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Field Oriented Control of an Induction Machine in a High Frequency Link Power System

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ABSTRACT

In this paper a field oriented controlled induction machine drive operating with a high frequency single phase sinusoidal voltage link is presented. System performance is investigated by computer simulation and is verified by test on an actual prototype system. A novel control loop to minimize the link voltage fluctuation is proposed. The capability of rapid demagnetization of the induction machine by current regulation is investigated. A new current modulation technique, termed 'Mode Control', is proposed and its performance is compared with the conventional delta modulation technique.

INTRODUCTION

Static power converters for ac drives have traditionally employed a dc link as an interface between the fixed frequency power of the source and the variable frequency power of the load. The dc link is ideal for temporary energy storage since the energy storage can be easily accomplished at relatively low cost. However, the dc link has also several disadvantages. In particular, the "hard" switching of the power devices generates a high level of losses and device stresses which restricts the switching frequency to a few kHz, at most, when the power exceeds several tens of kilowatts The lower switching frequency results in poorer system response and reduced power densities. A switching frequency of a few kHz also results in troublesome audible and electrical noise.

Power density considerations are a particularly important aspect of avionic and space systems. In general, avionic systems use 400 Hz as the distribution frequency because of its higher power density compared to commercial 60/50 Hz. However, recent work has suggested the use of a 20 kHz single phase ac for avionic and space station power distribution [1,2]. Also, a new power converter topology and modulation technique to synthesize low frequency voltage and current from a 20 kHz link has been reported [3,4]. These new systems offer the potential for greatly improved power density by reducing the size of bulky transformers and by decreasing the heat sink requirements of the power converters.

In this paper a complete electro-mechanical energy conversion system operating with a high frequency link is investigated. The induction machine is selected as the electromechanical energy converter because of its ruggedness, low cost and capability for rapid demagnetization. The last point, demagnetization, is particularly important in the space station application, where rapid replacement or rewind is not practical and where reliability is a particular concern. In such an application the rotating magnetic field within the machine must be extinguished upon experiencing an internal fault. The induction machine is ideally suited to this requirement since the machine inherently looses excitation when the terminal voltages are reduced to zero.

In order to provide good torque control over a wide speed range, a field oriented control is typically embedded in the system. Instantaneous current regulation with indirect field orientated control also permits faster response for the demagnetization and protection from over-current conditions. The performance of field oriented control systems using instantaneous current regulation greatly depends on how accurately the actual machine current follows its reference. In conventional dc link systems the delta modulation technique is frequently used [5]. The delta modulation method has also been modified for use in zero voltage switching converters [3,4]. This control method, also termed *area comparison* pulse width modulation, uses the integral of the error to operate a comparator which, in turn, performs the appropriate switching of the converter switches. When current rather than voltage is the regulated variable, the integration function is inherently performed by the load inductance and the explicit integrator can be eliminated [6,7] When the ratio between the switching frequency and the synthesized output frequency is large or when the load inductance is sufficiently great, delta modulation is sufficient to guarantee good performance of the field oriented control. However, in other cases, for example when driving a low inductance 400 Hz induction machine, the performance of the delta modulator is not sufficient to guarantee good current regulation. In this paper, a new current modulation technique for zero voltage switching type converters which substanially improves the frequency response of the high frequency link converter is proposed and verified by experiment [8].

20 kHz SINGLE PHASE SOURCE

In an orbiting space station or avionic application, energy is typically stored in dc form so that one side of the 20 kHz link must be interfaced to a dc source. Hence, the 20 kHz link energy must initally be obtained from the dc source. There are several means to establish a 20 kHz single phase voltage bus from dc source. The most well known method is to utilize a Parallel Output Series Resonant (POSR) converter [9,10]. In this system the output frequency can be accurately maintained regardless of slight variations of the parameters of the resonant tank circuit. The output voltage can be regulated automatically within the expected range of the load variation. However, due to the high frequency switching in the presence of high voltage the switching loss is considerable. Also, substantial ac current circulates on the dc side. This additional current increases the stresses of all power semiconductors in the POSR converter.

Another possibility for converting dc power to 20 kHz is to utilize a single phase converter which has same topology as the converter used to synthesize three phase, low frequency from the 20 kHz link. Because the converter has a capability of bidirectional power flow, the 20 kHz link voltage link can be energized in controlled fashion by transfer of power from the dc side to the resonant tank.

