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A Versatile Power Converter for High Frequency Link Systems

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Abstract

The single-phase high frequency link appears to be an attractive alternative to the dc link commonly employed in power conversion systems. This paper proposes a power converter suitable for one-step conversion of the single-phase high frequency link voltage to the three-phase low frequency voltages typically required for interfacing with system sources and loads. The converter is utilizes zero voltage switching principles to minimize switching losses and uses an easy to implement technique of pulse density modulation for the control of the amplitude, frequency and the waveshape of the synthesized low frequency signals. Adaptation of the proposed topology for power conversion to single-phase ac and dc voltage or currents outputs is shown to be straight forward. The feasibility of the proposed power circuit and the control technique have been experimentally verified.

1 INTRODUCTION

Power conversion systems typically utilize dc voltage or current links for power distribution to the input and output converters and to support temporary energy storage requiements of the converters. Recently, however, use of a single-phase high-frequency (20 kHz or more) sinusoidal voltage bus as a link has been proposed as an alternative to the dc link approach [1,2,3]. A high frequency ac link allows the flexibility of adjusting the link voltage according to the individual needs of the load/source together with easy electrical isolation for safer grounding or noise suppression by means of compact and light weight transformers on the link side of the converters. In addition, high frequency link systems show potential improvements in such performance areas as: speed of response of the component converters, the overall system levels of audible noise, interference at lower frequencies, safety and reliability and compatibility with high frequency machines.

Interface Converter Requirements

As in any link system, power converters are invariably needed to interface system loads and source to the link since few load/sources are able to operate directly from the link as a power source. Performance of the overall power conversion system depends to a large extent on the capability of these power converters to effectively and efficiently perform this interface function. In general, the following characteristics can be considered desirable in power converters used as interface converters in the high frequency link systems.

- High efficiency for increased system efficiency and for reduced size and weight of the heat dissipating components.
- Inherent bi-directional power flow capability(not requiring substantial modifications in the power circuit).
- Low distortion output waveform to fundamental frequencies as high as 1000 Hz for increased power density of associated mechanical systems.
- Simple and reliable means of controlling converter output voltage and frequency.
- Minimum voltage or frequency disturbances to the link.
- Adaptable to different types of loads/sources for a higher level of uniformity and reliability in the system.

Limitation of Familiar Converter Topologies

. Converters not designed specifically for operation from a high frequency link are unlikely to perform adequately as interface converters for high frequency link systems. Consider for example, the phase-controlled converter (cycloconverter) which is frequently used when one-step power conversion from an ac voltage source is required. A major limitation of such a converter in a high frequency link system would be the excessive switching losses resulting from a high switching rate (forty thousand switches per second for a 20 kHz link) and an inherently high loss per switching of the phase-angle control scheme. In addition, phase-controlled converters cause a varying (and lagging, if naturally commutated) current to be returned to the link making it more difficult to regulate the link, and contain objectionable levels of dv/dt's in the generated voltage waveforms.

Intermediate dc link converters are possible which might operate by converting the high frequency link power to an intermediate dc form from which another dc input converter would then generate the desired low frequency ac or adjustable amplitude dc.

However, such two-stage topologies are inherently less efficient and tend to have limited capabilities in such aspects of converter performance as output frequency limit, converter bandwidth, ease of protection, reliability, and others due to the "hard" switching used in dc link converters. Resonant techniques are being increasingly employed to eliminate or reduce these drawbacks [4,5,6]. However, there appears to be some difficulty in using resonant converter topologies for bi-directional power transfer from an existing high frequency voltage.

This paper describes a power conversion technique which take advantage of, instead of being limited by, the high frequency of the link. Utilizing this conversion technique, a class of one-step bi-directional power converters are proposed that are suitable for interfacing a wide variety of sources and loads to the high frequency link.

2 PROPOSED POWER CONVERSION TECHNIQUE

It is clear that the link voltage in an ac link system crosses through zero twice per cycle of the link frequency. By restricting all switching in the converter operating directly from the link to these zero crossing points, converter switching losses can be made small and switching related device voltage stresses are minimized. Purely capacitive (hence lossless) snubbers can be used when needed, and the generated voltage waveforms become free of abrupt transients seen in phase-controlled converters. In addition, zero voltage switching causes the current returned to the link to be always in phase (or 180 degrees out of phase) with the link voltage which makes control of the frequency and distortion of the link voltage. Recently reported work [7,8] shows that the advantages of zero voltage switching are being more widely recognized and will find applications outside of ac link systems discussed here.

