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RESONANT LINK CONVERTERS: A NEW DIRECTION IN SOLID STATE POWER CONVERSION

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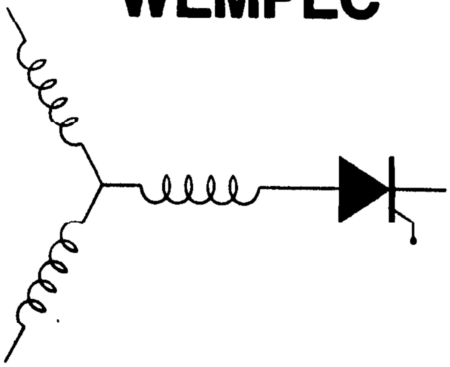

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Resonant Link Converters: A New Direction in Solid State Power Conversion

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Abstract This paper summarizes recent work on a new class of power converters, the resonant link power conversion family These converters utilize a high frequency link to introduce zero voltage or zero current intervals. By switching at the zero crossings of the voltage or current the converter switch losses can be greatly reduced permitting an order of magnitude increase in the converter switching frequency. The converters synthesize nearly sinusoidal currents on both input and output converters and can maintain unity power factor at the system input. These systems are suitable for new types of ac motor drives which have superior dynamic performance as well as lighter weight and high system efficiency.

Introduction

With the recent advances in power electronics, variable speed induction motor drives using frequency changers has now become a well established technology. The most widely used and highly developed frequency changers are the variable amplitude (six step) and and fixed amplitude (pulse width modulated or PWM) dc voltage link inverter which synthesize variable frequency and variable voltage ac output from a dc voltage input. The second class of highly developed frequency changers is the variable amplitude dc current link converter. These dc link based power conversion systems have several inherent limitations. One important drawback is the excessive switching loss and device stress which occur during switching intervals. As a result, the devices require a large Safe Operating Area and the reliability of the system may be compromised. The typical switching frequency in medium size 10-50 kw PWM inverters is, at best, 5 kHz. Larger converters require lower switching frequencies or cannot even be contemplated because of the loss issue. Because of the relatively low switching frequency it is difficult to realize dramatic gains in important system attributes such as faster system response, increased output frequency, improved power densities and reduction in audible and electrical noise particularly when the motor is operating at high speeds.

In recent years remarkable progress has been made in the development of high power density ac/ac converters which incorporate resonant-link schemes rather than the more conventional dc link. These converters, called "resonant link converters", utilize high speed devices such as fast recovery transistors, thyristors and GTOs to achieve a relatively high switching frequency and thereby markedly reduce the output current distortion compared to dc link schemes. In addition, these new converters also have high power density made possible by very low switching losses. The purpose of this paper is to summarize the state of the art in this important new branch of high power electronics.

Parallel Resonant AC Voltage Link Power Conversion

In general, switching schemes for high power resonant link converters can be classified according to whether they involve a resonant ac voltage or current impressed on the link or incorporate a pulsating dc component, i.e. the link is "dc resonant". Figure 1 shows a schematic illustration of the simplest configuration, the parallel resonant ac voltage link first described in [1]. In this configuration a single-phase ac voltage link operating at a fixed frequency of 20 kHz or higher serves as the interface between two six pulse transistor bridges. The bridges operate from the bi-directional high-frequency voltage of the link to

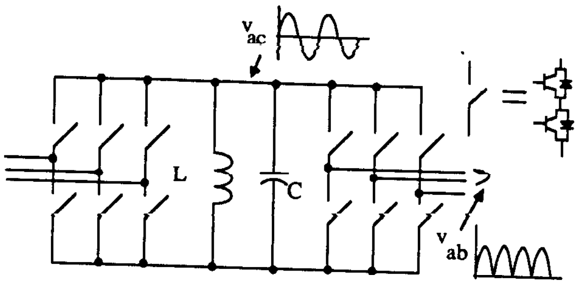

Fig. 1 Parallel Resonant AC Voltage Link Power Conversion System.

synthesize low frequency (including dc or zero frequency) voltage or current source outputs as appropriate.