The overall system under consideration in this paper is shown in Fig. 1. Note that each interface converter is equipped with a resonant tank. The series inductance in the high frequency link is the equivalent inductance of the 20 kHz link distribution line. Each switch is assumed to have bidirectional current flow and voltage blocking capability.

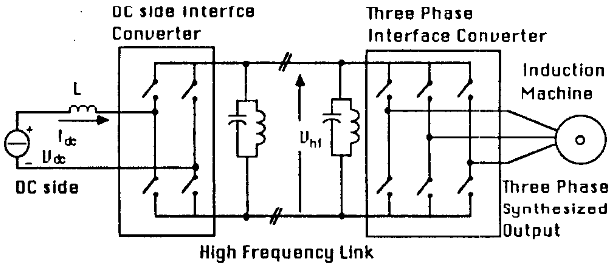

Fig. 1 Schematic of the system under consideration utilizing two interface converters and two resonant tank circuits.

Since the circuit is resonant, the ac link voltage must be regulated by means of a voltage regulator. The link voltage can be readily controlled by adjusting the dc side current , that is by regulating the power fed to the link tank circuit. The problem of link voltage regulation is addressed in another portion of this paper. It is clear that the link frequency is solely determined by the parameters of the tank circuit. A computer simulation illustrating voltage built-up and regulation of the ac link is shown in Fig. 2. The parameters of the link and converter are L_o=22.5 µh, C_o=3 µf, L=3 mh, V_{dc}=115 volts . Losses of the inductors are also included.

FIELD ORIENTED CONTROL

To demonstrate the feasibility of field oriented control with a 20 kHz sinusoidal high frequency link, the system shown in Fig. 3 has been simulated. In this simulation, the high frequency link is assumed to function as an ideal voltage source. Hence, the LC tank circuit and the effects of power flow to the resonant link are neglected. Typical starting and load torque transient responses are shown in Figs. 4.a and b. It should be noted that the machine side current synthesized from the high frequency link voltage is nearly sinusoidal and varies exactly according to the torque variations. The torque and speed responses also demonstrate very good performance.

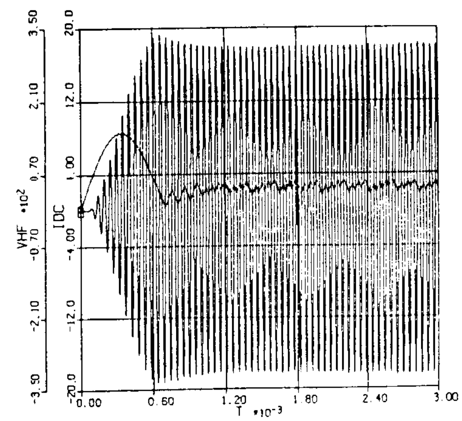

Fig. 2 Simulation results of high frequency link voltage build-up and regulation with three phase interface converter disabled. Traces show current in amperes and voltage in volts.

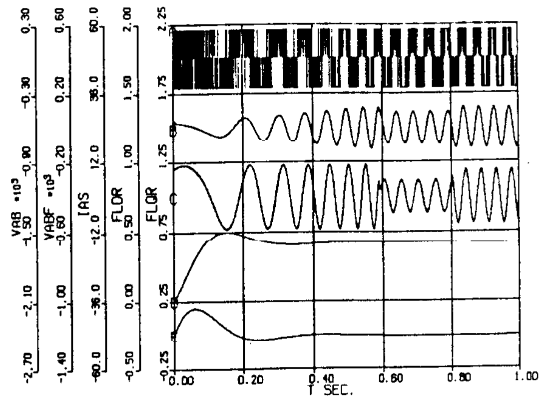

Fig. 4.a Response during starting and with load torque transient using high frequency link interface converter fed field oriented controlled induction machine. Traces: line voltage and filtered line voltage in volts, line current in amperes, rotor flux d- q- axis component in webers in synchronously rotating reference frame.