Zero voltage switching in a fixed frequency system creates a fixed converter switching rate. This requires that new modulation strategies be developed to allow control of frequency, amplitude and waveshape of the low-frequency signal synthesized from the high frequency voltage of the link. The technique of area comparison - pulse density modulation has been suggested earlier by the authors [3] for this purpose and will be reviewed here briefly.

3 REVIEW OF PULSE DENSITY MODULATION (PDM)

Figure 1 illustrates the principle of the zero voltage switching constraint and how a one-stage power converter is used to generate a low frequency voltage component by synthesizing the desired fundamental component from complete half cycles of the high frequency link voltage. It is clear that such low frequency waveforms can be synthesized either by programmed logic (analogous to programmed PWM for dc link systems) or, it can be generated using a type of modulation scheme (analogous to the Sine-Triangle PWM).

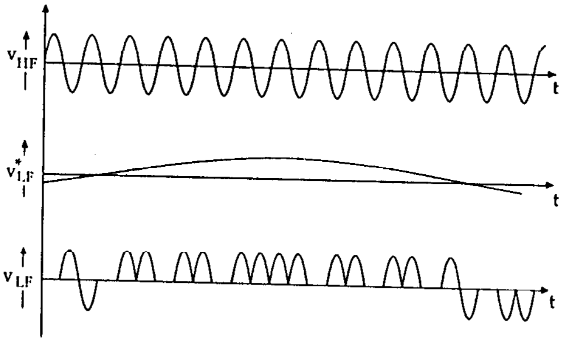


Figure 1: Pulse-density-modulated (PDM) synthesis of a low frequency voltage.

Figure 2 shows the block schematic of one such modulation scheme based on the concept of *area comparison*. In this scheme, the area under the reference signal is compared with the area of the synthesized signal. If the comparison indicates that the area of the synthesized signal is more (less) than desired then the controller causes the next half cycle pulse to be applied so that this area is decreased (increased). In this manner, voltages or currents having a fundamental component of dc, sinusoidal ac or any other smooth waveform may be synthesized using a single integrator, a comparator and a few logic gates. This simple implementation results in the density of the half cycle pulses in the synthesized voltage to be modulated in close accordance with the amplitude of the reference signal. The term *Area Comparison - Pulse Density Modulation* (AC-PDM) has been used to differentiate this scheme from other PDM scheme and possible programmed methods of generating such waveforms.

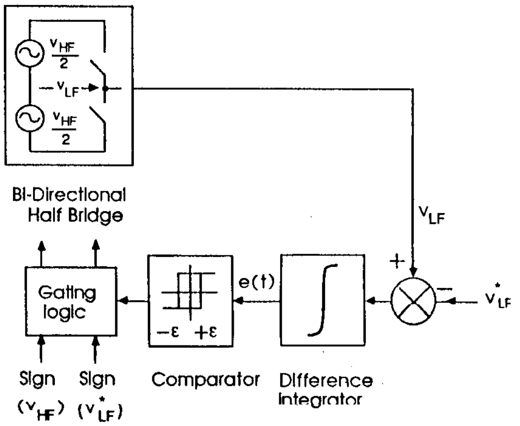


Figure 2: Area comparison - pulse density modulation (AC-PDM) scheme.

It has previously been shown [3] that if the link frequency is sufficiently high (by a factor of 20 or more) and if the modulation index does not exceed unity, then the synthesized signals have very little low order distortion for a wide range of frequency and amplitude of the synthesized signal. Also, the high frequency harmonics occur only as the side band of the switching frequency where they pose no problem to most loads/sources. The spectral characteristics over the intermediate frequency range tend to be nearly flat. This broad band spectrum over the audio range produces lower and easier to tolerate audible noise levels in ac machines operated from PDM converters.

4 THREE-PHASE AC BRIDGE INTERFACE CONVERTER

Based on the zero-voltage switching PDM power conversion technique, topologies for conversion of single-phase high frequency voltage to three- or single-phase, dc or ac low frequency voltage or currents can be visualized. The three-phase case has been considered initially because it represents the general case of down conversion from a high frequency link. Synthesis of single-phase ac can be visualized as restricting the number of phases on the low frequency side of the three-phase converter. An additional restriction of zero frequency then degenerates into the case of dc voltage or current synthesis.

