

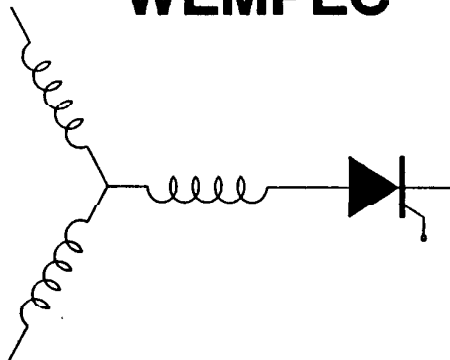
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DESIGN AND PERFORMANCE OF A HIGH FREQUENCY LINK
INDUCTION MOTOR DRIVE OPERATING AT UNITY POWER FACTOR

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Abstract The design and performance of a complete three phase converter system and field oriented induction motor drive based upon a 20 kHz ac link is described. By using same converter for the ac input side as well as the output load side, it is shown that power can be transferred in either direction. It is also shown that with the use of a current regulator both power flow on the link and the link voltage amplitude can be regulated. In addition, by suitable feedback control, the power factor at the input to the converter can be adjusted to unity. Both computer and experimental results shows unity power factor operation, low harmonic current both in the input and output of the system, and bidirectional power flow capability.

Introduction

With the recent advances in power electronics, variable speed operation of an ac machine by use of frequency changers has now become a well established technology. The most widely used and highly developed frequency changers are the Six Step and Pulse Width Modulated (PWM) inverters which synthesize variable frequency and variable voltage ac output from a dc input. These inverters utilize a dc voltage link which is obtained by rectifying and filtering the utility source voltages.

An important factor behind the wide spread use of the dc voltage link has been the ease and effectiveness by which the energy storage function, essential for decoupling the source from load, can be implemented in a dc link. Electrolytic capacitors provide low-cost, high density energy storage in the dc voltage link of a voltage source inverter. However, this type of dc link based power conversion system has several inherent limitations. One important drawback is the excessive switching loss and device stress which occur during switching intervals. As a result, the typical switching frequency in medium size 10-50 kw PWM inverters is, at best, 5 kHz. 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. Another difficulty worth mentioning is the presence of the rectifier bridge which is used to obtain dc from the ac voltage source. Conventional full bridge rectifiers inject considerable low-order harmonics to the utility grid. In addition, the power flow is unidirectional, and regenerative operation of the system is possible only with considerable added expense.

Recently, resonant ac or dc links have been studied and suggested as strong candidates for the power conversion link. With the resonant link the switching frequency can be increased with less than proportional increases in losses or device stress by restricting switching time to the instants of zero voltage on the link [1-2]. By increasing the resonant link frequency to 15-25 kHz, the problems associated with switching limitations can be overcome. In particular, the resonant ac link principle has recently been investigated for the power distribution system of the NASA Orbiting Space Station and as the secondary power system of advanced aircraft [3-4] and a 20 kHz single phase resonant voltage link has been developed for this purpose. Suitable control algorithms for an interface converter operating from a 20 kHz ac link have already been developed and verified [5-6].

In this paper, the design and performance of a complete three phase to three phase converter system based upon a 20 kHz ac link is described. By using same converter for the ac input side as well

as the output load side, power can be readily transferred in either direction. At present, this type of topology requires twelve bidirectional switches, so that it appears to be a costly system. However, with the development of new power devices such as MOS-Controlled thyristor it is anticipated that cost effective, bi-directional devices will soon become available. Hence, the converter described in this paper holds promise as a means for obtaining unity power factor and low harmonic current on the source side of a frequency converter as well as providing fast response with high efficiency, no acoustic and markedly reduced electrical noise at the output.

Overall System Description

The overall system described in this paper is shown in Fig. 1 wherein two converters are connected through a 20 kHz resonant link. The link voltage is supported by a parallel resonant tank circuit. Each switch of the converter has the capability of bi-directional current flow and bi-directional voltage blocking. 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 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 current in 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 condition. The induction machine is controlled by a current regulated field oriented controller equipped with a speed regulation loop.

