an SRM has been developed.

Due to the current pulses through the phase coil of SRM, vibrations are generating, which cause torque performance. Acoustic noise reduction and hence torque improvement in SRM, is one of the other live topic among researchers. A work [13] attempts to survey the current research status on noise and vibrations in SRMs. A clear perspective is given on existing literature, various sources of noise in SRMs, and proposed solutions. The inadequacies of current knowledge in this field are described and new research directions are proposed. Another work [14] on the identification of noise sources and techniques to mitigate noises. It points the reader to relevant research in the past on acoustic noise identification and mitigation techniques. The paper also describes the current standards and practices and some of the suggestions in literature to intensify these standards. The paper summarizes the emerging future directions in acoustic noise mitigation studies. A comparison between the acoustic noise produced by a two-phase switched reluctance drive and a flux-switching motor and drive shows, shows that, there is over 2 dB less acoustic noise from the flux-switching topology relative to the equivalent two-phase switched reluctance machine [15]. A powerful new design aspect to reduce acoustic noise and

vibration of electromagnetic origin for electrical machines, by introducing improved slot wedges referred to as "structural stator spacers", is presented in [16].

The vibrations of electric motors are mainly determined by two factors, radial force excitation and structure borne transfer function. An analysis [17] on both causes and derived that vibration could be reduced by increasing electrical constant time and delaying radial force falling time. A control strategy for reduced acoustic noise and sensor less operation of a switched reluctance (SR) motor is proposed [18] for heating, ventilation, and air conditioning (HVAC) application, where the magnitude of the dc-bus voltage is controlled as a function of speed and the motor is operated in a single-pulse mode for all speed range. An investigation on same topic [19] and concluded that, a desired torque and thus mmf production should be obtained by a higher number of turns and low current because this will decrease the slope of the radial force and vibration. But motor will probably be operated under single pulse mode, dynamic performance deteriorates and the overload ability of the maximum torque is limited.

The applications of a variable structure system (VSS) to the control of a switched reluctance motor (SRM) drive are presented in [20]. After reviewing the operation of an SRM drive, a VSS-based scheme is formulated to control the drive speed. The study shows that the VSS control is effective in reducing the torque ripple of the motor, compensating for the nonlinear torque characteristics, and making the drive insensitive to parameter variations and disturbances.

Direct torque controller with Lyapunov function based is presented in [21], which avoids the complex process of torque-to-current conversion. By using the port controlled Hamiltonian (PCH) systems theory, a full-order nonlinear controlled model is developed and a non linear passivity-based robust adaptive control of SRM in the presence of external disturbances for the purpose of torque ripple reduction and characteristic improvement is presented [22].

A detailed comparison between Field oriented control (FOC) and Direct torque control (DTC), control techniques, emphasizing their advantages and disadvantages is given in [23]. The performance of these two control schemes is evaluated in terms of torque and flux ripple and their transient response to step variations of the torque command.

POWER QUALITY

In general, ac-dc converters, which are also called rectifiers, are developed using diodes and thyristors to provide controlled and uncontrolled dc power with unidirectional and bidirectional power flow. Due to injected current harmonics, causes voltage distortion and poor power factor at input ac mains and slow varying rippled dc output at load end, low efficiency and large size of ac and dc filters, which results



Poor power quality [24]. Because of strict requirement of power quality at input ac mains several standards have been developed and are being enforced on the consumers. Because of severity of power quality issues some other options such as passive filters, active filters (AFs), and hybrid filters along with conventional rectifiers, have been extensively developed especially in high power rating and already existing installations.

Power quality is one of the important subjects in industrial applications and various researches are going on the same, targeting better quality. An overview about active filters based on power electronics technology and their future prospects is given in [25]. Another review on the subject of active power line conditioning is given in [26] with comparison among existing methodologies. A comprehensive review of active filter (AF) configurations, control strategies, selection of components, other related economic and technical considerations, and their selection for specific applications with a referral of more than 200 research is given in [27]. Another review on active power filters are given in [28] based on topology and control technologies.