Although other three-phase power circuit topologies are possible [9], discussion here will be limited to a three-phase ac bridge circuit which can be derived from the dc link three-phase bridge circuit by direct analogy.

Topologic Equivalence to the dc Link Bridge

Figure 3 shows the DC link bridge converter which is well known as the minimal power structure for transforming dc power to three-phase voltages or currents of controllable frequency and amplitude. A shunt filter (large electrolytic capacitor) provides a low impedance path to the harmonics in the current returned to the link by the switching action of the power circuit. As a result, the distortion (resulting ripple) of the link voltage is kept to a minimum. Once charged, the shunt filter offers a high impedance to the current of the link frequency (dc current).

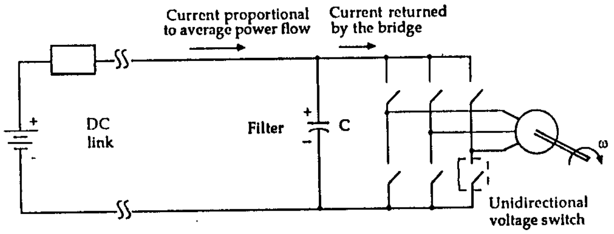


Figure 3: DC link bridge converter.

Figure 4 shows the three-phase ac bridge. Like the dc bridge, it is a minimal topology consisting of six hybrid switches (now with reverse voltage blocking capability). The ac bridge also operates from fixed frequency and the regulated voltage of the link to generate three-phase voltages or currents of controllable frequency and amplitude. The bridge must again have a filter on the link side for circulating harmonic currents. One possible filter configuration for this purpose is a shunt connected LC tank circuit resonant at the frequency of the link. Once "charged", the tank circuit offers a high impedance to the current of the link frequency and a lower impedance to currents of all other frequencies. The size of this tank circuit determines the amount of fluctuations ("ripple") in the link voltage in much the same manner as for the dc link system.

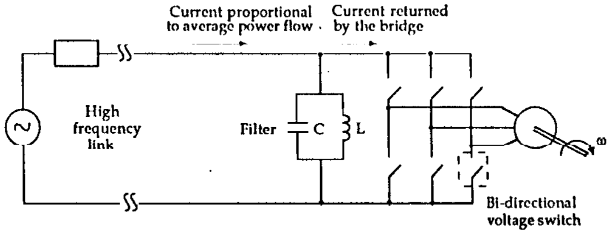


Figure 4: Bridge converter with an ac link.

Voltage Conversion Ratio

The output to input voltage ratio of the three-phase PDM bridge converter can be derived as follows. Reference [3] gives the expression for the fundamental voltage that can be realized by a half bridge circuit before the AC-PDM controller begins to saturate as

$$V_{LFmax} = \frac{V_{HF}}{\pi} \tag{1}$$

where V_{LFmax} is the maximum level of the dc signal or the peak value of an ac signal which can be synthesized from a high frequency link voltage of peak value V_{HF}. The maximum rms fundamental line voltage is thus given as

$$v_{\ell-\ell max} = \frac{\sqrt{3}\, v_{HF}}{\pi} \tag{2}$$

where v_{HF} is the rms value of the link voltage. Finally, the ratio of these two rms quantities is

$$\frac{v_{\ell-\ell max}}{v_{HF}} = \frac{\sqrt{3}}{\pi} \tag{3}$$

Equation 3 shows that no more than 55 percent of the link rms voltage can be converted to line voltage on the low frequency side before the PDM controller begins to saturate. Conversely, for one per unit line voltage at the converter output, the link voltage must be 1.8 times larger. To provide some basis for comparison, similar ratios have been computed for for PWM dc link converters and for recently proposed "resonant dc link" converter [7] which seeks to eliminate the losses and stresses associated with the "hard" switching of the dc link converters by using resonant zero voltage switching but retains its unipolar link structure. Table 1 shows the voltage conversion ratios along with the theoretical voltage ratings required of devices for each type of converter. Note that practical constraint such as dead times, device safety factors to account for snubber overshoots, etc. can significantly effect the comparison. In general, zero voltage switching converters are much less prone to derating because of these factors due to reduced voltage near switching intervals and the lack of snubber overshoots.