It is important to mention that the resonance of this converter is set solely by the link L and C and is essentially independent of the load parameters. This is in contrast to more traditional "resonant converters", used for example in induction heating, in which the load forms a portion of the resonant circuit.

With such constraints on the switching of the converter switches, one half cycle of the high frequency voltage becomes the basic unit of synthesis of the low frequency output signals. Converter switching is restricted to the zero crossing points of the link voltage so that the switching losses, which dominate the converter losses at these high frequencies do not become excessive. Start up of the resonant link can readily be accomplished through proper control of the converter connected to the source.

Figure 2 illustrates the principle of zero voltage switching and how a low frequency voltage component can be obtained by synthesizing the desired fundamental component from complete half cycles of the high frequency link voltage. Figure 3 shows a typical voltage and current waveforms observed across one converter switch. The waveforms clearly demonstrate the zero voltage switching nature of the parallel resonant ac link converter.

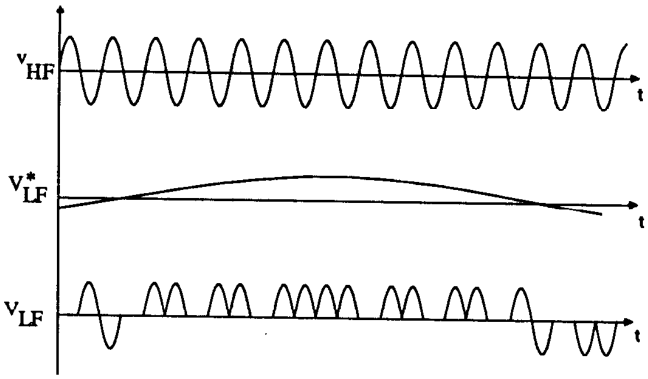

Fig. 2 Modulation Principle of Parallel Resonant AC Voltage Link Converter.

Parallel Resonant DC Voltage Link Power Conversion

At present, the primary disadvantage of the parallel resonant ac voltage link system is the need for bidirectional voltage blocking devices. This need, coupled with the normal requirement for bidirectional current conducting paths, results in a switch mechanization utilizing dual transistor/inverse diode packages as shown in Fig. 1. With the recent development of the MOS controlled thyristor [3], however, a true bidirectional

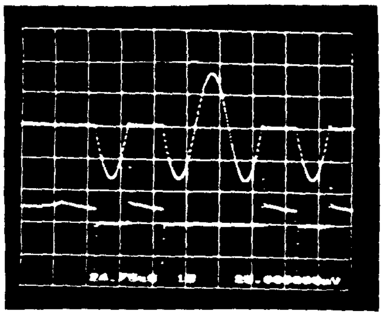

Fig. 3 Typical Voltage and Current Waveforms Observed Across One Converter Switch. Upper Trace: Switch Voltage: 125 V/div. Lower Trace: Switch Current: 5 A/div, Time: 25 ms/div.

voltage/current blocking switch may be realized in the near future. An alternative to permitting the voltage link to reverse polarity is to bias the link with a dc voltage as shown in Fig. 4 [4]. In this case the link resonates at the tank frequency defined by L and C. Capacitor C_0 is a conventional electrolytic capacitor used to provide the dc bias to the link. The link voltage now takes the approximate form of a biased cosine wave. Again the switches of both converters operate only when the link voltage reaches zero. In order to reduce the effects of the stray capacitance, the link capacitor C can be distributed across the poles of both converters or even across the switches themselves.

The major concern for successful operation of this scheme is to ensure that the link voltage reaches zero during each resonant pulse. It can be shown that if losses are included, the voltage across the capacitor C is a damped wave which does not reach zero as predicted ideally. A zero voltage interval can, however, be ensured by giving the link inductor L an initial current condition. The initial condition can be accomplished by briefly shorting the capacitor C by simultaneously triggering both top and bottom legs of one phase of the converter before the capacitor is released and an oscillation cycle commences.

