Performance Analysis of Classical Converter Using Different Control Strategies for Switched Reluctance Motor with Dynamic Loading

Ritika Asati and Deepak S. Bankar

Abstract Among the researchers, switched reluctance motor (SRM) is generating a lot of interest as it is a permanent magnet-free motor which significantly differs from the other polyphase machines. Due to the absence of brushes, windings, and permanent magnet on rotor, its structure is lightweight. Other than the structure, it has many other attractive characteristics suitable for variable speed applications. Special applications include aerospace, renewable and electric vehicle (EV). Lack of reserves of permanent magnet and continuous rise in its price are forcing motor manufacturers to look for an alternate motor which does not require permanent magnet. SRM is the best alternate solution to mitigate these challenges. Performance of SRM drive depends on the type of power converter and control technique used. Over the years, many converters have been developed and analyzed; among those, asymmetric bridge converter gives the highest performance in terms of independent switch control, good fault tolerance capability, and easy power regeneration. This paper represents the simulation of 7.5 kW, 8/6 pole, four-phase SRM using asymmetric bridge converter with current hysteresis chopping and pulse-width modulation (PWM) technique for dynamic load. Asymmetric bridge converter with current chopping or hysteresis current control offers better performance in terms of current as it is limited to 35 A under the range of peak current and appropriate speed–torque for dynamic loading.

Keywords Asymmetric bridge converter (ABC) · Switched reluctance motor (SRM) · Hysteresis current control (HCC) · Pulse-width modulation (PWM) · Dynamic load

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1 Introduction

Switched reluctance drive (SRD) is gaining significant traction in the field of renewable energy, electric vehicles, aerospace, and other variable speed application due to its lightweight rotor. Switched reluctance motor (SRM) is a permanent magnet-free motor with no brushes and windings on its rotor [1]. The origin of the nomenclature (switched reluctance) comes from the fact that the rotor of SRM continuously changes its position with respect to the variable reluctance path. Construction of SRM is different from the other multi-phase machines because of the doubly salient structure [2]. SRM's primary advantage lies in the fact that it does not need permanent magnet for its construction unlike most of the other motors which require permanent magnet for their construction. Permanent magnets are manufactured from rare-earth element which usually involves high cost of refining and mining, thereby increasing the cost of the motors. Very few countries around the world have these rare-earth elements reserve.

SRM is characterized by its wide speed range, good fault tolerance, high speed in a wide constant power range, low cost, simple, and light structure motor. Due to these characteristics, constant advancements are being made with the consideration that SRM can be used as an alternative to permanent magnet motors [3]. In spite of many attractive features and suitability to EV application, doubly salient structure of SRM creates noise, vibration, and torque ripple which limit its acceptance.

Figure 1 shows the basic components of SRM drive giving input to a dynamic load. Battery and its management system supply DC power for the motor through power electronics converter. For the movement of the rotor, stator winding needs to be energized in steps with the help of power electronic converters. Switching pulses for this converter excite each phase of the motor to conduct independently [4]. Motor controller block controls all the switching signals applied to the power converter. Different control techniques can be used on the same type of power converter based on the performance requirement of the load.

Multiple current and torque control methods have already been discussed in literature for asymmetric bridge converter like commutation angle control, torque sharing function (TSF), model predictive control (MPC), direct instantaneous torque control (DITC), and many more. Commutation angle control has wide torque adjustment range and suitable for higher speed. By controlling the dwell angle and advanced angle of switching devices, regulated phase current waveform can be obtained, but this angle control causes changes in other phase current waveforms and also makes it non-suitable for low-speed operation [5, 6]. TSF is generally discussed and analyzed in literature, and it uses the SRM flux linkage characteristics for current reference profiling purpose [7]. This method is effective at both base speed and above the base speed as well. TSF needs larger memory size and exhaustive computation [8]. MPC predicts the future nature of the controlled variables by predefining the criterion of optimization. Motor can work both with voltage and current controls but requires large memory to store these data and is sensitive for system variable changes [9]. In