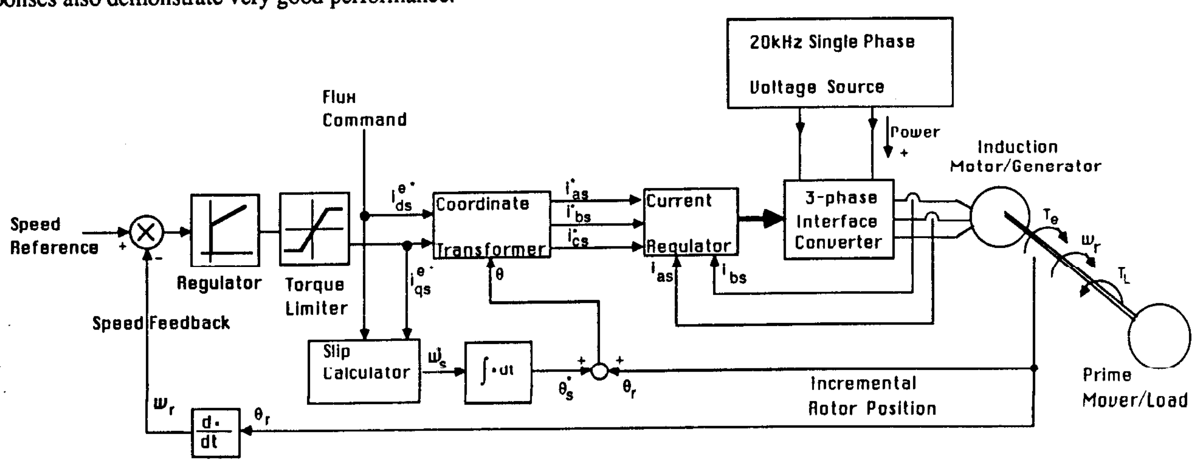

Fig. 3 Control block diagram of field oriented control induction machine drive system utilizing a high frequency source.

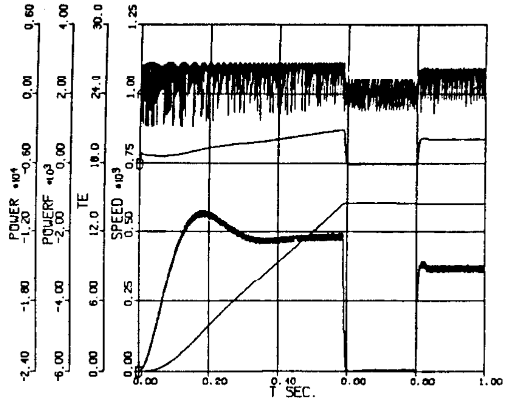

Fig. 4.b Response of system during starting and with load torque transient using high frequency interface converter fed field oriented controlled induction machine. Traces: input power to interface converter and filtered input power in watts, machine torque in nt-m, speed in rpm and slip angular velocity in rad./sec.

One important aspect of the circuit behavior is the response of the input power entering the interface converter. It can be noted that the instantaneous power at this point varies very widely and even changes its sign although its filtered value indicates no negative values. Because the converter is switched according to the error between the reference current and actual current, it is clear that the power may be negative during a certain switching instant even though the average power remains positive.

The response of demagnetization control is shown in Fig. 5. Demagnetization of the induction machine is achieved within a few cycles after the command is initiated without presence voltage spikes. For all of the above simulations the parameters of a 3 hp, 4 pole, and 60 hz induction machine has been used.

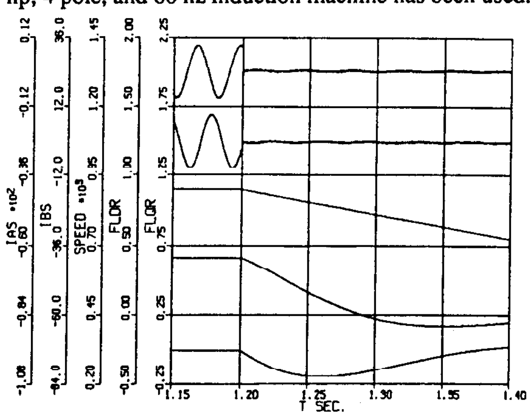

Fig. 5 Response of high frequency link interface converter fed, field oriented controlled induction machine during demagnetization. Traces: A phase and B phase line current in amperes, speed in rpm, rotor flux d- and q-axis components in webers

VOLTAGE REGULATION

It is clear that the instantaneous power variation mentioned in the previous section results in a link voltage variation unless the variation in power is matched perfectly by the other converter and source in the same link. However, the number of switching modes of the dc side interface converter is only three while that of the machine side interface converter is seven. Moreover, the rate at which the dc source power can change is determined by the dc source voltage, high frequency link voltage, and dc source filter inductance. Hence, power matching control on an instantaneous basis does not appear to be possible. At best, with an ideal controller, average power matching can be achieved. Hence, the ripple power must be handled by the tank circuit at the cost of the link voltage variation. With an well designed average power matching controller, however, the link voltage variation can be minimized.