In order to meet the increased industrial requirements to meet better power quality, advanced rectifier/ converters are developed with new solid state self commutating devices such as MOSFET, IGBT, thyristors etc. Such converters are using either as switch mode rectifiers (SMR), power factor correctors (PFC), pulse width modulation (PWM) rectifiers, multilevel rectifiers etc. A comprehensive review of single phase improved power quality converters (IPQCs) configurations, control approaches, design features, selection of components, other related considerations, and their suitability and selection for specific applications by referring more than 450 research publications is given in [29]. Same approach to a three-phase ac-dc converters is given in [30].

A study on switch mode rectifier (SMR) with a focus of improvement in power quality is interesting to address. The current wave shaping or control technique with continuous or discontinuous mode of conduction defines the power quality capability of the SMR [31-32]. Improvement in input current waveform control with ripple compensation is presented in [33]. SMR with hysteresis current controlled PWM scheme is considered in [34].

A single-loop current sensor less controls (SLCSC) for single-phase boost-type switching-mode-rectifiers (SMRs) is developed and digitally implemented with DSP-based system [35-36]. The control has only one voltage loop where its output is used to shift the nominal duty ratio pattern generated from the sensed input and output voltage. Because of no current loop, the efforts of sampling and tracking inductor current are unnecessary. Another DSP based circuitry for SMR control, which has current waveform tracking control for better power quality is given in [37]. A novel duty phase control (DPC) for single-phase boost-type switching-mode-rectifier (SMR) is developed and implemented in DSP-based system [38]. The

phase feed forward control (PFFC) for single-phase boost-type switching-mode-rectifier (SMR) is proposed in [39]. A novel duty phase control (DPC) for single-phase boost-type switching-mode-rectifier (SMR) is developed and digitally implemented in DSP-based system in [40]. The effect of the differences between nominal and real circuit parameters on the input current waveforms of SLCSC (single-loop current sensor less controls) are addressed in detail [41].

POWER FACTOR CORRECTION

Due to the nonlinear operation of dc converters/power supplies causes substantial distortion to the line current and emit electromagnetic noise via conduction and radiation, interfering the operations of nearby equipments. In order to ensure a sufficiently high quality of power supplies, design standards have been tightened to restrict the level of harmonic distortion. A useful measure of power quality is power factor, which is termed as the ratio of the real power to the apparent power. Mathematically we can express the power factor as the product of a displacement factor and distortion factor, ie.

$$\text{Power factor} = \cos \Phi / \sqrt{1 + \text{THD}^2}, \quad (1)$$

where $\cos \Phi$ - displacement power factor

THD- total harmonic distortion.

To improve the power factor in DC load applications, converter design is the main improvement area, with advancement in controller topologies.

An overview [42] about various current control methods and general averaging method for characterizing the large signal behavior of single-phase PFC circuits with these current control methods. A review of high-performance, state-of-the-art, active power-factor-correction (PFC) techniques for high-power, single-phase applications is presented in [43] with the merits and limitations of several PFC techniques.

The topologies for power factor correction circuits for small dc to dc power supplies and large motor drives are very different [44]. The predominant PFC circuit used in the dc to dc power supplies is the single switch boost topology and the power levels rarely exceed 1kW. Beyond this power level, the bridge configurations are preferred. The single switch boost topology is very ideal for the appliance drives as they are quite feasible within the power level of 1kW and mostly operate from a single phase utility input.

At higher power levels, the continuous-conduction - mode (CCM) boost converter is preferred topology for implementing a front end with power factor correction (PFC). The bridgeless PFC boost converter reduces the overall conduction loss of the PFC converter stage by reducing the number of rectifiers that conduct current from the input to the output by essentially

eliminating the diode bridge rectifier. The advancement in semiconductor technology provides cheaper, faster, compact and efficient PFC circuits, which got more attraction to the industry. An overview about the various control schemes for this boost converter including their tradeoffs as to power factor, output voltage transient regulation, and cost of implementation is given in [45].

