

# Power Electronics for Linear Synchronous Motor Propulsion Systems

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**Abstract** - Drive requirements for linear synchronous motor propulsion systems are described, and the potential converter architectures for this application compared. A series connection of current source converters is proposed which makes it feasible to take power directly from a medium dc voltage distribution bus through a chopper, reducing transformer and distribution line costs. Design tradeoffs for series connected converters are also discussed. Finally, a brief discussion of the economics of converter design is presented.

## INTRODUCTION

Linear synchronous motor propulsion systems represent a challenging application for power conversion technology. Drives for this application must be designed to handle the transition of vehicles between blocks of the LSM [1]. If a load-commutated drive is used, such as the cycloconverter system at Miyazaki, the system must be designed to only deliver power when a back emf is present for commutation [2]. Even if the system is force-commutated, such as the German designs and the newer Japanese design [3], [4], the converter must be able to handle the rapid load changes which occur. Fault-tolerance is also a critical issue for any commercially viable propulsion system. Power converters for this application must be designed to survive at least a single point failure in any device or winding and remain operable to provide high availability. The special nature of the load thus places stringent requirements on the power conditioning equipment.

## PROPULSION POWER REQUIREMENTS

The LSM requires power electronics for converting fixed voltage, fixed frequency power from the utilities to variable frequency power for exciting the N-phase motor windings. The power converters must have independent control over the magnitude, frequency and phase of the currents induced in the windings. Depending on the motor design, the back emf (and the desired current waveform) may not even be sinusoidal.

The fundamental output frequency the power converter must synthesize is determined by the vehicle speed and the pole pitch of the motor (1).

$$f = \frac{V}{2P} \quad (1)$$

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Typical pole pitches for EDS suspension maglev systems are on the order of half a meter or more, yielding maximum output frequencies below 150 Hz. EMS systems typically have a shorter pole length, and thus a higher maximum output frequency. For comparison, the Japanese EDS design has a pole pitch of 2 meters, while Transrapid uses a pole pitch of 0.258 meters.

Table 1 gives a rough idea for the power requirements for level travel at different speeds for a maglev vehicle capable of carrying about 120 passengers. This table assumes aerodynamic drag power varies as the cube of speed, eddy current loss is proportional to speed, power loss in the magnetic suspension is constant, and the linear motor losses are proportional to the square of thrust [5]. These calculations are in line with the 200 passenger TR07 maglev vehicle, which is estimated to consume 4.2 MW on a level guideway at 111 m/s, as well as other power analyses [6]. For a maximum speed of 135 m/s, the inverter must be able to provide about 6.6 MW for level cruise. However, while a typical maglev vehicle requires around 40-50 kN of thrust for level cruise at these speeds, peak thrusts on the order of 120 kN are necessary to accommodate acceleration requirements [5]. Thus, the inverter should be sized for almost three times the power required for level travel at the maximum operating speed. If the guideway is level and straight, a reduction in acceleration may be acceptable, but we will assume that the power converter should produce peak power on the order of 10-20 MW.

While the power required is specified by the mechanical requirements, there are possible tradeoffs between voltage, current and number of phases. Most practical designs use between 3 and 6 phases for the motor. The motor voltage is determined by the length of the propulsion magnets, the motor width, the average magnetic field, and the number of turns per "slot" (1 or 2 being most common in today's designs). Voltages which result vary from a thousand volts to over 10 kV. This tradeoff has a major impact on the design of the power converters.

Other parameters of major importance in the design of the power converters are the inductance and resistance of the motor windings. Motor reactance per unit length is determined by the materials and geometry of the motor windings (along with the effects of any magnetic materials), and determines the practical limit on block lengths [7]. Typical winding inductances can range from below a millihenry to over twenty millihenries per phase, with typical per phase resistances on the order of an Ohm [3], [4], and [5].