The simplest approach for obtaining average power information is to measure the power supplied to the induction machine and use a low pass filter, as shown in Fig. 6. However, with this method time delays resulting from the low pass filter is 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. To lessen this problem, a voltage regulation loop which generates a current reference from the link voltage error can be added to the power matching loop as a minor loop. The simulation results of this controller are shown in Figs. 7.a and b.

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 control algorithm used to control the induction machine [9]. If the current regulation is perfect and if the machine parameters do not change and are known, the average machine

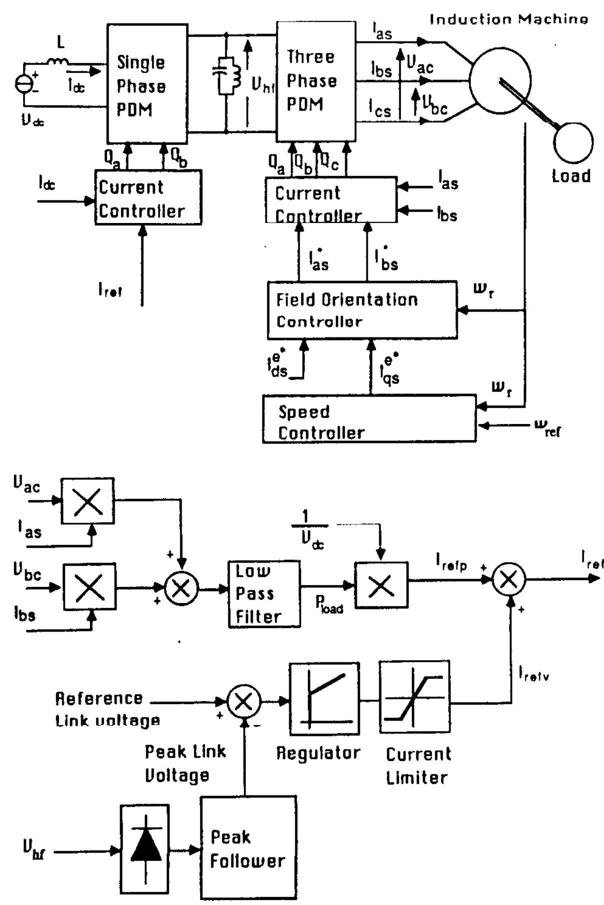

Fig. 6 System control block diagram and controller utilizing power measurement and filtering.

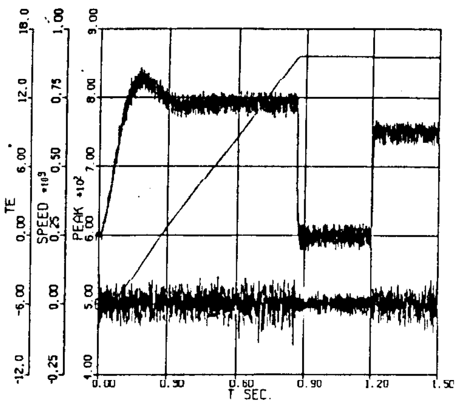

Fig. 7.a Response of voltage controller with power measurement. Traces: Electromagnetic torque in nt-m, speed in rpm, and peak voltage of the high frequency link in volts.

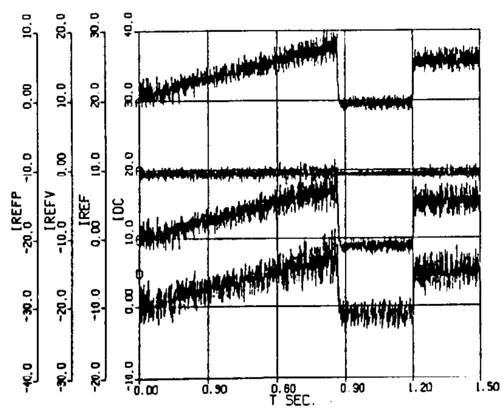

Fig. 7 b Response of voltage controller with power measurement. Traces show: component of reference current for power matching in amperes, component of reference current for voltage regulation in amperes, reference current in amperes, and dc source current in amperes.

power can be estimated without any time delay. 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 as in the previous method. The block diagram of this controller is shown in Fig. 8 and the corresponding simulation results are given in Fig. 9.a and b.