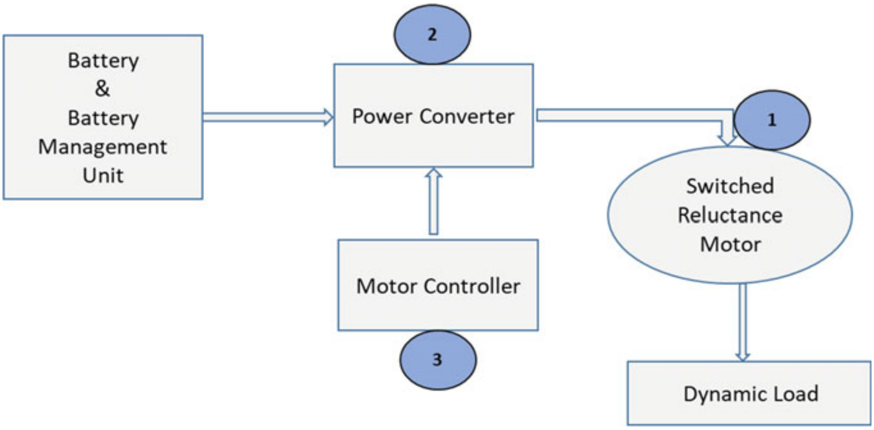


Fig. 1 Basic components of switched reluctance motor drive

DITC technique, controller maintains the torque within hysteresis band by controlling the switching pulses of converter to energize the incoming and outgoing phase [10], but fixed commutation angles are unable to avoid the negative torque in DITC method [11]. PWM voltage control provides fixed frequency operation but is not suitable for dynamic load as current is very high during the starting because of the absence of current limiter [5].

Hysteresis current control technique provides better response and has good current control to protect the switches and windings of motor [12]. The starting and running torque provided by this method is sufficient to drive dynamic load in an electric vehicle. Table 1 lists the SRM specification used in the MATLAB simulation of asymmetric bridge converter for the comparison of commonly used PI (proportional plus integral)-based current chopping or pulse-width modulation control techniques. Here, simulation waveform presented that the hysteresis or current chopping control is the simple control technique which provides both current and speed controls.

Table 1 Switched reluctance motor specifications

Parameters	Value
Type	8/6
Stator resistance (ohm)	0.5
Inertia (Kg m^2)	200 * 0.28 * 0.28
Friction (N-m s)	0.02
Unaligned inductance (H)	9.15×10^{-3}
Aligned inductance (H)	145.9×10^{-3}
Saturated aligned inductance (H)	0.15×10^{-3}
Maximum current (A)	35
Maximum flux linkage (V s)	0.9

The paper is arranged in different segments as follows: Here, Sect. 2 presents role and requirement of converter, SRM, and EV specification; Sect. 3 will give overview of asymmetric bridge converter with its operation mode; detailed block diagram and working of hysteresis and PWM control technique are demonstrated in Sect. 4; waveform comparison and simulation result discussion are shown in Sect. 5; and at last, Sect. 6 presents the conclusion and scope of extension of this work.

2 SRM Requirements

Input DC voltage to SRM is obtained from a battery through power electronics converter to excite the respective stator phase which offers low reluctance path [13]. In SR motor, it is assumed that the mutual coupling between the different phases is negligible, which helps each phase of the motor to be independently controlled [14].

$$V = R_S i + L(\theta, i)\frac{\mathrm{d}i}{\mathrm{d}t} + \frac{\mathrm{d}L(\theta, i)}{\mathrm{d}\theta}\omega_m i. \tag{1}$$

Equation 1 [3] shows the voltage applied across each phase of the motor winding. First two components on the right side of Eq. 1 denote voltage drop in resistance and inductance of the motor winding, and the third component of Eq. 1 indicates the generated back emf, which primarily depends on the variable inductance with rotor position and speed.

The instantaneous torque produced in SRM is given by:

$$T = \frac{1}{2} i^2 \frac{\mathrm{d}L}{\mathrm{d}\theta}. \tag{2}$$

As per the torque Eq. 2 [3], it is observed that SRM torque can be controlled by the following parameters:

(1) By controlling the current in the stator winding.
(2) By controlling DC voltage to stator.
(3) By advanced or dwell angle control [5].

Based on these parameters, speed or torque can be controlled using commonly used or advanced control methods.