Link Voltage Regulation

For cost reasons the energy storage capacity of the link tank circuit is not as large as the dc capacitor in the dc voltage link. Hence, the power balance between the load and source must be done actively. The ideal method for balancing the power flow between source and load is to measure the instantaneous power delivered to the load and system losses and deliver this exact power to the tank circuit by the source side converter. However, such an instantaneous power matching control appears to be impossible because of the difference in the source and load frequency and voltage. The best approach for handling the power balancing problem is to attempt power balance only on an average basis. The instantaneous power unbalance must then be handled by tank circuit at the cost of link voltage variations.

Fortunately, a moderate variation of link voltage is not a severe problem because the power converter connected source or load has the capability of fast regulation and the current in the source and load can be controlled as desired even in the presence of high frequency link voltage fluctuations. A small or moderate variation will, perhaps, only produce slightly more harmonic content in output current. A large variation of link voltage could, however, create more severe problems. In particular, if the voltage is instantaneously below the minimum voltage needed to synthesize the desired reference command, the actual signal will not be able to follow the reference suggesting the possibility of control instability.

The simplest approach for obtaining average power

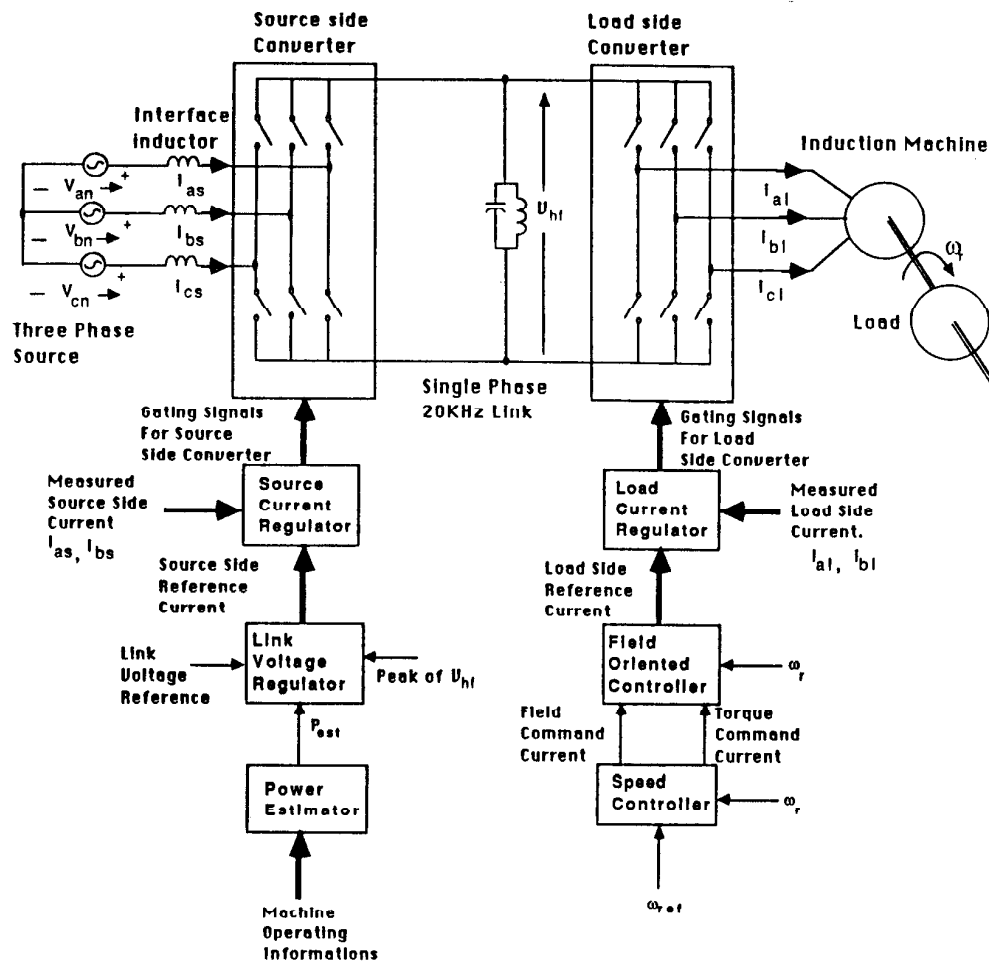


Fig. 1 Power circuit and system control block diagram.

information is to measure the power delivered to the induction machine using a low pass filter. However, with this method time delays resulting from the low pass filter are inevitable. Thus, during the delay time the difference in average power should be covered by the power capability of the tank circuit. This observation, in turn, implies a degradation in the link voltage regulation. Another method to obtain average power is to estimate the power with information derived from the reference currents of the induction machine which are, in turn, available from the field oriented controller used to control the induction machine. If the current regulation is perfect and if the machine parameters do not change and are known, the average machine power can be estimated without any time delay and without any measurement. In practice, of course, there are always differences between the actual currents and their references. Moreover, the parameters of the machine change according to flux level and operating temperature so that some error between estimated power and the actual power is inevitable. However, these errors can be compensated by using a voltage regulating loop as a minor loop[6-7].