In this simulation the value of power which is used for average power matching is 90% of the exact value. In order to allow for an error in the estimation, an intentional 10% estimation error is made. From Fig. 9.a, it can be observed that the torque and speed responses are nearly the same as using actual power measurement. For the purpose of evaluating the regulation capability of the various controller it is usefull to define the error criterion

$$\text{Criterion} = \int^{T} (V_{ref} - V_{hf\,peak})^2\, dt\,,$$

where T is the simulation interval.

The criterion value of the former power measurement controller is 222 while the result using power estimation is 190.

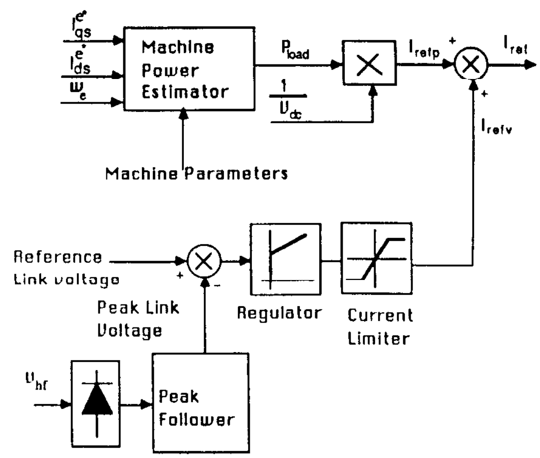

Fig. 8 Controller block diagram utilizing power estimation.

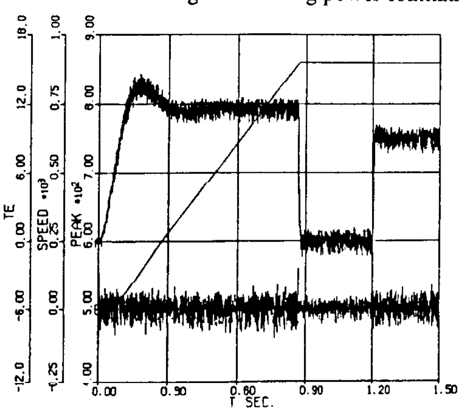

Fig. 9.a Response of voltage controller utilizing power estimation. Traces: electromagnetic torque in nt-m, speed in rpm, and peak voltage of the high frequency link in volts.

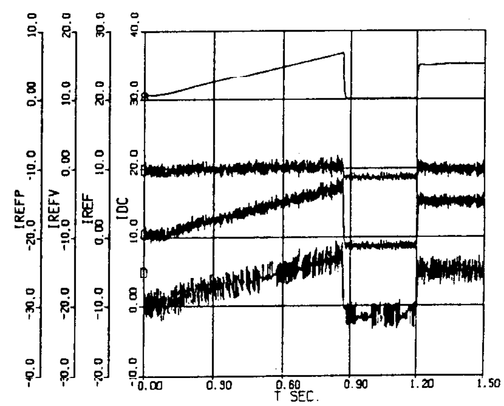

Fig. 9.b Response of voltage controller employing power estimation Computer traces: component of reference current for power matching in amperes, component of reference current for voltage regulation in amperes, reference current in amperes, and dc source current in amperes.

Hence, the regulation of this controller is better regardless of the 10% estimation error. Note that the component of the reference current for average power matching shown in Fig. 9.b contains no ripples since it comes from the estimated power. The component derived from the minor voltage regulation loop has some ripple. However, the ripple in the reference current is smaller than that of previous case. Therefore, the ripples in actual current in dc source is less severe In the actual implementation, reduced ripple in the actual current has many advantages such as lower losses in power components, lower current rating of power components and easier protection of system. It is important to mention that while the power estimation method has superior response, it is also easier to implement since it requires no additional power measurement.