3 Asymmetric or Classical Converter

Asymmetric bridge converter (ABC) is the highly flexible, four-quadrant commonly used converter for SR motor drive. Figure 2 is showing the classical asymmetric bridge converter for a four-phase SRM drive where each phase is using two power

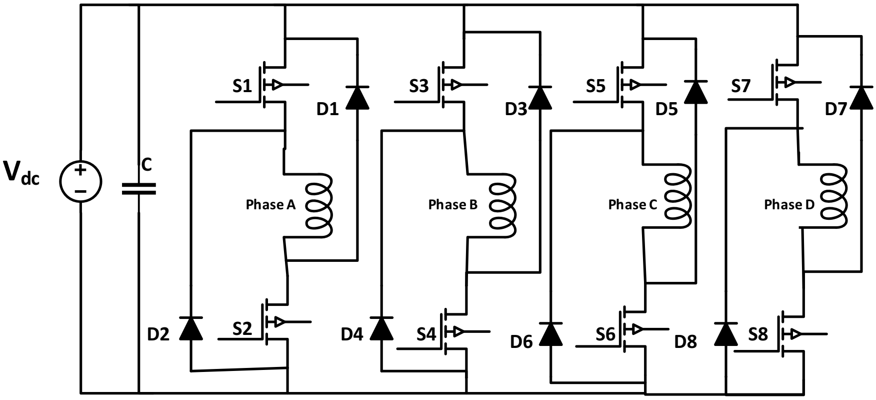


Fig. 2 Classical asymmetric bridge converter for four-phase SRM

switches and two diodes. The voltage stress experienced by each switch is equal to dc link supply voltage.

The supply voltage (+U, −U, and zero) appears across the phases and can be controlled independently which makes this converter suitable for high-speed application [15, 16]. The asymmetric bridge converter can work in two modes by using three different means of current conduction magnetization, demagnetization, and freewheeling.

(i) **Hard chopping mode**: In Fig. 2, if we will turn on both the switches S_1 and S_2, phase A will be energized and current will start flowing through V_{dc}, S_1, Phase A, S_2. For turning off the phase A, both the switches S_1 and S_2 will turn off and diodes D_1 and D_2 will be on, and the phase A energy will be supplied back to source in this mode called regeneration as negative supply voltage will appear across the winding and current will decrease rapidly bringing it below the commanded value [6].

(ii) **Soft chopping mode**: In soft chopping mode for turning off phase A, only one switch say S_2 will be off, while S_1 will remain on and diode D_1 will be forward-biased, and this will circulate the current through phase winding, D_1 and S_1. The voltage appeared across the winding will be zero during this mode (assuming voltage drop across switches and diodes is negligible) that will assist in reduction of current rate in comparison with the hard chopping mode. This mode will help in reducing the switching frequency and later the switching losses [6, 14].

Asymmetric bridge converter does not need any additional winding or commutation circuit, that helps in decreasing the copper loss and high heat loss [15]; this converter is highly flexible in controlling the phase current value and also has good fault tolerance capability that can effectively improve the reliability of the SRM drive.

4 Control of SRM

Control techniques for SRM are different than the other permanent magnet motor due to the extremely nonlinear behavior of it. Salient pole stator–rotor and no magnet on rotor create variable inductance to produce torque [7]. From Eq. 1, we can see that torque is controlled by controlling the amplitude of current. As by changing the supply voltage, phase current can also be changed. Therefore, voltage and current controls can be used for controlling the speed or torque of the SRM. By proper selection of control scheme, performance of the SRM drive can be enhanced for dynamic loading condition.

4.1 Hysteresis Current or Current Chopping Control Technique

Current chopping or hysteresis current control is the most commonly applied control method in SRM with asymmetric bridge converter due to its fast dynamic response, model independence, and it requires to set only current band for control [4]. Various parameters of motor mainly current, speed, and torque have significantly affected by the choice of current controller [7]. The block diagram of a hysteresis or current chopping control approach is presented in Fig. 3 [6]. For the SRM operation below base speed and at a suitable DC voltage, current control technique is levied. In this control hysteresis band ΔI is set as per the maximum value of phase winding current. The winding current is limited around the set reference current I^*. Power converter gets switching pulses from the control circuit when the current is lower than the set value and turns off the switches when current reaches upper limit of hysteresis band [17].

In current chopping technique, frequency of gate pulse varies with the speed. Therefore, speed monitoring and reference current are required to achieve steady-state speed. Speed controller block in Fig. 3 compares reference speed with actual measured speed to produce speed error. This error is processed through the speed