TABLE I  
BASELINE POWER REQUIREMENTS FOR LEVEL TRAVEL FOR A TYPICAL 120  
PASSENGER MAGLEV VEHICLE

Speed	m/s	30	60	90	120	135	150
Power	MW	0.86	1.23	2.45	4.86	6.65	8.91

## CONVERTER ARCHITECTURES

Converter architectures for this application can be broadly classified into 3 basic types: those that convert directly from ac to ac, those that convert a controlled dc voltage to ac, and those that convert a controlled dc current to ac [8], [9]. Direct ac/ac conversion requires an ac distribution bus, while the dc link of the other methods may be created from either ac or dc distribution using either rectifiers or choppers, as required.

### Cycloconverter

Cycloconverters use bridges of switches to directly synthesize an ac output waveform from ac line voltages, without any intermediate energy storage (Fig. 1). This type of structure was employed in the MLU002 Japanese maglev system to generate power at up to 34 Hz [2]. Despite the large number of switches required, the elimination of energy storage elements makes this converter an economic solution at high powers if natural commutation is employed. However, the lack of energy storage also leads to some serious drawbacks. The output voltage and the input line current both have significant harmonics which vary with the output frequency and load, making them hard to filter. Furthermore, the converter fundamentally operates with less than unity power factor, and the power factor degrades as the output voltage is lowered. These drawbacks, along with a limited output frequency, make this converter an unlikely candidate for a commercial propulsion system.

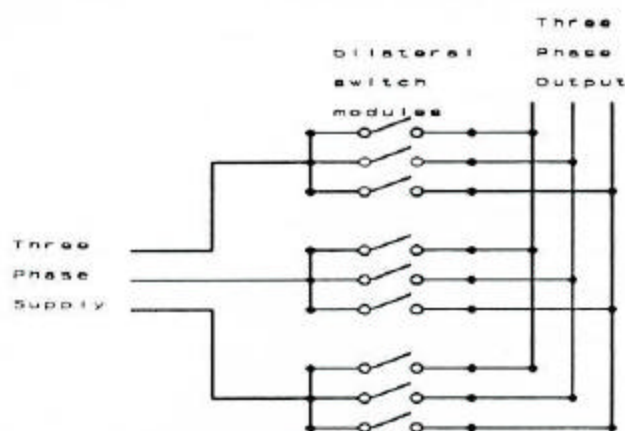


Fig. 1 A Cycloconverter structure.

### Voltage-Source Inverter

The Voltage-Source Inverter (VSI) is the most widely used power inverter up to the low megawatt range (Fig. 2). Sinusoidal output currents are obtained using sinusoidal or programmed Pulse Width Modulation (PWM), or hysteresis current control [10],[11],[12]. This converter has the advantages of a wide output frequency range, limited only by switching losses or thyristor commutation, and frequencies of over 200 Hz are easily achieved at the megawatt level. Input and output harmonics are well defined, and both harmonics and output voltage can be controlled via the PWM scheme. Also, VSIs may be paralleled to increase power rating, with the potential to improve waveform quality and fault tolerance. Paralleled VSIs are the basis of the German and newer Japanese designs [3], [13]. It may be preferable to use an ac power distribution scheme with VSIs to allow the distribution voltages to be easily converted to the lower dc link levels. However, if regeneration is desired, two quadrant input rectifiers are needed. Furthermore, the number and size of the transformers required for this approach is significant. Some designs, such as Transrapid, even need additional transformers to boost the inverter output voltage for high-speed operation.

### Current-Source Inverter

Current-Source Inverters (CSIs) function by switching a dc current link to generate an ac output current waveform, and are often used at the megawatt level. Two approaches are widely used for current-source inverters. The first approach is to generate quasi-square current waveforms using pulse-commutated SCRs, as outlined in [14], [15]. The single-phase ASCII Inverter of Fig. 3 is of this type, with the capacitors serving to both commutate the SCRs and absorb the reactive energy stored in the out-going motor phase. The second approach is the use of fully controlled switches (such as GTO's) and a separate capacitive filter network, shown in Fig. 4 for a single phase and described in [16], [17] for three-phase bridges. The switches are controlled to generate a PWM waveform in the filter/load circuit, yielding quasi-sinusoidal currents in the load.