Clearly, a reduced value of the voltage conversion ratio is the trade off for dramatic improvements in switching performance seen in zero voltage switching converters. Note that the ac link PDM converter offers an excellent compromise in this regard.

Converter Power Switches

It may appear that an ac bridge operating from a high frequency link would require a large number of very special devices making the power circuit complex and unreliable. This need not be the case however The device capabilities needed for a PDM bridge operating from a link frequency in the neighborhood of 20 kHz are not markedly different from those needed in the present day PWM inverters operating at switching frequencies nearly one order of magnitude lower. This is because the switching frequency in PWM converters is limited primarily by high losses and high device stresses generated as a result of "hard" switching from the dc link. The zero voltage switching used in the PDM converters drastically reduces these stresses. The number of devices needed should also not pose any serious difficulty because the same considerations (minimization of stray leakage, ease of manufacturing, reliability etc.) that lead to the evolution of the present day hybrid switches for PWM converters (transistor-reverse diode or GTO- reverse diode, etc.) can be expected to eventually produce similar hybrid realizations suitable for converters operating from an ac link.

Operation with Natural Commutation

Automatic reversal of the ac link voltage offers an opportunity to also naturally commutate the devices in a PDM converter. However, the need to establish circulating current of appropriate polarity to achieve turn-off of the conducting device now causes the converter operation to become somewhat dependent on the power factor at the low-frequency end. In particular, when the power flow in the converter is in the direction of the high-frequency link, incoming switches have to be activated in advance of the voltage reversal to ensure circulating current of the correct polarity to turn off the outgoing devices. This advance firing increases the distortion of the link voltage and the voltage synthesized on the low frequency end. It also increases the switching losses in the converter. However, if the load power factor is high then the advance firing is limited to relatively few of the high frequency half-cycles of the generated signal. Naturally commutated PDM converters may then be used without a major deterioration of converter characteristics.

Link Filter

The parallel connected LC tank circuit tuned to the link frequency functions in an ac link system functions much like the electrolytic capacitor of a dc link system. By locating the capacitor of the tank circuit close to the PDM converter power bus, a low impedance path is provided which shunts the high frequency components of the current returned by the converter to the link. The tank filter also stores energy which helps meet the pulsating instantaneous power need of the PDM converter. The effectiveness of this power averaging by such a filter depends on factors as the filter configuration and capacity, the frequency characteristics of the link impedance, converter circuit topology, and the number of converters operating simultaneously from the link. The size of the required filter can vary depending upon these factors and the amount of voltage "ripple" that can be tolerated. In this respect, each system must be optimized to meet its individual requirements. Alternate filter topologies and optimization procedures for a given system requirements appear to be area for further study.

AC-PDM Tolerance to Link Voltage Ripple

The desire to minimize the size and losses associated with the PDM filter suggests that there will always be some "ripple" variations in the link voltage. Fortunately, the AC-PDM is a closed loop control scheme and automatically compensates for link voltage variations whether they be on a cycle by cycle basis or whether they be the slow variations in the "average" amplitude.

5 CONVERTER OPERATION

A PDM converter can generate a balanced set of three-phase voltages with sinusoidal fundamental component whose amplitude and frequency can be controlled independently. Such a synthesized set of voltages can supply a passive RL load or be used to interface an ac machine to the high frequency link. We shall limit the discussion here to operation of an induction machine from the proposed PDM converter with either direction of power flow.

Interfacing Induction Machines

Using computer models (see [9] for discussion of these models) of the PDM converter and an induction machine, with a converter interface has been studied. A 400 Hz, 210 V three-phase machine having parameters (Table 2) typical of a machine in its class has been assumed. The converter output frequency is controlled so that the slip, the difference between the converter frequency and the actual rotor speed, corresponds to the desired amount and direction of power flow to the machine. Fig. 5 shows the block diagram of this slip controller. Figure 6 shows system waveforms as the slip frequency is controlled from zero to its rated value and then reduced steadily to the rated negative value. In the process, it can be noted that the power flow from the PDM converter goes through a range of zero to full positive and then is reversed to full negative at which point the machine is operating as a generator feeding power back to the high frequency link. This simulation result demonstrates that:

1. There is no fundamental difficulty in having the proposed PDM converter operate an induction machine either as a motor or a generator.