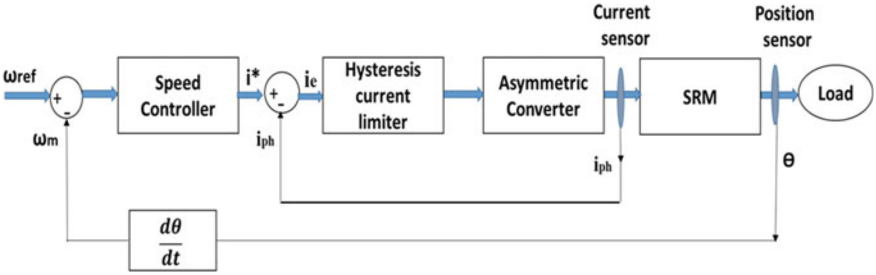


Fig. 3 Closed-loop hysteresis current control with asymmetric bridge converter

controller block to generate reference current. Current limit needs to be set in the speed controller. By proper selection of pulses, required phase can be turned on to control the value of torque and speed. Selecting the value of hysteresis band is a cumbersome task, which also affects the performance of the drive. Here, a PI controller is used to process the speed error, so by adjusting the proper value of K_p, K_i, and reference speed, desired closed-loop performance can be achieved [6].

The main characteristics of the current chopping control are: It is simple and direct method, smooth torque, and appropriate for low-speed operation [5]. The current ripples in SRM are much prominent at low-speed operation. Variation in switching frequency affects the hysteresis band of current. [7] These current ripples can be reduced by narrow down the hysteresis band ΔI [17]. The main purpose of the controller in this system is to use the information from position and current sensor and compared with the set value [18].

4.2 Pulse-Width Modulation (PWM) or Voltage Chopping Control Technique

In this closed loop, voltage chopping method by keeping θ_{on} and θ_{off} unchanged; reference speed is set into the controller as input, instead of PWM duty cycle. Continuous motor speed can be obtained either by differentiating the rotor position or position sensor. PWM control method can be applied to the winding voltage [5]. By varying the duty cycle of the pulses in PWM, average output DC voltage to the phase winding can be controlled. This in turn controls the phase current of the winding and regulates the torque and speed of the SR motor drive. This control method is usually employed when rotor position is available. The actual motor speed is derived by differentiating the rotor position. All the power switches in the converter operate in the pulse-width modulation (PWM) mode [6].

In closed-loop PWM control system shown in Fig. 4, reference and actual speeds are compared and generated speed error (difference between two speeds) is processed through speed controller. This speed controller adjusts the PWM duty cycles to reduce the speed error to zero. Speed controller will continuously adjust the duty cycle to get the desired reference speed. It provides the desired performance in terms of settling time and no overshoot in speed. But sudden increase in the duty cycle during starting condition leads to high value of phase current which can damage the stator windings [6]. This method is appropriate for low- and high-speed operation, but at low-speed torque ripple produced through this control technique is more. There are always some benefits and limitations of using any new technique [19–21].

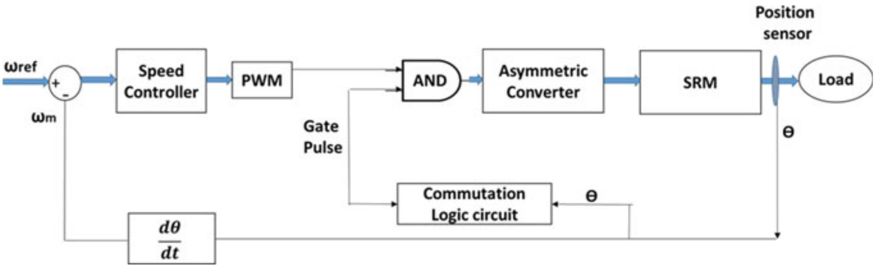


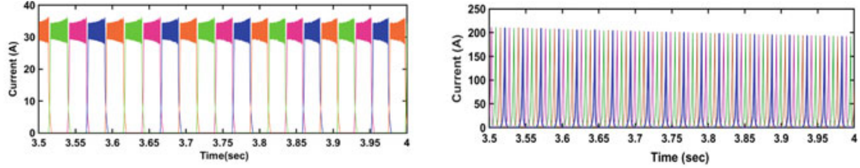
Fig. 4 Closed-loop voltage PWM control

5 Results and Discussion on Waveform

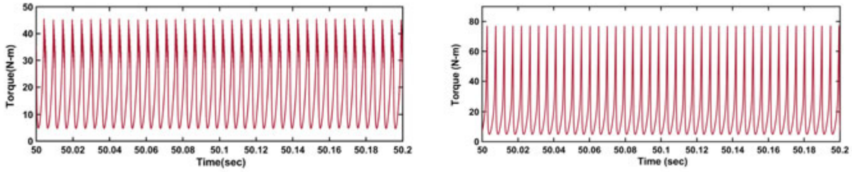
In this section, MATLAB simulation model of a four-phase, 7.5 kW, 8/6 pole SR motor with closed-loop hysteresis current control and pulse-width modulation technique are presented as shown in Fig. 5. The load used for these simulations is 200 kg weight dynamic load model. Current limit set in both the controllers is 35 A. For the entire speed range, angle of turn on is 40° and angle of turn off is 55° during the entire speed range. In both the control techniques, supply DC voltage to SRM is 200 V and these control techniques are implemented on asymmetric or classical converter. The simulation has been run for 60 s, and Fig. 5 is representing simulation waveform of current, torque, and speed of asymmetric bridge converter with hysteresis current and PWM voltage control technique.