A detailed block diagram of the voltage regulator and power estimator is shown in Fig. 2, in which the source power factor is controlled as unity. The source power factor can be controlled by shifting the phase of the reference current command so long as average power balance is maintained. Hence, the input power factor can be easily programmed to be leading or lagging as desired. In the figure, the magnitude of the reference current is the sum of the value from the power estimator and the value from the link voltage regulator. The phase of the reference current is controlled according to the source voltage.

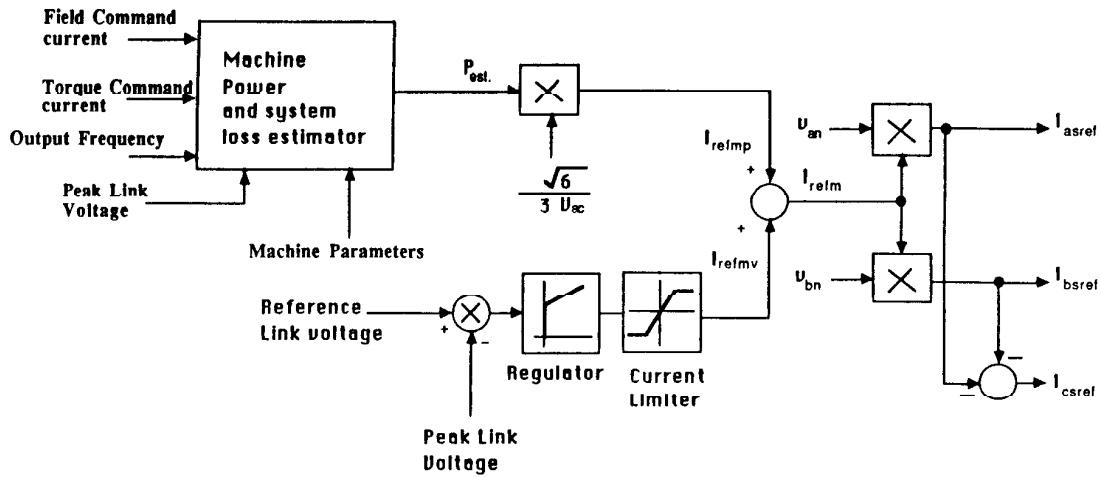
Transient Behavior of Resonant Link

A computer simulation trace illustrating link voltage build-up is shown in Figs. 3.a and b. It can be noted that the energy from the source is pumped to the resonant tank circuit and the tank voltage gradually increases to the given reference value. After overshooting the voltage settles down to reference value. In the simulation reference voltage is 500 volts and the parameters of the tank circuit are 22.5 μ h, 3 μ f, and 0.01 Ω . The resistance is incorporated to account for losses in the resonant tank circuit. After settling down it can be noted that the source current is almost zero supplying only the losses of the system.

Another simulation result illustrating the operating characteristics of the system as a whole is shown in Fig.4. In this simulation it is assumed that 3 HP induction machine is operating in the steady state at 40 Hz with rated torque. It can be observed that the link voltage amplitude is reasonably well regulated. The A phase source current reveals unity power factor operation and indicates only very high frequency harmonics. The synthesized load current is nearly sinusoidal, and has virtually no harmonics less than 40 kHz.

Current Regulator

In the case of a resonant link system, the current regulator most widely used is the Pulse Density Modulator or Delta modulator[1],[5],[7]. In general, both types of regulators are essentially the identical. In the above simulation the Pulse Density Modulator was used for the current regulator. Pulse density modulation performs very well in almost cases except for cases of low load inductance or when synthesizing fairly high frequency



U_{sc} : Source line to line voltage in rms.

U_{an}, U_{bn} : Instantaneous phase voltage of source

Fig. 2 Block diagram of voltage regulator.