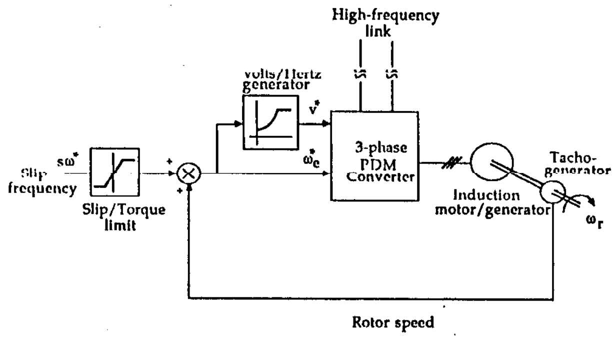


Figure 5: Block diagram of the slip controller.

2. Slip control strategy is adequate to change direction of power flow to the machine
3. Synthesized voltages do not contain troublesome lower order harmonics. Higher order distortion has no significant effect on machine operation. Thus, no filters are needed between the PDM converter and the machine.

Adaptation to Single Phase ac and dc

The power conversion technique of zero-voltage switching with PDM control can be used to synthesize any low frequency waveform that meets the frequency and amplitude limits discussed earlier. Suitable power circuits are derivatives of the three-phase ac bridge described above. Figure 7 shows possible circuits suitable for synthesis of single-phase ac or dc with full four-quadrant V-I characteristics at the low-frequency end. It has previously been mentioned that the reference signal supplied to the PDM controller determines whether an ac or dc waveform is generated at the low-frequency end. Similarly, if a current source, instead of a voltage source, is desired at the low frequency end then the feedback signal to the PDM controller is changed to the resulting low-frequency current. Additional impedance may be necessary in some cases to limit the ripple current on the low frequency side.

6 EXPERIMENTAL VERIFICATION

To demonstrate hardware feasibility and to provide experimental verification of the converter computer model a 5 kW laboratory breadboard of the proposed PDM converter has been built and operated successfully. In the breadboard system, a parallel-output-series-resonant (POSR) converter [4, 10] operating from a rectified 60 Hz supply provides the high frequency sinusoidal "link" voltage from which a three-phase PDM bridge converter operates to supply three-phase passive loads or an induction machine.

Figure 8 shows the power circuit of the laboratory PDM bridge converter. Although it is somewhat sensitive to the reverse recovery characteristics of the internal diodes. the two transistor inverse-series realization was used for the bi-directional switches because it minimizes the number of power interconnections and because power darlingtons are readily available. Table 3 gives important component values used in this breadboard.

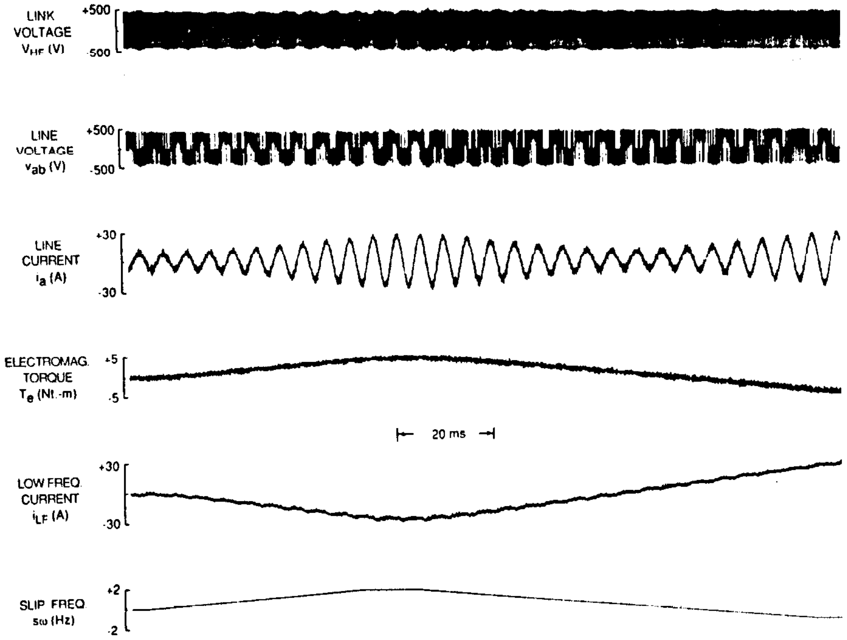


Figure 6: Motor/generator operation of an induction machine supplied from high-frequency link PDM converter.