It can be deduced from the simulation results given by comparative table in Fig. 5. In Fig. 5a, current waveforms are shown which indicating that in hysteresis current control, initial current is 35 A under set hysteresis band, while in PWM voltage control, initial current peak is too high and goes around 500 A for short duration as no current limiter is applied in this technique after 15 s current value reaches to 70 A. From the torque waveform in Fig. 5b, it can be monitored that initial torque peak is 58 N-m in current control latter this torque becomes constant near 45 N-m in 50 s. Though, initial torque peak is extremely high around 680 N-m in PWM voltage control, latter it is settled near 80 N-m in 15 s. Maximum speed reached is 490 RPM or 51.6 km/h and time required to settle at this constant speed is 50 s using current control approach; for voltage control approach, maximum speed is 520 RPM or 54.8 km/h and settling time for this speed is 20 s and can be observed from Fig. 5c for dynamic load. In both the control approaches, speed is almost same, but time to settle speed is more in current control technique.

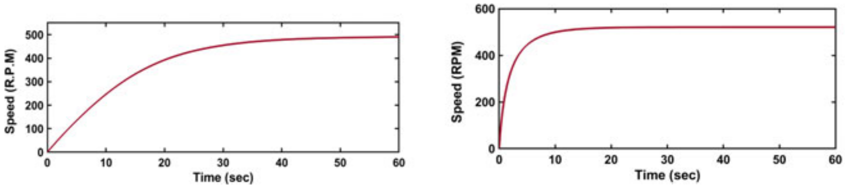
Hysteresis current control **PWM voltage control**



(a) Current vs. time (a) Current vs. time



(b) Torque vs. time (b) Torque vs. time



(c) Speed vs. time (c) Speed vs. time

Fig. 5 Comparison of the simulation results of hysteresis current control and PWM voltage control for four-phase SRM

Table 2 shows the comparison of two different control techniques based on the frequency, settling time, maximum torque, maximum current, and speed. From this comparison, it is observed that both of these SRM control techniques have their own advantages and drawbacks. The simulation waveforms in Fig. 5 for torque and speed of SR motor drive using both the control techniques substantiated the objective of this research paper. Speed waveform indicating that with increasing time, speed settles and becomes constant. The torque waveform demonstrates that, under dynamic load condition, the torque has a high initial value before becoming constant.

Table 2 Comparative of control techniques for four-phase SRM

Type of control scheme	Hysteresis current control	Pulse-width modulation (PWM)
Frequency	Variable	Fixed
Speed settling time	More (50 s)	Less (15–20 s)
Initial peak current	Set in hysteresis controller (35 A)	No current limiter (very high)
Maximum torque	Good starting torque of (80 N-m)	Very high initial peak torque (680 N-m)
Maximum speed	490 RPM or 51.6 km/h	521 M or 54.8 km/h

6 Conclusions and Scope of Extension

The work in this research paper presented the comparison of a four-phase, SRM drive to analyze the performance of classical asymmetric bridge converter with hysteresis current and PWM voltage control technique. For desired performance of SRM drive with dynamic load, selection of a control technique for any converter is an important task. It is perceived from the simulation waveform that average and maximum torque in PWM technique is higher than the current control technique and as required for a dynamic loading condition. Also, the initial high peak current can destroy the motor phase winding and switches in converter unit. The important benefit of using hysteresis current control is that it protects phase winding and switching device from high current peaks and reduces the power losses. Torque provided by hysteresis control is less compared to voltage control but sufficient to drive the dynamic load. The simulation results demonstrate that asymmetric bridge or classical converter with hysteresis current control is appropriate for better performance of dynamic load in comparison with the voltage PWM control.

From simulation result, observations are made that PWM voltage control technique fulfills all the desired features for dynamic loading and only high inrush current is an issue. In future work, current limiter or any advance control can be added along with the PWM voltage control technique to enhance its performance.

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