A comparative study of single-switch three phase high PF rectifiers is given in [46]. Specifically, the discontinuous-conduction-mode (DCM) boost rectifier with a 5th-harmonic-trap filter, the DCM boost rectifier with a harmonic-injection circuit, and the multi-resonant, zero current-switching buck rectifier were compared with respect to their efficiencies, compliance with the IEC555-2 specifications, volumes, weights, and costs. An overview of PFC in off-line power supplies is given in [47], which covers theoretical aspects, control strategies, power topologies and future trends. PFC in non linear system with PID control is presented in [48]. A non linear dynamics of PFC converter is presented in [49].

A novel single-stage switching power supply with half-bridge topology, which is formed from integration of one half-bridge ac/dc power factor corrector (PFC) and one half bridge dc/dc post regulator [50]. A novel active power factor correction method for power supplies with three-phase front-end diode rectifiers is proposed and analyzed [51]. An analysis of a unidirectional hybrid three-phase rectifier suitable for medium and high-power applications with low THD and good voltage regulation is given in [52]. The rectifier is composed of a single-switch diode bridge boost-type rectifier in parallel with a pulse width modulation (PWM) three-phase unidirectional boost rectifier. The parallel operation of modular power factor correction circuits is illustrated in [53]. The modular units using boost converters are operated at a constant frequency with variable duty ratio.

Due to its novelty and being a strong contender for low cost variable speed applications, it is timely to study the impact of PFC circuit on SRM drive system particularly the impact on overall system efficiency. The need of PFC circuit in SRM drives is analysed in [54]. Effect of PFC on SRM is analyzed and proposed on circuit for better PFC in [55].

A study on a three phase PWM inverter-fed induction motor drive with single phase utility input, and with and without a power factor correction circuit is given in [56]. In the case of the study, detailed comparisons of system and induction motor efficiencies, inverter output voltage and current and input power factor, against rotor speed and output are made.

RESONANT SWITCHING

In recent years, resonant converters have gained renewed interests due to their advantages of higher efficiency, smaller size and weight for passive components and lesser EMI problems over conventional PWM switching converters. Though they had been present for long time, their applications

were limited until the advent of high speed, low cost, controllable power semi conductor switches. Nowadays, resonant converters are widely used for switching applications like power supplies, converters, motor drives and various applications. Resonant converters can be broadly classified in to three categories like load resonant converters, quasi-resonant converters and resonant dc link converters.

In particular, the combination series-parallel converter can run over a large input voltage range and a large load range (no load to full load) while maintaining excellent efficiency. The half-bridge series-resonant, parallel-resonant, and combination series-parallel resonant converters are compared for use in low output voltage power supply applications [57]. It is shown that the combination series-parallel converter, which takes on the desirable characteristics of the pure series and the pure parallel converter, removes the main disadvantages of those two converters.

The basic strategy of resonant converters is to eliminate or reduce significantly the switching losses in the converter. This is achieved by making either the current through the switch or the voltage across it zero at the time when switch changes the state.

a. Zero Voltage Switching (ZVS)

Zero voltage switching (ZVS) topology where the switch turns on and off at zero voltage. The peak resonant voltage appears across the switch, but the peak switch current remains the same.

b. Zero current Switching (ZCS)

Zero - current switching (ZCS) topology where the switch turns on and turns off at zero current. The peak resonant current flows through the switch but the peak switch voltage remains the same.

CONVERTERS

The converter is a power supply unit that follows the commands of the controller to energize each phase of the motor at the appropriate times. Therefore, it does not only deliver energy to an electronic device from an electrical outlet, it also regulates the current to meet specific device requirement. The performance of the SR drive is highly affected by the performance and characteristic of converters. Several varieties of converter topologies have been presented in the last years. With continued research, different topologies have emerged presenting reduced numbers of power switches, faster excitation time, faster demagnetisation time, higher efficiency, higher power factor and high power.

i. SRM Converters

A review and analyzes on SRM converters is given in [58], which proposes a switched reluctance (SR) converter configuration that is classified based on the commutation type and magnetic energy path. The converter has three parts: utility interface, front-end circuit, and power converter. Another comparison about SRM converters by using a straightforward total semiconductor VA per sum and relative cost of the drive system elements is considered [59].