The relatively high inductance of the motor windings poses a major problem for the design of the inverter. The peak output frequency of both types of CSIs is limited by the need to commutate the link current between phases of the motor, with typical maximum frequencies on the order of 60 - 120 Hz. The peak output voltages of a CSI are also determined by the winding inductance. If the winding inductance is too high, a CSI is probably not a good choice. As a rough measure, assume the waveforms are sinusoidal, and compare the voltage across the winding inductance to the magnitude of the motor back voltage. If the inductive voltage is less than half the motor voltage, then a CSI may be a good choice. Otherwise, a voltage source inverter is probably preferable.

An advantage of CSIs for this application is the ease with which they can be connected in series [18], [19], [20]. For example, assuming that there are dual 3 phase motors, or a 6 phase motor, we can construct the circuit with two three



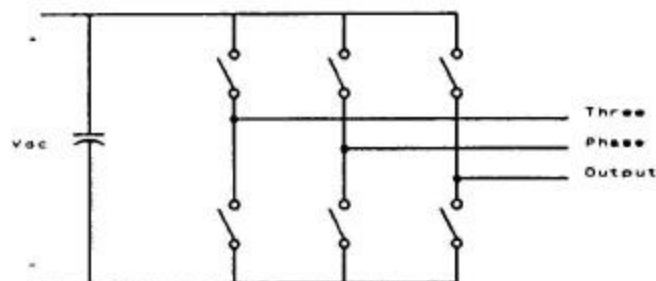


Fig. 2 A three-phase Voltage Source Inverter.

phase bridges in series, as described in [20]. We can carry the series converter idea one step further by using a separate H-bridge for each phase, and putting all the phases in series. A series-connected design makes it feasible to take power directly from a medium voltage dc distribution bus through a chopper, reducing transformer and distribution line costs. A degree of fault tolerance may also be obtained by this approach. For LSM designs where the maximum frequency not too high and reasonable care has been taken to reduce the winding inductance, the advantage of the series-connected CSI may be quite significant.

#### Other Alternatives

In soft-switched architectures, switching losses are decreased by using a resonant or quasi-resonant auxiliary circuit to obtain a zero-voltage and/or zero current switching opportunity for the main devices [21],[22]. The reduced switching losses which result can be used to improve efficiency or waveform quality, or reduce converter size, at the expense of complexity. Unless one of these benefits becomes an overriding criteria in a design, these architectures probably offer no advantage for this application.

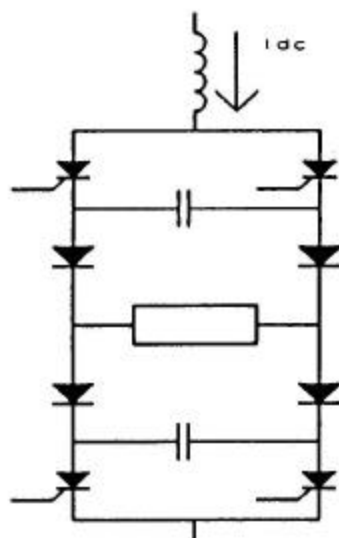


Fig. 3 The ASCI quasi-square wave CSI.

#### SERIES-CONNECTED CURRENT SOURCE INVERTER

As previously discussed, a series-connected current source inverter (SCCSI) can be advantageous if the required output frequency is not too high, and the winding inductance is sufficiently low. The ability to drive the series-connected converter directly from distribution level voltages eliminates the transformers that would otherwise be necessary. Furthermore, if bypass and breakout is provided for each series-connected converter, it is possible to achieve a degree of tolerance to single point failures in the converters or motor windings.

The selection of a SCCSI design approach depends heavily on the load parameters, including back voltage, current, winding inductance and number of phases. Design selections include the choice between quasi-square wave (QSW) and PWM architectures, use of three phase or separate h-bridge converters, and which quadrant is used to provide regeneration.

#### Quasi-square wave vs. PWM architectures

The selection of a CSI architecture for a given design is driven by the devices available and the parameters of the load. One major concern when designing these converters is the sizing of the filter and commutation elements, which must be tailored to the load parameters.