A potential disadvantage for such a converter is the relatively poor utilization of the semiconductor switches since the RMS value of the output voltage is roughly half the equivalent voltage of a dc voltage link PWM converter for the same switch voltage rating. This difficulty can be overcome by incorporating an active clamp which limits the link voltage to a predetermined value as shown in Fig. 5 [5]. In this circuit, diode D turns on and clamps the bus voltage at a predetermined value. With D conducting, the device S is turned on in a lossless manner. The current eventually transfers from the diode to the device S. The charge transferred to the capacitor C_c with D conducting is recovered during the interval when S is on. When the net charge transferred equals zero, S is turned off and the LC circuit resonates until the dc bus voltage reaches zero and C is again shorted. At this point the resonant cycle is reinitiated. In this manner it is possible to reduce the voltage stress from approximately 2.5 to 1.2-1.4 times the link dc capacitor voltage. Hence, the

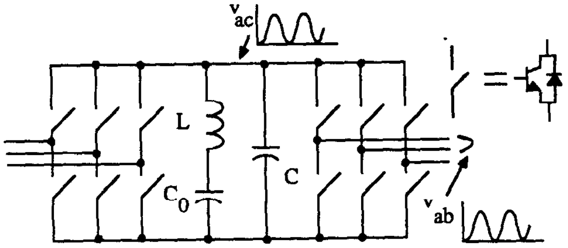

Fig. 4 Parallel Resonant DC Voltage Link Power Conversion System.

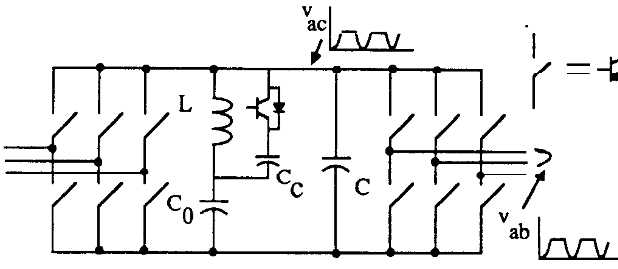

Fig. 5 Parallel Resonant DC Voltage Link with Active Voltage Clamp.

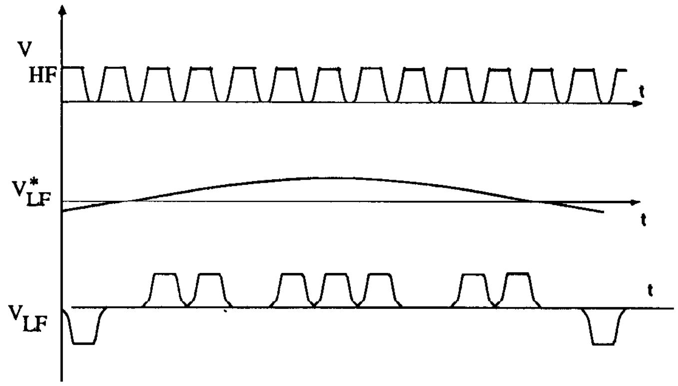

Fig. 6 DC Link Voltage and Line to Line Output Voltage Waveforms for System of Fig. 5.

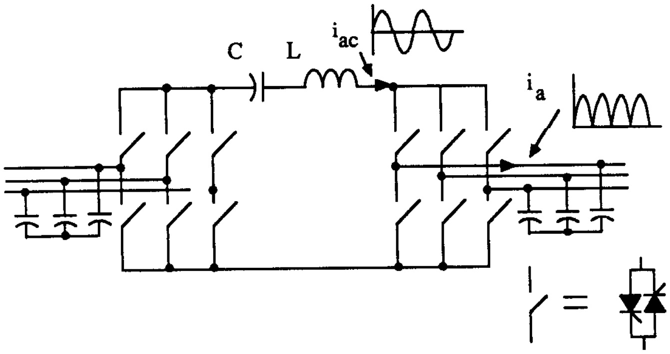

Fig. 7 Series Resonant AC Current Link Power Conversion System.

switch elements become only marginally greater than the equivalent switches of a dc link converter. Typical waveforms for the case of voltage clamping is shown in Fig. 6.