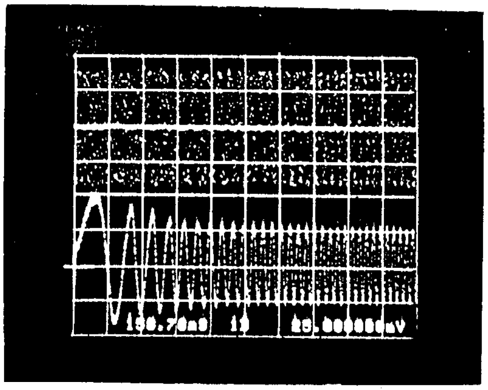


Figure 10: Machine voltage and current waveforms during soft-start with a 230 V., 60 Hz induction machine. Upper trace: Line voltage, v_{ab}; 250 V/div., Lower trace: Line current i_a; 5 A/div.

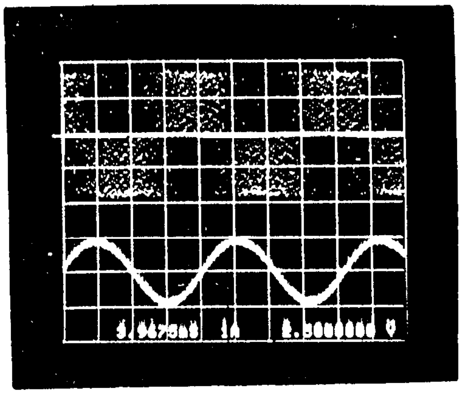


Figure 11: Typical set of machine voltage and current waveforms observed on the breadboard. Upper trace: Line voltage, v_{ab}; 250 V/div. Lower trace: Line current, i_a; 5 A/div.

This is in agreement with similar results observed in simulated operation with the induction machine and with experimentally observed waveforms for other conditions of PDM synthesis including three-phase passive loading [9]. The results of Fig. 12 demonstrate that an induction machine can be operated directly from a PDM converter with minimal influence of the harmonics on torque production and power flow in the machine. Also, the low level audible noise expected from the motor as a result of the distributed spectral characteristics of the distortion over the audible range has been experimentally verified. The noise observed on the breadboard system had the characteristics of what can be described as a low level hiss. As a result, the resulting noise is much easier to tolerate than the loud tonal noise generally observed with PWM converter fed machines.

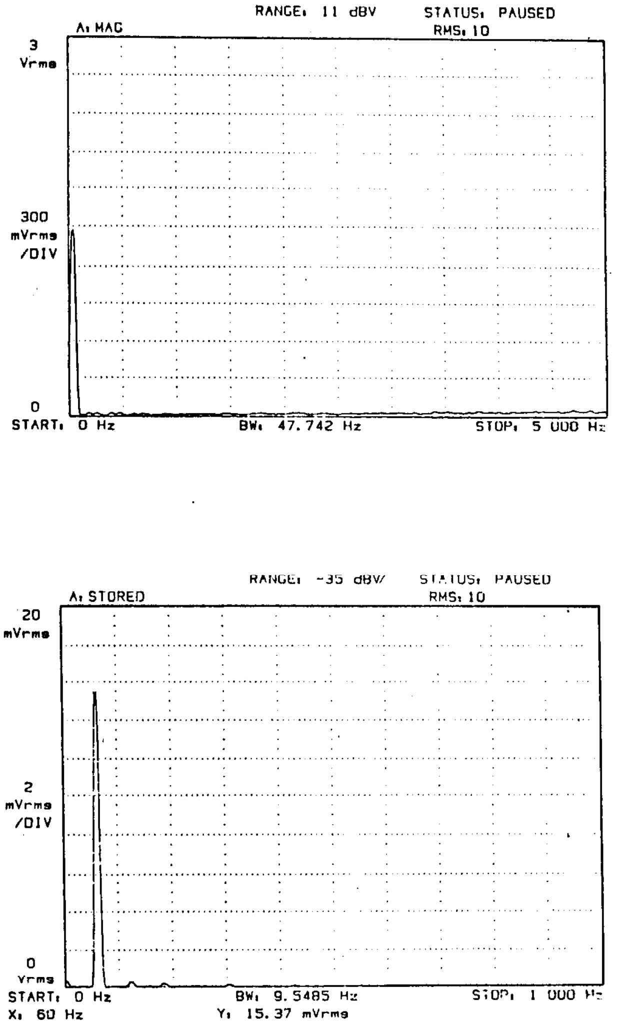
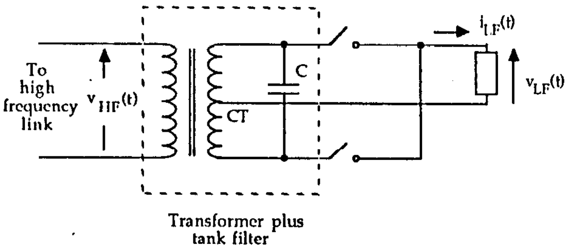