For quasi-square wave architectures, the fundamental limitation comes from commutation time requirements and the need to absorb all of the energy in the motor phase. Consider the single phase ASCI inverter of Fig. 3. The capacitor size is selected as large as possible, while still meeting commutation time limits at the highest frequency of operation [10]. Unless a separate clamp circuit is used, the capacitor has to absorb all the energy in the load, and will charge to a peak voltage roughly proportional as:

$$V_c \propto I \sqrt{\frac{L}{C}} \quad (2)$$

which determines the ratings of the switches and capacitors in the circuit. Thus, as the inductance and/or maximum current increase, the device ratings grow in size, and eventually make the approach impractical.

For the PWM circuit of fig 4, the limitations are somewhat different. The capacitive filter should be sized such that a quasi-sinusoidal current passes through the load, while the switching harmonics are shunted through the filter. For a simple capacitive filter then, the capacitance should be chosen by the criteria of (3), while remaining large enough such that the peak capacitor voltages are limited. The capacitor voltage limitation implies that as the load inductance and

$$f_{out} \ll \frac{1}{2\pi\sqrt{LC}} \ll f_{pwm} \quad (3)$$

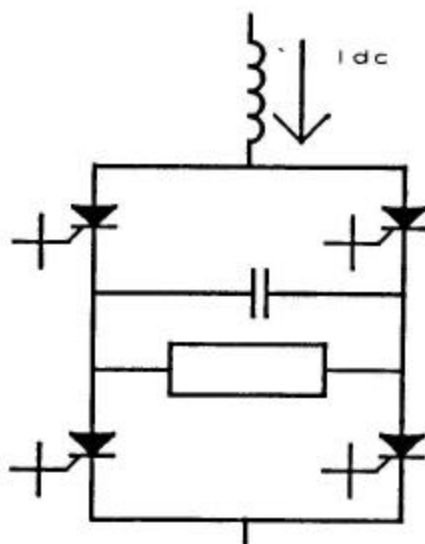


Fig. 4 A PWM Current Source Inverter

current increase, so does the switching frequency.

In many situations, either converter structure is practical from a design standpoint, and selection is based on economics and performance characteristics. PWM converters typically have smaller capacitors and link inductors than QSW converters, but require fully controlled switches such as GTOs. Furthermore, the waveforms available with the PWM converter are essentially sinusoidal, while QSW converters generate stepped waveforms, either of which may be preferable depending on the motor design. Finally, the dynamic response of the PWM converter is faster, but is more sensitive to transients and requires a more complex control system.

The simulated waveforms for the QSW CSI of Fig. 3 are shown in Fig. 5, for a motor with  $L_{phase} = 1$  mH and a peak back voltage of 1500 V running at 80 Hz. The simulation assumes 130  $\mu$ F commutation capacitors, and the 150° conduction patterns employed in [19]. The simulated waveforms of the PWM converter of Fig. 4 are shown in Fig. 6 for the same motor parameters, a 60  $\mu$ F filter capacitor, and an average switching frequency of 720 Hz. Equations for simulating these circuits can be found in [19] and [5]. The simulations illustrate the trade-offs between the converters. For this motor design, the QSW converter requires far more capacitive energy storage than the PWM converter, and also requires higher device ratings. However, if the back voltage was trapezoidal, this converter could transfer nearly 30% more power than the PWM topology. The PWM converter can generate an accurate sinusoidal phase currents using relatively small filter elements, at the expense of fully controlled switches and a high switching frequency.

#### Single phase vs. three phase bridges

Most long-stator LSM propulsion systems designed to date have used 3 phase stator windings, connected in a wye

configuration [23]. Depending on the space available for the windings and voltage limits, it may be possible to wind the LSM with separate single phase windings. In this case, one has the option of driving each phase separately with an H-bridge, and series connecting the bridges.

The major criteria for selecting between a series connection of single or three phase bridges is how the total voltage compares with the distribution level voltage. It is instructive to compare the two options, however, since the distribution voltage itself is a design parameter.