Series Resonant AC Voltage Link Power Conversion

Circuit duality plays an important role in power electronics and the duality of conventional dc voltage link and dc current link converters are well known. Voltage resonant links also have duals which possess similar properties as the conventional dc current link converters. Figure 7 shows the circuit dual of the parallel resonant ac voltage link. Historically, this type converter was the first to be developed [6]. However, the initial conception involved a complicated magnetic structure which prevented application to high power ratings. Recently, the circuit of Fig. 7 has been described and suggested for use in a variable speed hydro generator application [7].

In this case of this converter, the inductance L and capacitance C form a series resonant link. Switching of the devices of each converter occurs at zero current rather than zero voltage intervals. Since 4-layer devices turn off when the current becomes less than the holding current, this converter structure requires only thyristors in its implementation, an important advantage. Because the current in the link reverses, the switches are implemented with inverse parallel thyristors. Figure 8 shows the switching strategy for this converter. Note that the waveforms are essentially identical to Fig. 2.

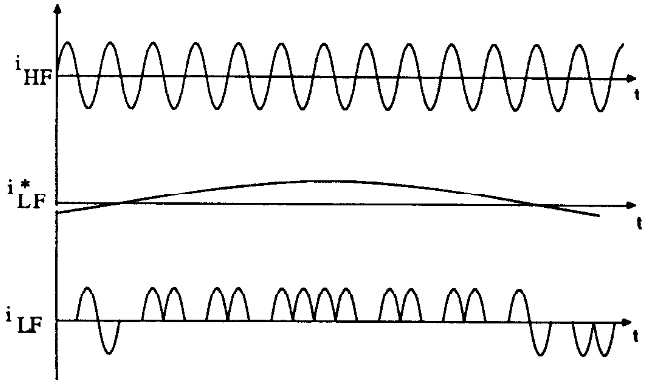

Fig. 8 Switching Strategy for Series Resonant AC Current Link Power Conversion System.

Series Resonant DC Voltage Link Power Conversion

The dual of the Parallel Resonant DC Voltage Link is the Series Resonant DC Current Link converter shown in Fig. 9 [8]. In this case a dc bias current is added to the link by employing a dc inductor L_0. The link current takes on the form of a displaced cosine wave. Again zero current intervals are used to turn off the conducting thyristors. However, since the current now remains unidirectional, the converter switches can be implement with single thyristors. Hence, each converter becomes no more complicated than the conventional thyristor bridge. In order to increase the switching frequency to as large a value as possible, fast turn off devices must be employed so that the cost of the bridge is somewhat greater than a simple phase controlled bridge.

When the losses in the system are considered the link current does not return to zero after each oscillation interval in much the same manner as the dc resonant voltage link. The problem can be solved in this case by properly regulating the current in inductor L_0 to ensure that the link current reaches zero after each cycle of oscillation. It is apparent that

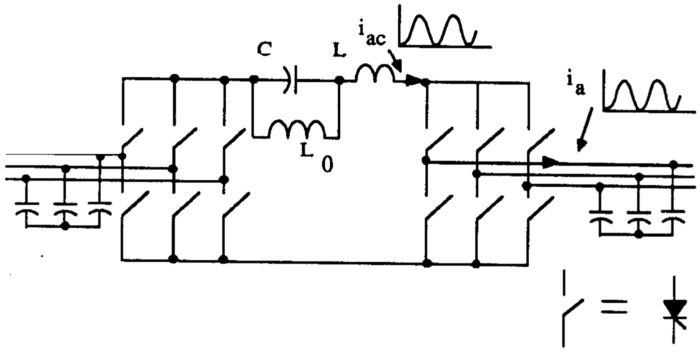

Fig. 9 Series Resonant DC Current Link Power Conversion System.

this converter suffers from the dual of the disadvantage of the dc resonant voltage link. That is, the RMS ac output current is relatively small compared to the current switch rating. However, in this case the problem is less serious since thyristors are used for the switch elements so that sufficient current carrying capability can easily be accommodated relatively modest cost.