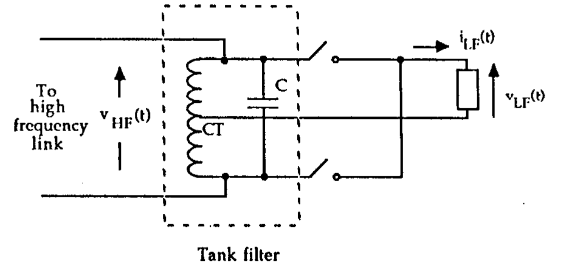
Figure 12: Spectra of the machine voltage and current. Upper trace: Spectrum of the line voltage, v_{ab}; 300 V. full scale. Lower trace: Line current, i_a; 4 A. full scale.

7 CONCLUSIONS

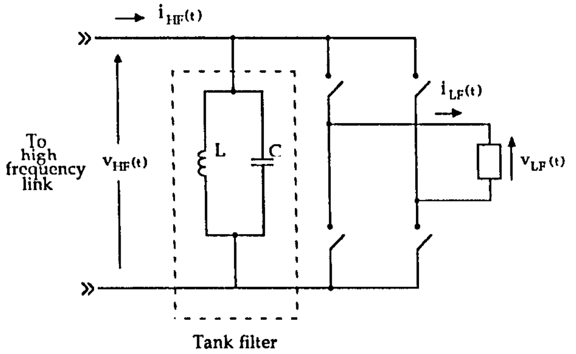
The PDM converters have some very favorable characteristics that make them an excellent candidate for the role of interface converters in a high frequency (appx. 20 kHz) link power conversion system. The basic PDM converter is capable of high conversion efficiencies due to its one-stage power handling and low switching losses. It is capable of inherent bi-directional power flow requiring no changes in the power or the control circuit to affect a change in the direction of power flow. Operation directly off a 20 kHz link gives the PDM converter an equivalent switching rate of forty thousand switches per second. As a result, PDM converters have very high bandwidths, can synthesize signals with very little lower order harmonics, and can readily generate fundamental frequencies as high as 1000 Hz. Finally, a generalized power structure and an unrestrictive control scheme makes the PDM converter very versatile so that it can interface a wide variety of loads and sources to the high frequency link.



(a)



(b)



(c)

Figure 7: Power circuits for single-phase PDM converter, (a) Center-tapped transformer half-bridge, (b) Center tapped inductor half-bridge, (c) Full-bridge.

A parallel LC tank circuit tuned to the link frequency is used as the link side filter. For the tank capacitor, General Electric 97F85 series polypropylene film capacitors have been used because of their high current ratings and a very low dissipation factor. Their performance has been very satisfactory. For tank inductor, a litz wire wound inductor with a ferrite core was used. The overall Q of the tank circuit was measured to be about 160 for link voltage of 318 V rms and a link frequency of 19.32 kHz.

The feedback signals required by the AC-PDM control are obtained indirectly by sensing the link voltage with a signal transformer and applying to this isolated and scaled signal the same logic that fires the power circuit of the bridge. In this manner, the difficult task of feeding back the actual pole voltages has been avoided.

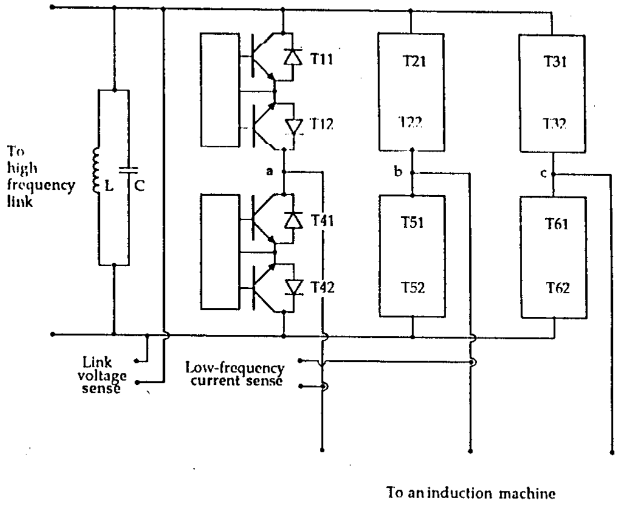


Figure 8: Breadboard realization of the three-phase PDM bridge. Component values are given in Table 7.3.