This paper [60] explores practical issues and use of modern power, control and sensing circuitries of a 6/4-pole Switched Reluctance Motor (SRM) drive. A DSP-based SRM drive system consists of classic bridge converter including power MOSFETs and their gate drivers, freewheeling diodes, sensing circuit, DSP controller and a SRM that is being controlled by the controller. The complete practical issues experienced with modern power, control and sensing circuitries of a 6/4-pole SRM drive is presented. Speeding up the winding current tracking response is considered to be the best method to enhance the operating performance of a switched reluctance motor drive. The most effective approach to achieving the DC-link voltage boosting. The analysis, simulation and implementation of a proposed DC-link voltage boosting circuit for SRM drives have been presented in the paper [61].

The main considerations in the design of a single -switch-per-phase converter for a SRM drive with particular attention to the choice of converter topology, the type of switching devices, the normalized rating of the power devices and input filter is given in [62]. The demands on control accuracy of switched reluctance machine traction drives and the traction controller sampling frequency, which are necessary to take advantage of the switched reluctance machine dynamic capabilities, are discussed in [63].

The application of four-quadrant operating to an SRM drive has been proposed in [64] to improve the overall performance of the drive and, at the same time, to provide a solution sample in implementation with DSP. The development of a front-end converter and its control for a battery powered switched-reluctance motor (SRM) drive is presented in [65]. In motoring mode, the converter is operated as a dc-dc boost converter to establish dynamically boostable and well-regulated dc-link voltage from battery. The digital control schemes of boost converter and motor drive are implemented using a common digital signal processor. A proper voltage boosting feedback controller is designed to effectively enhance the SRM winding current and speed dynamic responses.

Provision of faster rate of discharge for the phase current is one of the requirements for high speed. A new type of converter circuit for SRM [66], which uses bifilar topology in conjunction with a resonant circuit during turn off period. A two-quadrant front end converter for SRM drive is presented in

[67], which maintain controlled boosted DC-link voltage according to winding current tracking error results in improvement of dynamic response.

A new converter [68] topology for SRM drives is proposed with minimum number of power switching devices, same voltage rating for all of them, variable dc link voltage for application to the motor windings to reduce the switching frequency of the phase switches and hence the switching and core losses but higher and fixed dc link voltage for faster commutation of phase currents. A drive which employs a novel two phase SRM with fully pitched winding, based on a principle originally proposed in [69] for three phase machines. An analysis about the problems associated with Miller converter and modified Miller converter used for powering SRM drive. AN improved converter configuration which contains (2N-1) device is proposed in the paper [70]. The topology for several different C-dump converters is presented in [71]. A new bifilar drive circuit which uses dump capacitor during discharge period is presented [72]. The new topology utilizes the bifilar winding in conjunction with the dump capacitor to produce resonance in order to provide faster rate of current discharge. This technique permits the motor to operate at higher speeds. Another single switch per phase converter for two-phase SRM drive that employs a voltage doubler rectifier circuit charging a split dc supply made up of two low value film capacitors given in [73]. A DSP-based SRM drive with its dc-link voltage being established by a 3P1SW SMR is presented in [74], the key proposed control spirit is to treat the SMR line current and output voltage ripples as disturbances and to perform their automatic and robust cancellation controls.

The combined asymmetric half-bridge power converter topology is often used to drive switched reluctance machines (SRMs). This letter [75] describes a transformer-isolated power Semiconductor gate driver circuit that uses only two transformers to supply all three power devices in a combined asymmetric half bridge with local power supplies and drive signals. Therefore, the entire gate driver circuitry for a six-switch converter driving a four-phase SRM requires only four isolation transformers, thereby reducing cost.

ii. DC Converters-General

A general study on dc converters, its recent developments in control topologies, various approaches summarized in this section. A simplified analysis of PWM converters using model of PWM switch in discontinuous conduction mode is given in [76]. A review on various topologies used in UPS power supplies given in [77]. A novel control principle of a bi-directional dc-dc power converter with galvanic isolation is given in [78]. The converter consists of a current side and a voltage side. Three basic circuit topologies are possible on both converter sides.

Circuit topologies of the dc-dc converter with bi-directional power flow control and conversion capability, with galvanic isolation between the two sides through a single transformer