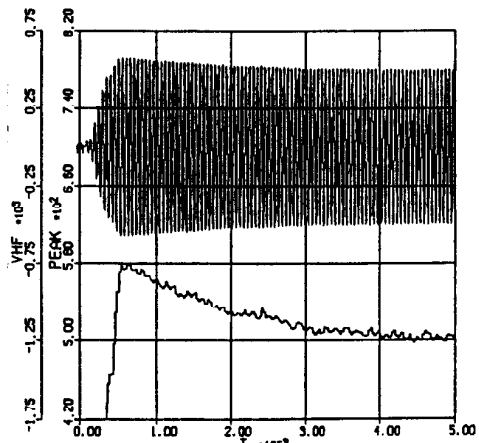


Fig. 3(a) Simulation result of high frequency link voltage build-up. Top trace: link voltage in volts, Bottom trace: peak amplitude of the link voltage.

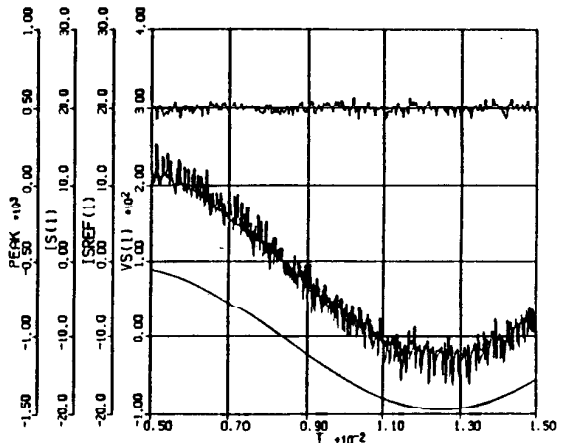


Fig. 4(a) Simulation result of operating characteristics of the system. From the top, trace of peak link voltage in volts., A phase source current and its reference in amperes, and A phase source voltage in volts.

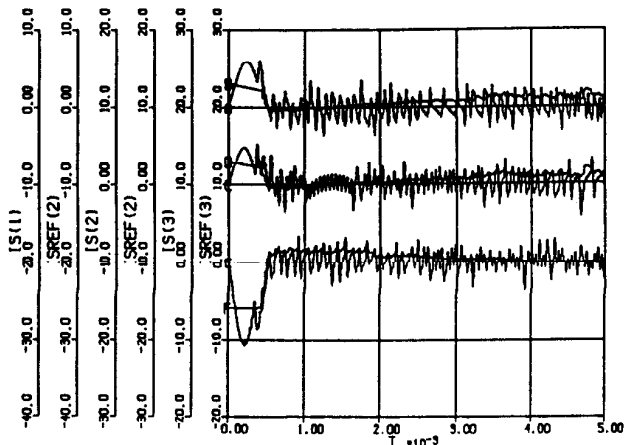


Fig. 3(b) Simulation result of high frequency link voltage build-up. From the top, A phase source current and its reference, B phase current and its reference, and C phase current and its reference. All traces in amperes.

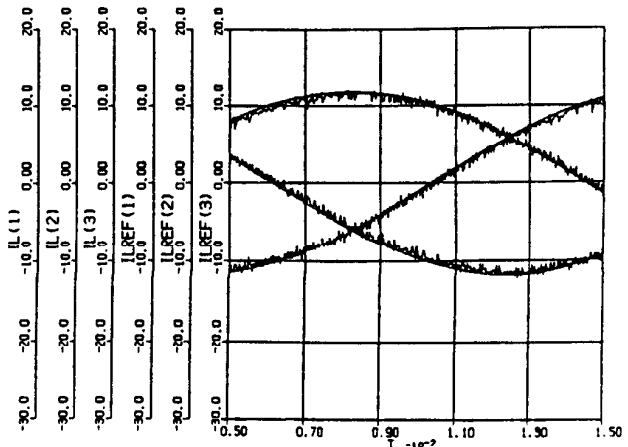


Fig. 4(b) Simulation traces showing operating characteristics of the system. A,B, and C phase load current and corresponding references. All traces are in amperes.

output. Recently, the authors have reported a new type of current regulator, termed a *mode selection controller* [6,8]. The mode selection controller operates on-line to select the switching pattern for the next switching mode which will minimize a given error function based upon the predicted values of voltage and current at the next switching instant. This type of current regulator can be extended to the control of a complete bidirectional double bridge system. Mode selection is very effective and easy to apply especially as a source side current regulator, where the source voltage and current can be easily measured and independent upon system operating conditions. Also, by utilizing mode selection the controller can simultaneously regulate the current as well as the link voltage. In this particular case the required error function is shown to be simply the sum of the absolute error of each phase current plus that of the link voltage.