The problem of switch utilization can be eased by incorporating a current clamp as shown in Fig. 10 [8]. In this case the clamp thyristor is inserted across the capacitance C and only a portion of the inductance L (approximately 10%). Waveforms for a typical motor load is shown in Fig. 11. As is true for all current fed systems with capacitors across the load, resonances can be set up between these capacitors and the motor leakage inductance. Numerous possibilities exist to minimize its detrimental effects. One method which as been found particularly useful is to add a damping circuit to the terminals of the motor load as shown in Fig. 12 [8]. It can be shown that the power absorbed by the damper is very small

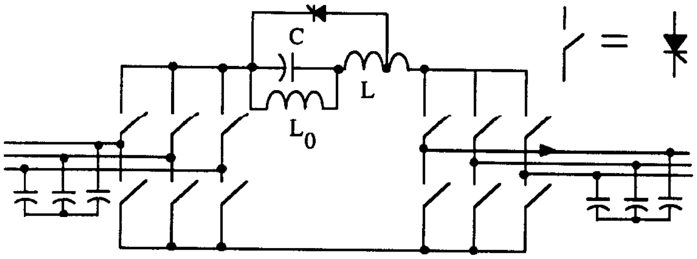

Fig. 10 Series Resonant DC Current Link with Active Current Clamp.

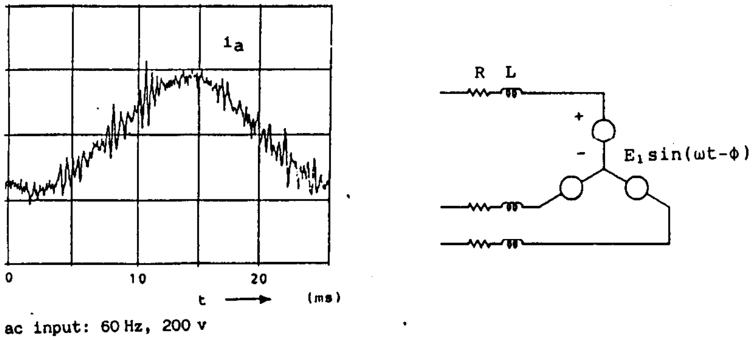

Fig. 11. Motor Current Waveform for the Case R = 5.0W, L = 1.0 mh, E = 100 V, f = 10°.

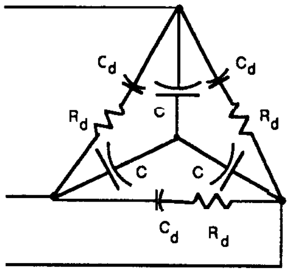

Fig. 12 R-C Damping Circuit for Reducing Motor Resonance Condition.

Modulation Strategies

Figure 13 shows the block schematic of a typical modulation scheme used for resonant voltage link systems based on the concept of area comparison [2]. In this scheme, the area under the reference signal is compared with the area of the synthesized voltage signal. If the comparison indicates that the area of the synthesized signal is more (less) than the desired value then the controller causes the next half cycle pulse to be applied so that this area is increased (decreased). In this manner, voltages 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 delta modulation has been used to describe this type of switching scheme. Figure 14 shows a typical spectrum of the voltage obtained by such a modulation strategy. It can be noted that very low level harmonics exist evenly over the spectrum from the fundamental to twice the link frequency (40 kHz). This is in contrast to many types of dc link converters in which the harmonic spectrum has characteristic "blips" at well defined multiples of the fundamental. Similar results can be shown to be possible for the dc resonant ac voltage link configuration except that the basic switching frequency is one full cycle rather than a half cycle resulting in a "blip" at 20 rather than 40 kHz.

