Investigation and Comparison on Different Switching Circuit Topologies for Linear Switched Reluctance Motors

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***Abstract*-The Linear Switched Reluctance Motor (LSRM) has never been widely used for direct drive motion control applications partly due to its nonstandard drive circuit. In order to obtain the optimum converter configuration, five topologies are analyzed in detail and compared based on their overall performance in this paper. Experimental result is then obtained from a prototyping system that uses the dSPACE board and a three- phase LSRM.**

I. INTRODUCTION

The Linear Switched Reluctance Motor has a simple and robust structure with low inertia and direct drive capability, and is particularly suitable for high precision and high speed manufacturing machinery. Unlike other types of motion actuators, mechanical couplings, lead screws, magnets, and brushes are not required in LSRM. Special mechanical adjustments or alignments are also not necessary. Comparing to permanent magnet linear motor, the proposed actuator has a much simpler structure and is less expensive. Moreover, it is also more robust and more fault tolerant, and has less overheating problem [1]. However, the Linear Switched Reluctance Motor has never been a popular choice for direct drive motion control applications. This is due to the motor's highly nonlinear characteristics, and its non-standard drive circuit configurations.

This paper considers five converter topologies, which are probably the most representative, and makes comparisons on different configurations of drives for LSRM, based on their electrical characteristic and overall performance. The objective is to find out the most optimum configuration of drive topology at different applications, and make the linear motion actuator system more popular and user friendly to the end-users.

This paper is organized as follow. In section 2 it is presented the construction of LSRM we applied and its requirements for converter. The detailed analysis and comparison of converter topologies is given in section 3. In section 4 the experimental results of LSRM driven by some of these converters are presented. Finally, the conclusions of this paper are given in section 5.

II. LSRM AND REQUIREMENTS FOR CONVERTER

The prototype of LSRM we applied is composed of a moving platform and a stator track which is laminated with silicon-steel plates. The stator contains no windings, while the mover consists of a set of three-phase coils. It can move back and forth through two linear motion guides which install on the surface of station track. The construction is shown in Figure 1.

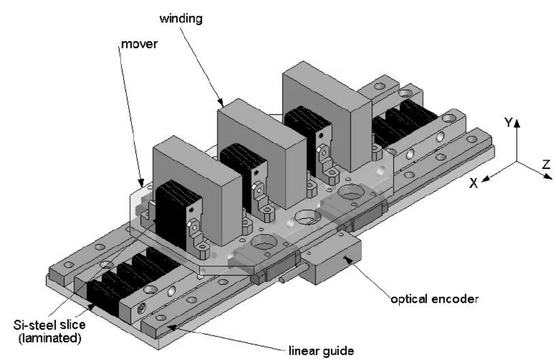


Figure 1. Construction of the prototype LSRM

In order to adopt the optimum driver for this LSRM, the following requirements have to be met for converter topology. First, the converter has to perform well in a wide speed range. That means PWM current control can be used at low speed, and magnetizing voltage can be sufficient to build the flux in phase winding at high speed. Secondly, a high enough demagnetizing voltage is required to shorten the current tail, thus decreasing negative torque. Third, efficiency is also considered as an important parameter. A main reason of low efficiency for converter is the disability to apply zero voltage on the phase winding during current conduction. Such an operational constraint increases the circulation of energy between the machine and dc link, resulting in higher losses and reduced system efficiency. Finally, the cost of converter has to be considered, besides the performance aspects presented above.

III. CONVERTER TOPOLOGY

Many converter topologies are studied and introduced by previous papers, yet there is not a standard topology that widely used so far. Asymmetric half-bridge converter, bifilar converter, C-dump converter, Variable dc link converter and Three-phase Bridge module converter analyzed below are regarded as the most representative and promising converter. Comparisons of these topologies are then made with the aim to help users to choose the optimum topology.

A. Asymmetric Half-bridge Converter

Asymmetric bridge converter is the most popular topology ever used. It consists of two discrete switching devices and two freewheeling diodes per phase, as shown in Figure 2. Each phase of converter is independent of others, so independent current control can be applied and it is efficient for fault-tolerant, even if one phase happens to breakdown, it would not influence other phases [2].