CURRENT REGULATION

The regulation of the induction machine side current is crucial for satisfactory performance of current regulated field oriented control. If the ratio between switching frequency and output frequency is large, or if the load inductance is substantial, then the simple delta modulator is sufficient to obtain reasonable performance. However, in aerospace appications, control of a 400 Hz induction machine is frequently required. Figure 10 depicts a new *mode controller* which is specifically designed to obtain optimum performace from a high frequency link. In almost kind of resonant converter which uses a zero voltage or zero current switching scheme, the switching instant and pulse duration is given. Hence, the problem of current modulation reduces to finding the next optimal combination of switch states at the every 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 pattern can be selected which minimizes a specified error function. If current regulation only is required, the error function may be the sum of the absolute current regulation errors of each phase or the sum of the square of the individual errors. This error function can be extended to any form which satisfies a specific demand. For example, to obtain improved voltage regulation, it may be useful to include a term which depends upon the instantaneous power variation.

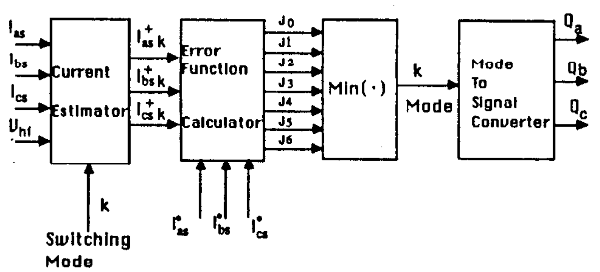

Fig. 10 Block diagram of mode controller for current regulation.

The performance of the mode controller is compared with delta modulation can be evaluated by computer simulation. The results are shown in Figs. 11 and 12. In these simulations a 400 Hz, 7.5 Hp, 4 pole induction machine is considered and the 20 kHz link is again assumed as an ideal single phase voltage source. To compare the regulation following criterion has also been calculated for each case.

$$\text{Criterion} = \int^{T} (i_{as} - i_{aref})^2 + (i_{bs} - i_{bref})^2 + (i_{cs} - i_{cref})^2\, dt$$

The value for delta modulation and for the mode controller corresponding to Figs. 11 and 12 are 0.2297 and 0.1081 respectively. It appears the mode controller offer substantial improvements in the current regulation over the delta modulator. The drawback of this controller is that it requires numerous mathematical operations which are difficult to accomplish in real time so that the controller becomes much more complex than other controllers.

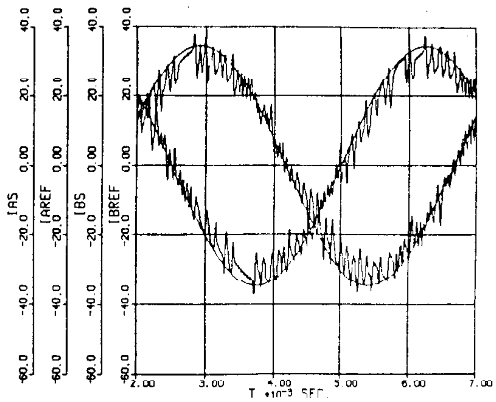

Fig. 11 Response of current regulator employing delta modulator. Traces: A phase and B phase line currents and reference currents in amperes

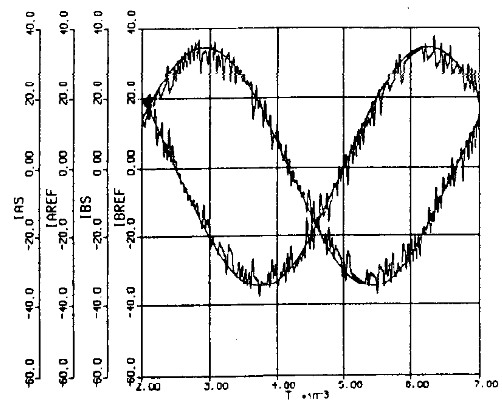

Fig. 12 Response of current regulator employing mode controller. Traces: A phase and B phase line currents and reference currents in amperes.

EXPERIMENTAL RESULTS

The high frequency link motor drive which was studied by means of simulation has been constructed and test in the laboratory. In particular, the complete system of Fig. 2 has been constructed together with an indirect field oriented controller (Fig. 3) voltage regulator (Fig.8) and mode control current regulator (Fig. 10).

Voltage Build-up.

The experimental result during controlled voltage build-up is shown in Fig. 13. A smooth, controlled build-up can be observed which agrees well with the simulation results shown in Fig. 2. It can be noted that during the steady state, the current which supplies the loss of the system continues to flow from the dc source.