The performance of the mode selection controller as source current regulator is shown in Fig.5.a and b for the case of link voltage build up. In these traces all parameters are identical with the case of Fig.3 except for the current regulator. By comparing Fig.3 and Fig.5 it can be noted that the voltage overshoot is decreased and also the current ripple is also attenuated. Thus, overall performance has clearly been improved.

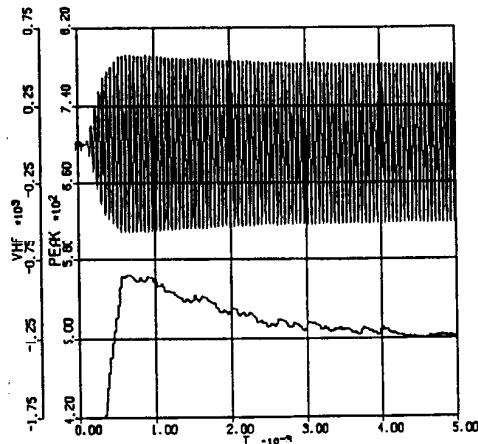


Fig. 5(a) Simulation result showing high frequency link voltage build-up with mode controller as source current regulator. Top trace: link voltage in volts, Bottom trace: peak amplitude of the link voltage.

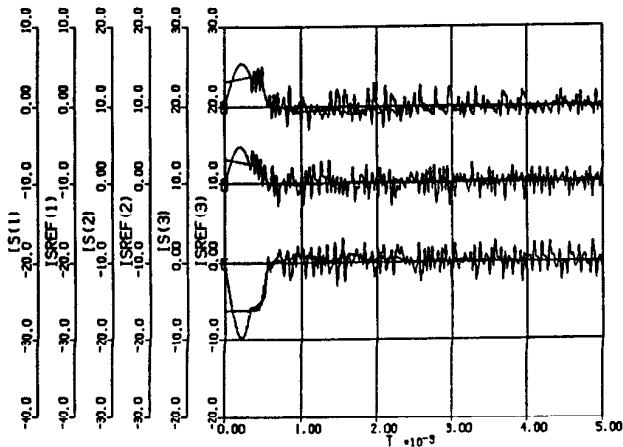


Fig. 5(b) Simulation result of high frequency link voltage build-up with mode controller as source current regulator. From the top, A phase source current and reference, B phase current and its reference, and C phase current and its reference. All traces in amperes.

Experimental Results

The system shown in Fig. 1 has been constructed and thoroughly tested in the laboratory. The Speed Controller of Fig 1 is the conventional proportional and integral regulator, and the indirect current regulated field orientation algorithm has been used to implement field oriented controller. The Current Regulator of both the line side and load side converters employ the Pulse Density Modulation principle. The link voltage regulator, speed controller and power estimator were implemented by analog circuits.

The inductors used on the source side are 1.5 mh, ferrite core Litz wire inductors. In the experimental set-up two resonant tank circuits were used. The parameters of each tank are 3 μ f, 22.5 μ h. Two power transistors were used as a bidirectional power switch and were connected as shown in Fig. 6 [3]. Typical voltage and current wave forms across a switch during normal operation is shown in Fig. 7. As expected, the switching occurs only at the zero crossing points of the link voltage. As a load a 3 Hp, 4 pole, and 60 Hz induction machine was employed and the machine was mechanically coupled to a 7.5 kw dc machine to apply torque to the induction machine in the positive or negative direction.

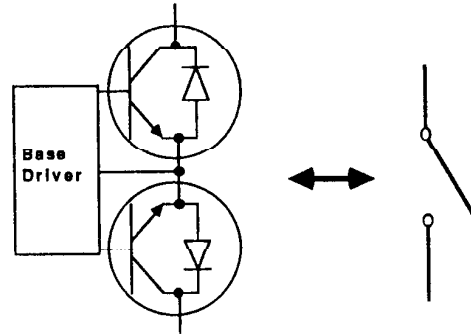


Fig.6 Implementation of bidirectional switch.