An open loop constant Volts/Hertz type controller was built to allow operation of an induction machine from the breadboard converter. This controller supplies the PDM controller with the frequency and amplitude commands required for synthesizing the low frequency voltages impressed on the machine. Also, a soft start and a current limit were added as safety features.

Figure 9 shows typical voltage and current waveforms observed across one converter switch. The waveforms demonstrate the zero voltage switching of the PDM converters. Line voltage and current waveforms during soft start of a 60 Hz 220 V induction machine fed from PDM bridge converter are shown in Fig. 10. The same set of waveforms is shown in Fig. 11 for no load steady state condition of operation of the machine. Fig. 12 shows the frequency spectrum of the waveforms of Fig. 11. Note that the lower order harmonics in either spectrum are very small.

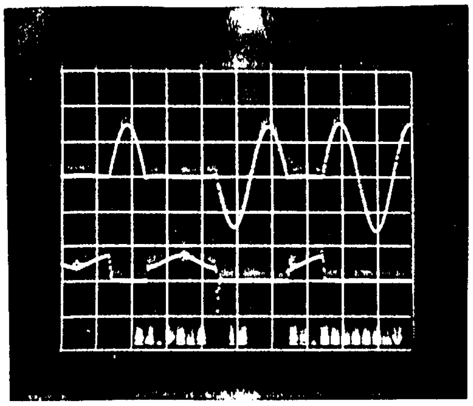


Figure 9: Typical voltage and current waveforms observed across one switch of the PDM converter. Upper trace: Swtich voltage; 250 V/div. Lower trace: Switch current; 12.5 A/div.

8 ACKNOWLEDGEMENT

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Inverter Type	Max. Fundamental Pole Voltage (peak)	Max. Fundamental Line Voltage (rms)	Line Voltage to Link Voltage ratio (rms/rms)	Device Voltage to Line Voltage ratio (peak/rms)
DC link PWM	$\frac{1}{2}V_d$	$\frac{\sqrt{3}}{2\sqrt{2}}V_d$	$\frac{\sqrt{3}}{2\sqrt{2}} = 0.612$	$\frac{2\sqrt{2}}{\sqrt{3}} = 1.6$
AC link PDM	$\frac{1}{\pi}V_p$	$\frac{\sqrt{3}}{\pi\sqrt{2}}V_p$	$\frac{\sqrt{3}}{\pi} = 0.551$	$\frac{\pi\sqrt{2}}{\sqrt{3}} = 2.56$
Resonant dc link PDM [7]	$\frac{1}{4}V_p$	$\frac{\sqrt{3}}{4\sqrt{2}}V_p$	$\frac{1}{2}$	$\frac{4\sqrt{2}}{\sqrt{3}} = 3.27$

Table 1: Comparison of voltage conversion ratios and device voltage ratings for three high performance converters.

Rated power	7.5 HP
Rate voltage	210 V
Rated frequency	400 Hz
Rated speed	11200 rpm
Stator and rotor resistance	0.15 pu
Stator and rotor reactance	0.1 pu
Unsaturated magnetizing reactance	3 pu
Normalized inertia	0.2 s

Table 2: Induction machine parameters used in simulation study.

Component	Circuit Symbol	Key Specifications	Comments
Power - darlingtons	T 11 - T 62	50 A, $V_{ceo(sus)} = 500$, $V_{cev} = 700$ V, $t_s = 5$ µs	MJE 10016
Snubber capacitor	C 1 - C 6	0.047 µF, 1200 VDC	Sprague 715P series
Filter capacitor	C_T	3.0 µF, 1000 Vpk, 114 A	Three GE97F8522FC
Filter inductor	L_T	22.5 µH, 120 A	Litz wire, Ferrite core
Current sensors		100 A, 1000:1, DC-100kHz	LEM LT 100-S

Table 3: Component values for the breadboard PDM converter of Fig. 8