Dynamic Performance of Field Oriented Control

The test results illustrating performace of the field oriented controller is shown in Fig. 14 a and again appear similar to the simulation results except in time scale. The difference of the time scale is mainly due to the difference of the inertia of the mechanical system. In the simulation the small inertia was considered to save simulation time. In the test drive, a 7.5 kw dc machine and pulley was coupled to the induction machine. Also in the experiment, the difference in deceleration and acceleration is due to the difference of the friction constant of the dc machine which depends on the direction of rotation. The

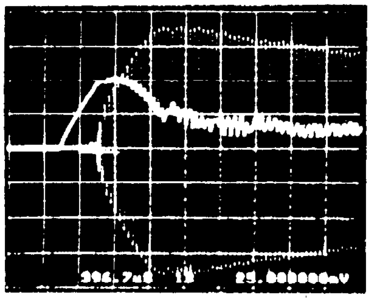

Fig. 13 Experimental waveforms of high frequency link voltage and dc source current during voltage build-up. Traces: high frequency link voltage: 120 volts/div., dc source current; 5 A/div., time scale: 396.7 µsec/div.

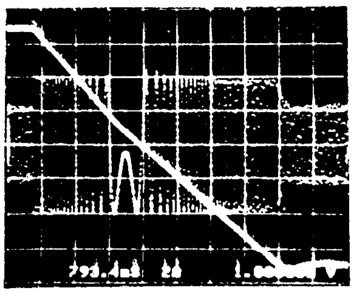

Fig. 14.a Speed reversal performance of induction machine using field oriented controller. Speed: 190 rpm/div., reference: 4 div. from the bottom., A phase current: 5 A/div., time scale: 793.4 ms/div.

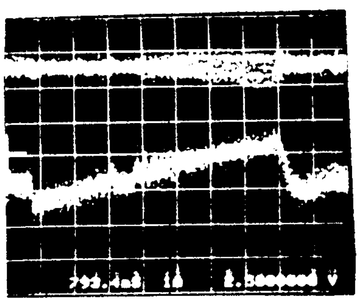

Fig. 14.b Experimental waveforms corresponding to Fig. 14a. Top trace: peak voltage: 130 volts/div., reference: 4 div. from the bottom. Bottom trace: dc source current: 5 A/div., reference: 3 div. from the bottom. Time scale: 793.4 ms/div.

trace of the A phase current reveals good current regulation. In this test the delta modulator is used as the current regulator. In Fig. 14.b, the waveforms of the dc side current and the peak of the high frequency link voltage are shown. The dc current varies according to the mechanical power to produce a power balance. The trace corresponding to the peak of the link voltage shows reasonably good voltage regulation.

Demagnetization

The waveforms of A phase current of the induction machine during demagnetization is shown in Fig. 15. Note that the current is brought to zero within 500 µsec. The line to line voltage at the command remain negative to decrease the current. The figures clearly demonstrates very fast extinction of the machine current without any voltage spikes (i.e high di/dt).

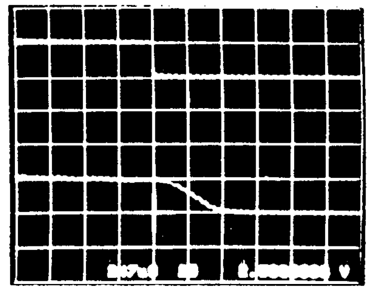

Fig. 15 a Measured waveforms during rapid demagnetization. Top trace: demagnetizatoin command. Bottom trace: A phase induction machine current; Scale; 5 A/div., Time scale; 247 µs/div.

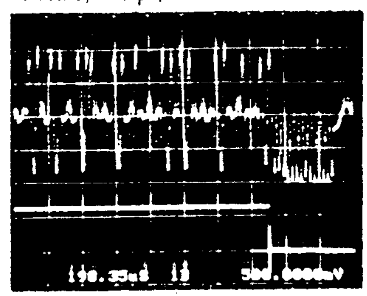

Fig. 15 b Waveforms during rapid demagnetization Top trace: induction machine AB line to line voltage. Scale: 200 volts/div., bottom trace: demagnetization command, time scale: 198.35 µs/div.

Power Estimation Controller

The behavior of the power estimation controller is clearly shown in Fig. 16. With the starting of the induction machine the reference current from estimated power gradually increased, and after settling of the speed, the current decreased to small value to supply only the loss 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 dc source reference current come from power estimator. The experimental results shows good agreement with simulation results which were given in Fig. 9.