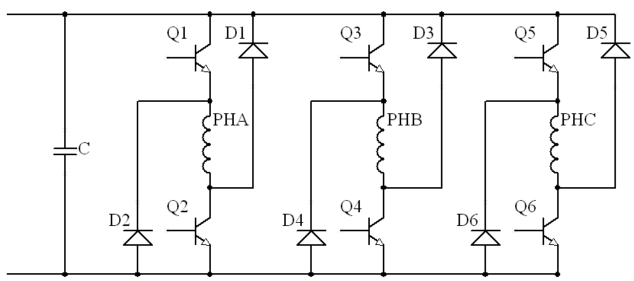


Figure 2. Asymmetric bridge converter

The Asymmetric bridge converter has three possible modes of operation. Take one phase into consideration, when both switching device are turned-on, positive magnetizing voltage is applied, and current rises rapidly in the phase winding. If under low-speed operation, phase current will exceed its demanded value fast. At this time, one switch turn off and current circulates though the other switch and one diode. There is no energy transfer between phase winding and dc source. This operation is the so-called freewheeling mode, which applies a low demagnetizing voltage to the phase winding. When both switching device turned off, winding current circulates through two diodes and recharge the capacitor. The demagnetization process is much quicker than freewheeling mode. However, it is because the presence of freewheeling mode that motor hysteretic losses and power dissipation in the dc-link capacitor are reduced when PWM current control is applied to the phase winding [3].

In addition to the advantages analyzed before, the relatively low voltage rating of switching device is another merit of this topology, while the main disadvantage of this topology is high switching component counts.

B. Bifilar Converter

One of special characteristics of the SRM is its unipolar operation which requires only unipolar current for four quadrant operation. It means only one switching device is required for each phase. The Bifilar converter, shown in Figure 3, is the earliest converter topology which use single switch per phase [4]. Besides, a bifilar winding and a diode are added to each phase to return the energy to the dc source.

The Bifilar converter has two simple modes of operation. Considering one phase, when the switching device is turned-on, the phase winding is energized by positive magnetizing voltage. When the switching device is turned-off, there is a negative current built in the bifilar winding, and circulates through forward-biased diode and dc source. During this mode, energy stored in bifilar winding is transferred back to dc source.

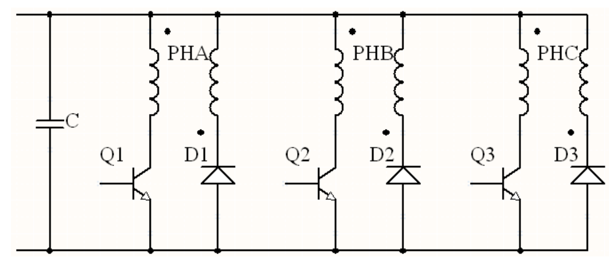


Figure 3. Bifilar converter

The main disadvantage of this topology is the high voltages suffering of switching device due to the leakage inductances of the bifilar windings. The transient voltages could be much higher than the dc link voltage when the switching device is turned-off, thus making this topology unsuitable for higher dc link voltage operated motors. Another drawback is that the bifilar winding enhances the cost and driver volume, and reduces the power density of the LSRM.

C. C-dump Converter

Figure 4 shows another converter configuration with single switch for each phase. Such topology is the so-called C-dump converter with an energy recovery circuit, which requires an additional switch and a diode.

The operation of C-dump topology is relatively more complicated than other topologies due to the energy recovery circuit. Four modes of operation are experienced to each phase. Take phase A for example, the phase winding is firstly energized by turning on Q1, and then transfers the energy to energy storage capacitor Cd when Q1 is turned-off. The capacitor Cd is then discharged by turning on Qr, and transfer the energy to dc side and inductor Lr, then Qr is turned-off, the current circulates though forward-biased diode, energy storage capacitor Cd and inductor Lr.