The primary advantage of the three-phase bridge is that it requires only half as many switches (and gate drives, snubbers, etc.) as an equivalent set of single phase converters. Comparing the device ratings of single phase converters to a three phase bridge driving a Wye connected load, we find that the voltage ratings in the single phase converter are  $1/\sqrt{3}$  as large [19]. The penalty for using a single phase setup is therefore not as severe as it would appear.

The filtering requirements are also different for the two topologies. In general, because of the flexibility in switching, the link inductance does not have to absorb as large a volt-second integral in the single phase connection, and thus the inductor can be made smaller. In one design, it was found that the link inductance could be reduced 30-35% for the same current ripple [19]. For QSW converters, the same total energy storage is required in the capacitors. However, the increased commutation flexibility in the single phase circuit allows larger capacitors to be used at a lower voltage, reducing the device ratings in the circuit even further [19]. Thus, while the single phase circuit requires more switches, the reduction of switch ratings and link inductor size help offset this cost.

The reduction in switches also implies that the three-phase converter cannot generate waveforms with triplen harmonics. This is desirable for sinusoidal back voltages, but may not be optimal otherwise. Many linear motor designs have back voltages that are substantially nonsinusoidal, and may have third harmonics as large as 20% of the fundamental. For LSMs with significant third harmonic terms, a series connection of single phase QSW converters allows power to be transferred via the third harmonic, increasing the thrust for the same peak voltages and link current. Furthermore, the use of single phase bridges increases the flexibility available in generating PWM waveforms [18].

In the final analysis, a series connection of single phase converters may be more expensive than a three phase connection. However, it offers flexibility in control, a higher stacked voltage, and the opportunity to use the independence of motor phases for fault tolerance.

#### Input converter design options

One advantage of series-stacked current source inverters is that they can be driven directly from a medium voltage distribution bus. If a three-phase AC bus is used, then a phase-controlled converter (either 6 or 12 pulse) can be used. If allowed, regeneration can be provided by running the



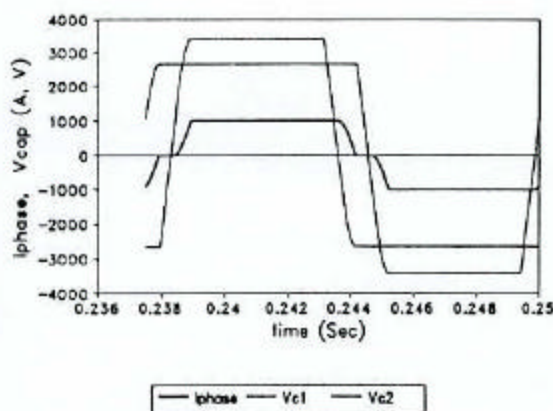


Fig. 5 Simulated behavior of the QSW CSI of Fig. 3

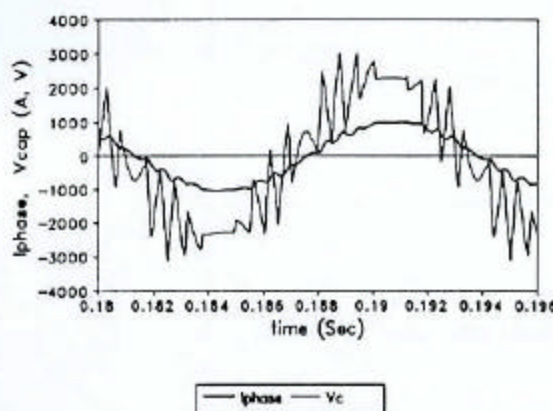


Fig. 6 Simulated behavior of the PWM CSI of Fig. 4

converter in the inversion region, while maintaining a positive link current.

Alternatively, the series-stacked CSI architecture can be driven through a chopper from a dc distribution bus, with an attending reduction in transformer and distribution costs. The dc bus can be used for transmitting regenerated power from a braking vehicle to one which needs the power. By using a 30 kV bus, it is possible to transmit power at least 30 km, so the probability of finding a vehicle to absorb the power is relatively high. The 30 kV bus could be created using separate +15 kV and -15 kV voltages, halving the maximum voltage to ground.