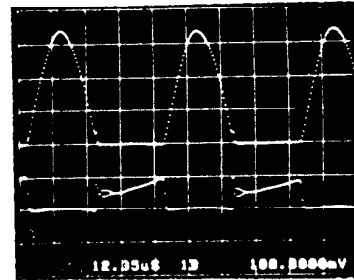


Fig. 7 Voltage and current waveform across a bidirectional switch. Top trace: voltage across switch: 130 volts/div., Ground: 4 div. from the bottom. Bottom trace: current across switch: 5 A/div., Ground: 2 div. from the bottom. Time scale: 12.35 μ s/div.

Link Voltage Build-up

The experimental result during controlled voltage build-up is shown in Fig. 8. The trace of the peak of the link voltage reveals smooth and well controlled behavior. Initially, the trace of the A phase current shows a sharp increase to store energy in the inductor. After build-up the current shows a sinusoidal variation which is in phase with A phase source voltage. The difference between experimental results and simulation results is due to the difference in the loss of the modeled and actual system. In the simulation the loss component was too small compared to the real system. The real system has some losses associated with the power switch, source side inductor and resonant tank inductor.

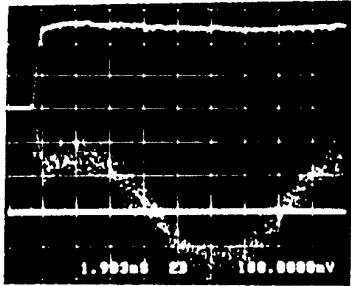


Fig. 8 Peak of the high frequency link voltage and A phase source current waveform during link voltage build-up. Top trace: peak of link voltage: 130 volts/div., Ground: 4 div. from the bottom. Bottom trace: A phase source current: 2 A/div., Ground: 2 div. from the bottom. Time scale: 1.983 ms/div.

Dynamic Performance of Field Oriented Controller

The test results illustrating performance of the field oriented controller is shown in Figs. 9 and 10. In Fig. 9(a), because of large inertia of the dc machine coupled to the induction machine, it takes several seconds to accomplish the speed change. While not clearly shown due to the large time scale Fig. 9(a) shows the variation of the power of the system. Before the transient the source supplies only the loss of the system including the mechanical loss. During the deceleration time the mechanical energy is converted to electrical energy. Hence, the current of the source rapidly decreases. When the machine begins to accelerate in negative direction, the current increases rapidly to supply the accelerating energy. A trace of the A phase of machine current in Fig. 9(b) clearly shows the change of the frequency as well as the phase. As shown in Fig. 9(b), the link voltage was well regulated during speed reversal. Figure 10 shows the system response of the same amount of speed change but this time without the coupled dc machine. The speed reversal was carried out within several tenths of a second. Both test results demonstrate good dynamic performance of the field oriented control incorporated with high frequency link power conversion system.

Unity power factor operation

In Figs. 11 and 12, the steady state characteristics of the system are shown during motoring and generating operation of the induction machine. In motoring operation, shown in Fig. 11, the source supplies all the losses of the system and mechanical energy of the induction machine. The trace of the A phase of the source current is in phase with A phase of the source voltage, which clearly demonstrates unity power factor operation. The trace of the peak of the link voltage demonstrates reasonable regulation. During generating operation shown in Fig. 12, the energy generated by the induction machine supplies all losses and the excess energy transfers to the source. Between phase A of the source voltage and the corresponding current there is 180° phase difference. The phase difference means that the source takes the energy from the system with unity power factor. The link voltage regulation for generating operation is poorer than that for motoring operation, because of a slight mismatch of the parameters of the power estimator.

Power Matching Controller

As mentioned before, the high frequency link system has no great reservoir of energy so that the power balance between source and load should be actively controlled. The behavior of the power estimation controller is shown in Fig. 13. During the starting of the induction machine the magnitude of the reference current from estimated power (I_{refmp}) was gradually increased, and after settling of the speed, the magnitude decreased to a small value to supply only the losses of the system. The reference current from voltage regulator, which is a minor loop, deviates around zero. By comparing the magnitude of the current it can be seen that the major part of the magnitude of the source reference current comes from the power estimator. The test result clearly explains the operation of the voltage regulator including the power estimator shown in Fig. 2.