Obviously, the C-dump converter has lower switch component counts and allows independent phase current control with minimum switches; moreover, it has another merit over other single-switch-per-phase converters that it requires no snubbers for the phase switches as their peak voltages are clamped by the energy storage capacitor [5]. The main drawback of this converter is that the current commutation is affected by the voltage difference between energy storage capacitor, and the dc link voltage. Higher voltage is required to achieve faster current response; however it increases the voltage rating of the power devices meanwhile. The efficiency is also decreased because of the additional losses caused by energy circulation between energy storage capacitor and the dc source.

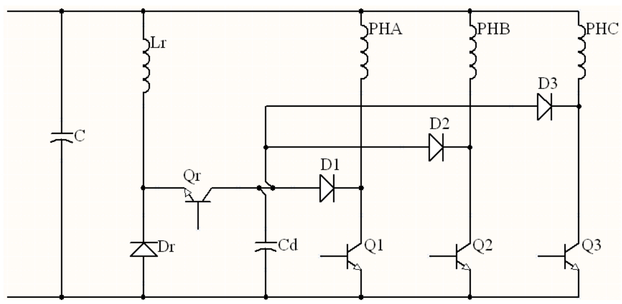


Figure 4. C-dump converter

D. Variable DC Link Converter

As analyzed before, one big reason that prevents LSRM from being widely used is its unique drive circuit configuration. However, the variable dc link converter, shown in Figure 5, is also applicable to half-wave controlled PM brushless dc motor drives [2]. In addition to other advantages, this topology may gain more attention, and provide a way of study to make SRM more popular.

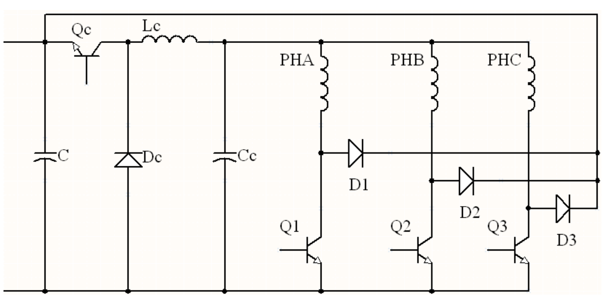


Figure 5. Variable DC link converter

The variable dc link converter has various modes of operation, as described in [6]. By controlling the chopper switch, different input voltage is obtained. When the phase switch is turned-on, phase winding is then energized by the modified input voltage. The chopper circuit also determines the freewheeling of the phase winding and commutation voltage when phase switch is turned-off, thus affects the current response.

The main advantage of this topology is the controllable input voltage, which can reduce the switching frequency of the phase switches and hence minimize switching and core losses. It has the disadvantages of requiring a chopper section with its attendant passive filter for reducing the dc link voltage for motor winding application [6].

E. Three-phase Bridge Module Converter

Induction motor is one of the most widely used machines, which has standard driver package. If LSRM can share the same driver of induction motor with minimal modification, it will be more likely to be adopted and become popular. Figure 6 shows a converter configuration of this kind, which consists of a three-phase bridge module and three diodes. Each diode is added in series with the phase winding, with the objective to make sure unidirectional current circulation in the delta connection [7].

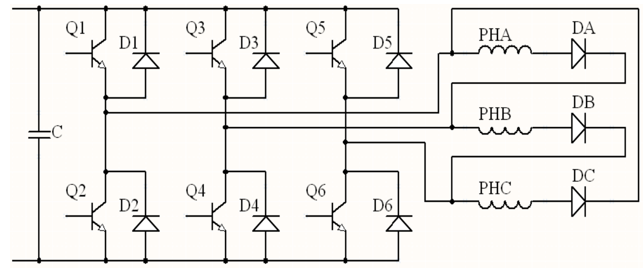


Figure 6. Three-phase bridge module converter

The three-phase bridge module converter has possible three modes of operation. Each phase winding is energized by turning on the top switch which connects directly with it, and the bottom switch which connects with it through the series-connected diode. The freewheeling mode is achieved by turning off the top switch with the bottom switch always turned-on, and the current freewheels through the bottom switch and another internally packaged diode. The rate of demagnetization is low during this mode. When both switches are turned off, the winding current charge the capacitor against the dc-link voltage through two diodes. The demagnetization process is much quicker than freewheeling mode.