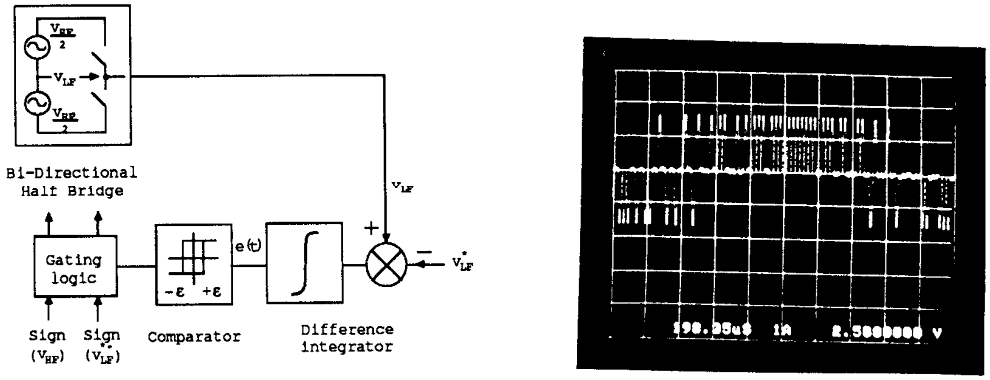

Fig. 13 Control Block Diagram for Area Comparison Pulse Density Modulation (Delta Modulation) and Resulting Line-to-Line Voltage Waveform. Voltage Scale 250 V/div. Time Scale 198.35 μs/div.

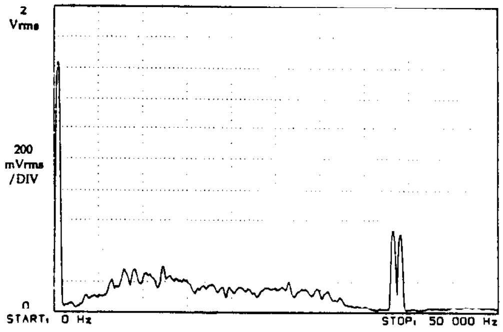

Fig. 14 Harmonic Spectra Associated with the Line Voltage Waveform of Fig. 13. Amplitude Scale: 20V/div., Frequency Range: 50 kHz.

The importance of current regulation in ac motor control has prompted a close look at current regulation in such drives [9,10]. Figure 15 shows the current waveform for the ac resonant voltage link system using a simple bang-bang controller. While this simple type of current controller is very adequate at low frequencies, the need for more sophisticated current regulators increases as the motor frequency rises. It can be noted that in zero voltage or zero current switching schemes, the switching instant and pulse duration is specified. Hence, the problem of current modulation reduces to finding the next optimal combination of switch states at each switching instant. If the load current for the next switching instant can be predicted for all possible switching states before the switching instant, the switching patter can be selected which minimizes specified error function. If only current regulation is required, the error function may be simply the sum of the absolute current regulation errors of each phase or, alternatively, the square of the individual errors. Figure 16 shows the block diagram of a *mode selection controller* based on this principle which realizes substantial improvement in the current waveform at high frequencies. A typical waveform for this controller is shown in Fig. 17 and can be compared with Fig. 15.

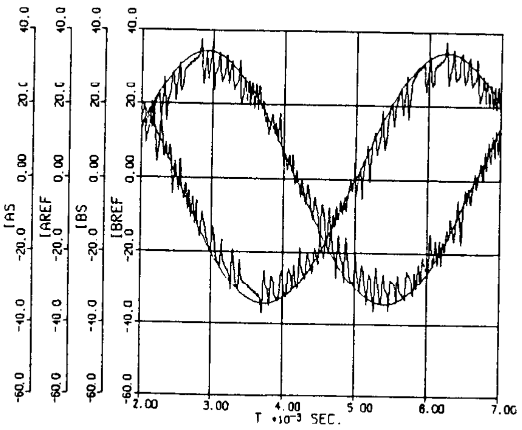

Fig. 15 Response of Current Regulator Employing Bang-Bang Current Regulation. Traces: A Phase and B Phase Line Currents and Corresponding Reference Currents in Amperes, Frequency 143 Hz.