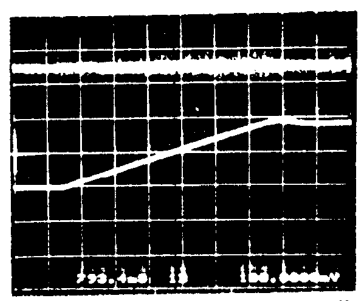

Fig. 16 a Operation of power estimation controller. Top trace: peak ac voltage, scale; 130 volts/div. Reference is 4 div. from the bottom. Bottom trace: induction motor mechanical speed; 190 rpm/div. Reference is 3 div. from the bottom. Time scale: 793.4 ms/div.

Current Regulation

Current regulation capability of the delta modulator is shown in Fig. 17. In this case a 13 Hz is synthesized with 3 hp,60 hz, pole induction machine load. It is apparent that the

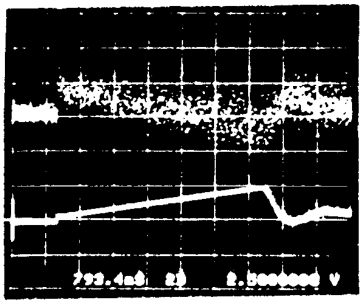

Fig. 16 b Operation of power estimation controller. Top trace: dc source current reference from voltage controller (I_{refv}), scale: 1.5 A/div. Zero reference 5 div. from the bottom. Bottom trace: reference current from power estimator (I_{refp}); scale: 5 A/div. Reference is 2 div. from the bottom. Time scale: 793.4 ms/div.

result is nearly perfect, so that if the mode controller were used there would be no noticeable difference. In order to better compare the delta modulator and the mode controller a 1 mh, 3 phase, Y connected inductor load was used in place of the induction motor and a 450 Hz synthesized from 20 kHz link. The results for the two current controllers are shown in Fig. 18. It is clear from the figures that the mode controller shows smaller ripple content and therefore improved tracking of the current command.

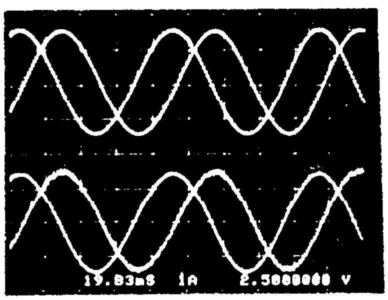

Fig. 17 Synthesis of 13 Hz currents using delta modulation. Top trace: A and B phase reference current, scale: 5 A/div. Bottom trace: Corresponding measured motor current, scale: 5 A/div. Time scale: 19.83 msec/div.

CONCLUSIONS

In this study the application of field oriented control to a high frequency resonant link system has been considered. The following results have been obtained.

1. A current regulated field oriented controller can be success-fully applied to high frequency link induction machine drive system. The response of the system is comparable or even exceeds more conventional current regulated PWM systems.
2. The excitation field of the induction machine can be readily eliminated within a few cycles by simply commanding the reference current to zero.
3. By use of power estimation control, high frequency ac link voltage fluctuations can be substantially reduced thereby reducing voltage blocking requirements of the converter switches.
4. Study of mode control for the synthesis of ac current reveals that substantial improvement in the current regulation capability is possible compared to delta modulation when synthesizing high frequency waveforms.

ACKNOWLEDGMENTS

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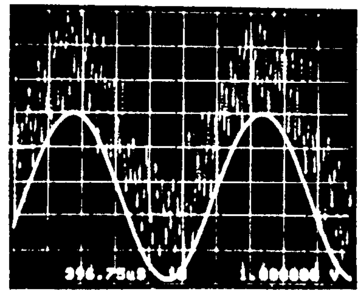

Fig. 18 a Current waveform synthesis of 450 Hz showing A phase actual current and corresponding reference using delta modulation. Magnitude: 2.5 A/div. Time scale: 396.75 µsec/div.

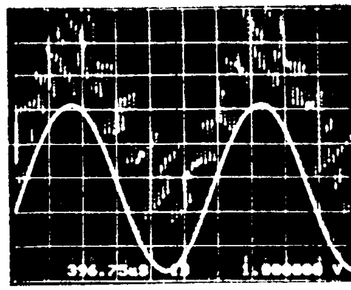

Fig. 18 b Current waveform synthesis of 450 Hz showing A phase actual current and corresponding reference using mode controller. Magnitude: 2.5 A/div. Time scale: 396.75 µsec/div.

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