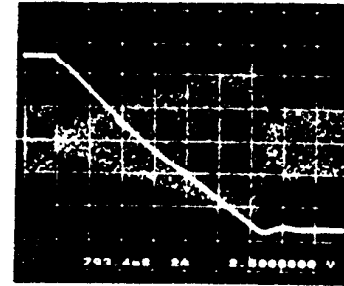


Fig. 9(a) Response of the field oriented control utilizing high frequency link power conversion. Mechanical rotational speed: 190 rpm/div., Ground 4 div. from the bottom. A phase of the source current : 5 A/div., Ground: 4 div. from the bottom. Time scale: 793.4 ms/div.

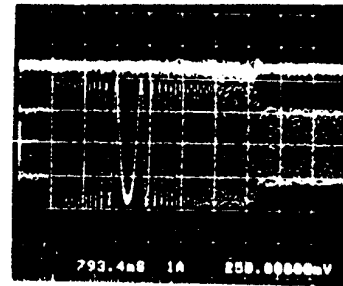


Fig. 9(b) Response of the field oriented control with high frequency link power conversion. Top trace: peak value of the link voltage: 130 volt/div. Ground: 4 div. from the bottom. Bottom trace: induction machine A phase current: 5 A/div., Ground: 4 div. from the bottom. Time scale: 793.4 ms/div.

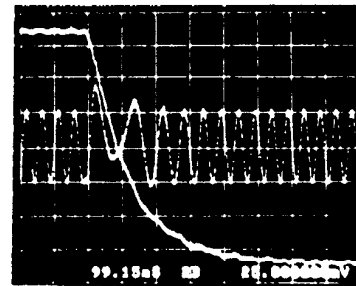


Fig. 10 Response of the field oriented control with high frequency link power conversion without coupled dc machine. Mechanical rotational speed: 190 rpm/div., Ground 4 div. from the bottom. A phase of the induction machine current: 5 A/div., Ground: 4 div. from the bottom. Time scale: 99.15 ms/div.

Current Regulation

The characteristics of the current regulator employing Pulse Density Modulation are shown in Fig. 14 and 15. In the case of the source current regulation the reference of the source current itself has some ripples to regulate link voltage and power matching control. The actual current accurately follows its reference. The load current reference is almost a ripple free sinusoidal wave during steady state operation of the induction machine. Hence, the actual current shows almost the same trace with its reference. It should be noted that during the operation of the system there was no acoustic noise from the power conversion system because of its high switching frequency.

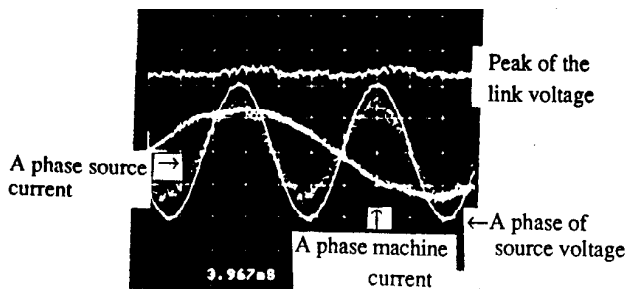


Fig. 11 Waveforms showing unity power factor operation of the system during motoring operation. Peak of the link voltage: 130 volts/div. A phase of the source voltage: 40 volts/div. A phase source current: 5 A/div. A phase induction machine current: 5 A/div. All grounds: 4 div. from the bottom. Time scale: 3.967 ms/div.

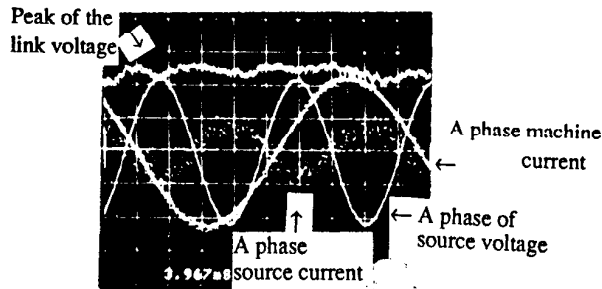


Fig. 12 System traces showing unity power factor operation of the system during regeneration. Peak link voltage: 130 volt/div. A phase of the source voltage: 40 volts/div. A phase of the source current: 5 A/div. A phase induction machine current: 5 A/div. All grounds: 4 div. from the bottom. Time scale: 3.967 ms/div.