Regeneration can be provided in one of two manners with this type of system. One method is to use a chopper which can generate positive or negative output voltage, while maintaining a unidirectional output current. One possible implementation of this approach is shown in Fig. 7. The disadvantage of this method is that the chopper devices have

to be rated for the full 30 kV bus voltage. Alternatively, a converter can be used which provides a positive output voltage, but can reverse the link current to regenerate power. This technique allows the simpler chopper implementation of Fig. 8, but requires bidirectional switch implementations in the inverter. The selection between these two approaches is fundamentally an economic one. In either case, fault tolerance and performance of the chopper can be improved using interleaving of multiple converters [7],[24].

## ECONOMIC ISSUES

Consider the pricing of industrial variable speed drives. Typically, companies manufacture standard "off the shelf" drives up through the 400-600 Horsepower range, while drives above this range are usually made to order. Most standard lower power units are of the PWM voltage-source type, employing various devices from transistor arrays to GTO's. Higher power drives (1000-10000 HP) are typically of the current-source type, either of the classic ASCI QSW type or the recent GTO-based PWM variety. (One exception to this is in the transportation industry, where weight and volume are often important.) Information from high power drives manufacturers indicate that a value of ~75-125 \$/kVA is a reasonable figure for industrial power inverters at the few megawatt level. Below a few hundred kVA, the price to power ratio increases due to fixed costs, and may increase above the 10 MVA level as well due to the lack of a large market.

An important observation is that the power switching devices often contribute to only about 5 or 10% of the total cost. Three-phase transformers alone are estimated to cost on the order of \$20/kVA, and may therefore be a sizeable fraction of the cost of an inverter station. Energy storage elements, control, heat removal equipment, and skilled labor can also represent a sizeable fraction of the cost. Thus, while it is considered that a factor of 2 to 3 reduction in cost may be possible via economies of scale, it is not clear that a factor of 10 reduction is possible.

## CONCLUSION

Drive requirements for linear synchronous motor propulsion systems have been described, and the potential converter architectures for this application have been compared. A series connection of current source converters has been proposed, which makes it feasible to take power directly from a medium dc voltage distribution bus through a chopper, reducing transformer and distribution line costs. Design tradeoffs for SCCSIs have also been discussed, including the selection between single and three-phase topologies, QSW or PWM converters, and appropriate input converters. Finally, a brief discussion of the economics of converter design has been presented.

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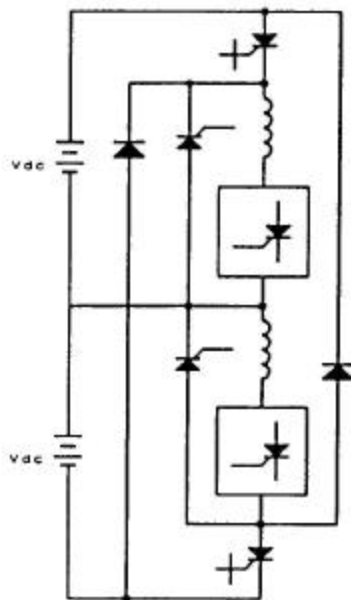


Fig. 7 A chopper with unidirectional I, bidirectional V.

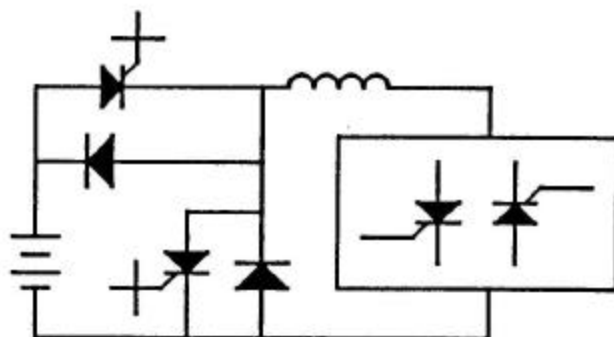


Fig. 8 A chopper with unidirectional V and bidirectional I.

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