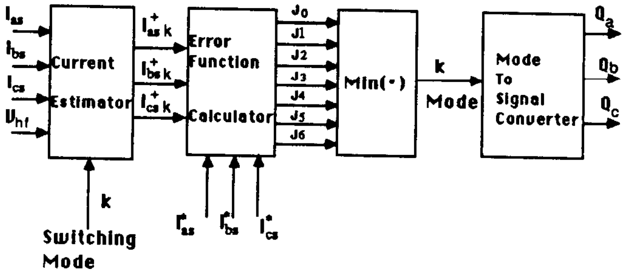

Fig. 16 Block Diagram of Mode Controller for Current Regulation.

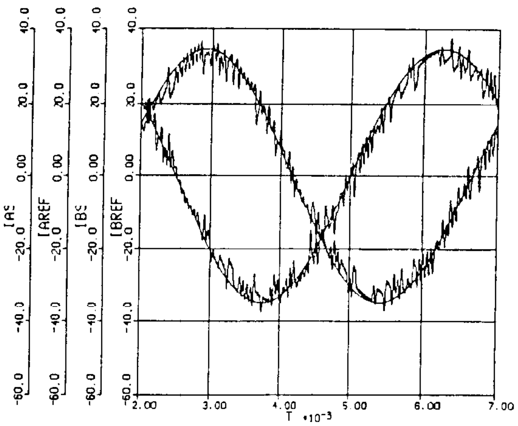

Fig. 17 Response of Current Regulator Employing Mode Selection Current Regulation. Traces: A Phase and B Phase Line Currents and Corresponding Reference Currents in Amperes, Frequency 143 Hz.

Field Oriented Controller

A complete system diagram for a field oriented induction motor controller utilizing high frequency link technology is shown in Fig. 18. The source side converter is nominally tied to the utility grid through interface inductors but since these inductors are small they may not be necessary if sufficient source impedance exists. The load side converter is connected directly to an induction machine without added capacitive filtering. The current of the source side converter is controlled by a link voltage regulator which regulates the link voltage by balancing the active power flow between the source and load. The current regulator at each converter regulates the current in both magnitude and phase. The power estimator provides an estimate of the current value of active power to the voltage regulator by calculating the average load power and the system losses based upon measurement of the current operating conditions. The induction machine is controlled by a current regulated field oriented controller equipped with a speed regulation loop.

A typical trace showing the transients characteristics of the drive is shown in Fig. 19. In particular, the trace shows system performance for a step change in torque command from 12 Nt-m to zero and then back to 12 Nt-m. It is apparent that the high effective switching frequency of the converter permits very rapid changes in motor current results, in turn, in an extremely fast acting torque controller. Figure 20 shows an experimental trace of the system for the condition where the motor is operating under a steady load condition and demonstrates the feasibility of operation with the supply current having a nearly sinusoidal waveform at unity power factor.

Conclusions

This paper has summarized recent work on a new class of power converters, the resonant link power converter. These converters utilize the zero crossings of the link voltage or current to realize nearly zero loss switching. Of particular importance is the fact that these new converters do not necessarily require extremely fast turn off devices (i.e. IGBTs or MCTs) for satisfactory operation but can, in fact utilize low cost bipolar transistors and thyristors as the switching elements. Since the effective switching frequency is high, the currents at the input and output of the converter are nearly sinusoidal. These new converters promise to play an important role in the next generation of power conversion equipment.