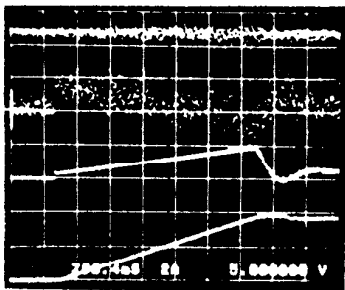


Fig. 13 Operation of power matching controller and voltage regulator. From the top, peak value of the link voltage; 130 volts/div., magnitude of reference current from voltage regulator (I_{refmv}); 3.5 A/div., magnitude of reference current from power estimator (I_{refmp}); 12 A/div., and mechanical rotational speed: 190 rpm/div. Grounds located, 5 div., 5 div., 3 div., 0 div. from the bottom respectively. Time scale: 793.4 ms/div.

Conclusions

In this study a new 3 phase to 3 phase power conversion topology based upon a 20 kHz single phase voltage link is proposed and tested by computer simulation. To demonstrate hardware feasibility of the system and to verify the simulation results, an experimental system was built and tested. The simulation results and experimental results agree and exhibit very good load current regulation as well as unity power factor operation of the source side current. Also, the system was shown to have inherent bidirectional power flow capability. The system should prove to be a viable alternative to conventional dc link systems in near future when the bidirectional power semiconductor switches become readily available.

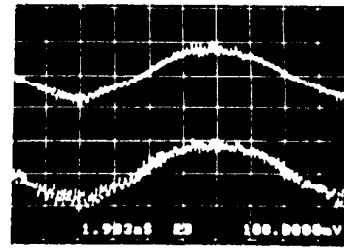


Fig. 14 System performance showing source side current regulation. Top trace: reference of A phase of the source current: 5 A/div. Bottom trace: A phase source current: 5 A/div. Ground: 5 div. from the bottom. Ground: 2 div. from the bottom. Time scale: 1.983 ms/div.

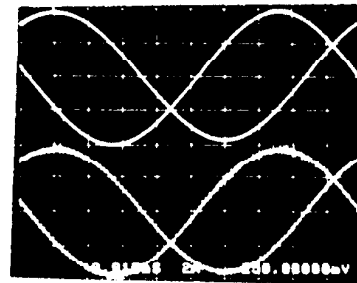


Fig. 15 Oscilloscope traces showing load side current regulation. Top trace: A and B phase induction machine current: 5 A/div. Ground: 6 div. from the bottom. Bottom trace: references for A and B phase induction machine current: 5 A/div. Ground: 2 div. from the bottom. Time scale: 9.915 ms/div.

Acknowledgments

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References

1. P.K. Sood and T. A. Lipo, *Power conversion distribution system using a resonant high-frequency ac link*, IEEE Trans. Ind. Appl. Soc., October 1986, pp. 533-541.
2. D. M. Divan, *The resonant dc link converter - a new concept in static power conversion*, In Conf. Rec. Annu. Meet. IEEE Ind. Appl., vol. IA-24, pp. 288-300, March/April 1988.
3. A. C. Hoffman, I.G. Hansen, R.F. Beach, et. al., *Advanced secondary power system for transport aircraft*, NASA Technical Paper 2463, 1985.
4. I. G. Hansen and G. R. Sundberg, *Space station 20 khz power management and distribution system*, In Conf. Rec. 1986 Power Electronics Specialist's Conference, Vancouver, Canada, June, 1986, pp. 676- 683.
5. P. K. Sood, *High Frequency Link Power Conversion System*, Ph.D Thesis, University of Wisconsin-Madison, January 1987.
6. S. K. Sul, and T. A. Lipo, *Design and test of bidirectional speed and torque control of induction machines operating from high frequency link converter*, NASA Report, Contract No.NAG 3-786, April 1988.
7. M. Kheraluwala and D. M. Divan, *Delta Modulation Strategies for Resonant Link Inverters*, Record of IEEE Power Electronics Specialists Conference, Blacksburg, Virginia, pp. 271-278, June 1987.
8. S. K. Sul, and T. A. Lipo, *Field oriented control of an induction machine in a high frequency link power system*, Conf. Record of IEEE Power Electronics Specialists Conference, Kyoto, Japan, April, 1988.