The most obvious merit of this topology is the use of three-phase bridge module, which not only share the same converter configuration with induction motor, but also reduce the volume and cost of converter. However, the bridge module also brings an inherent drawback to this topology. There is no implicit shoot-through protection [8].

F. Comparison

In order to choose the optimum topology at different applications, such as device VA rating, switching component counts and operation performance have to be taken into consideration. The topologies analyzed previously have their own merits and drawbacks; we can hardly determine which topology is the best under all situations. Take the bifilar converter for example, it has the least switching device counts, while possibly suffers the highest VA rating. Moreover, the main parameters to evaluate the performance of converter are efficiency, dynamic response and the ability of independent current control. The comparison is summarized in Table 1. Among these five topologies, Asymmetric half-bridge topology is most suitable for high-power high-voltage application, while Bifilar topology and C-dump topology is suitable for low-power low-voltage application due to their high voltage rating.

TABLE I
COMPARISON OF CONVERTER

Converter	Voltage Rating	Switching component counts	Independent current control	Zero-voltage loop	Current response	Shoot-through fault
Asymmetric	Vdc	2m	√	√	fast	×
Bifilar	(1+a)Vdc	m	√	×	fast	×
C-dump	>2Vdc	m+1	√	×	slow	×
Variable dc link	Vdc	m+1	√	√	slow	×
Three-phase bridge	Vdc	2m	×	√	fast	√

IV. IMPLEMENTATION AND EXPERIMENTAL RESULT

The experimental setup for LSRM driving system is shown in Figure 7. The whole system is based on a dSPACE DS1104 controller card, which is connected with host PC through PCI bus. The control algorithm is firstly developed under the MATLAB/SIMULINK environment, and then implemented directly by DS1104. The whole operation can be controlled by the host PC. In order to verify the performance of these topologies, three-phase bridge module converter are constructed and experimented with the three-phase LSRM described before. Figure 8 demonstrates the phase current of three-phase bridge module converter under hysteresis current control. Because only two current transducers are required in this topology, each current waveform contains current signals of two phases. The positive curves of these two figures represent current waveforms of phase V and U respectively, and the negative waveform of Figure 8(b) represents current waveform of phase W.

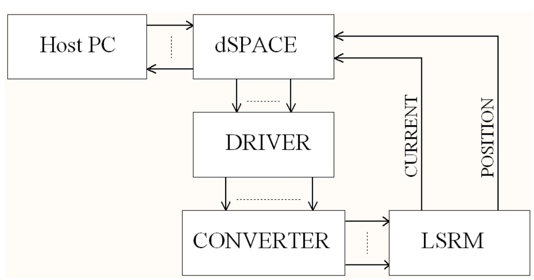
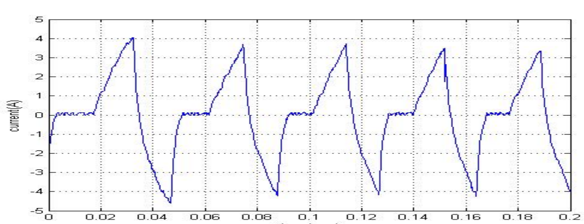
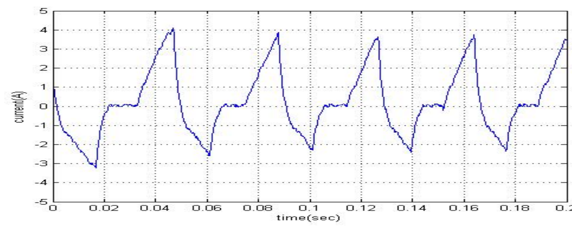


Figure 7. Experimental setup



(a) Current waveform of phase V and U



(b) Current waveform of phase U and W

Figure 8. Phase current waveforms of three-phase bridge module converter

V. CONCLUSIONS

In this paper, five converter topologies for LSRM are described regarding to their operation, merits and drawbacks. Comparisons are then made based on the overall performance. Each topology finds its most suitable application after comparison. Moreover, the latter two topologies bring a new train of thought that converters for LSRM can be transplanted from the widely used motor driver with little modification. Such topology as three-phase bridge converter will make the LSRM more popular.

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