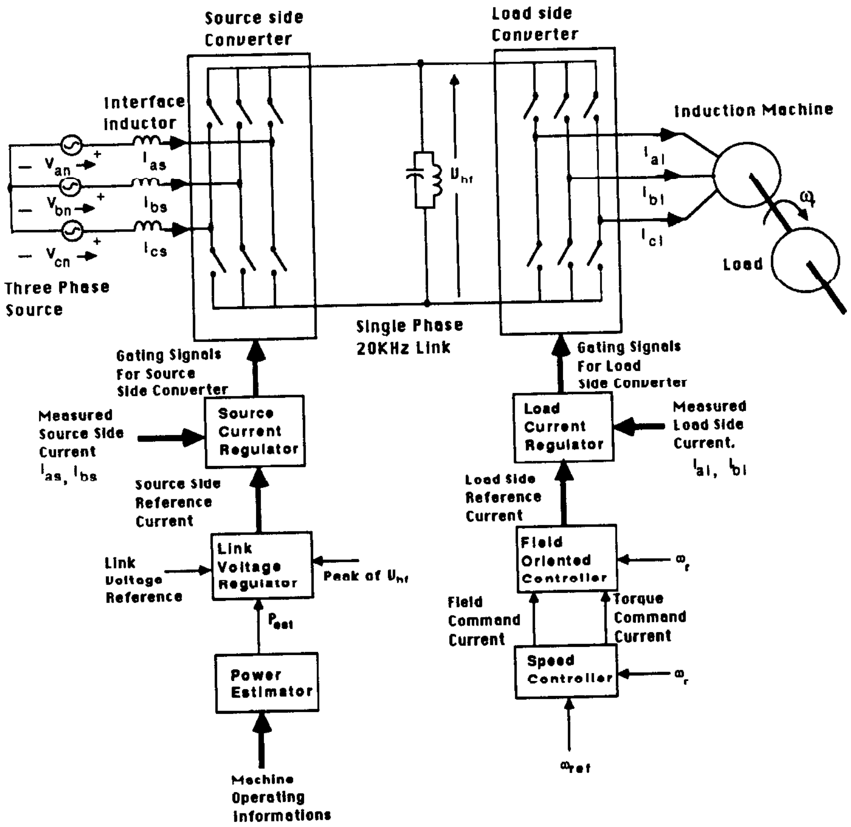

Fig. 18 Complete System Diagram of Resonant AC Voltage Link Power Conversion System.

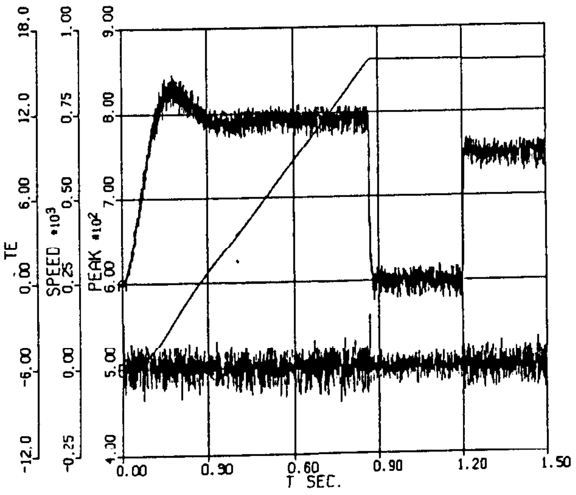

Fig. 19 Torque Response of System. Traces: Electromagnetic Torque in Nt-M, Speed in RPM and Peak Voltage of the High Frequency Link in Volts.

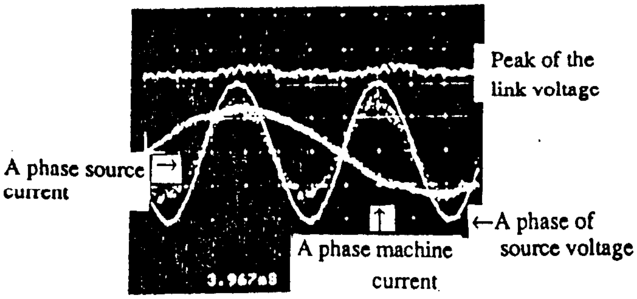

Fig. 20 Illustrating Unity Power Factor Operation of Line Side Converter During Motoring Operation. Traces: Peak of the Link Voltage: 130 V/div, A Phase Source Voltage, 40 V/div, A Phase Source Current: 5 A/div., A Phase Induction Machine Current: 5A/div. All Grounds 4 Div form the Bottom. Time Scale 3.967 ms/div.

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