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Improving Reliability of Induction Motor Drives by Means of Fast Acting Current Regulation

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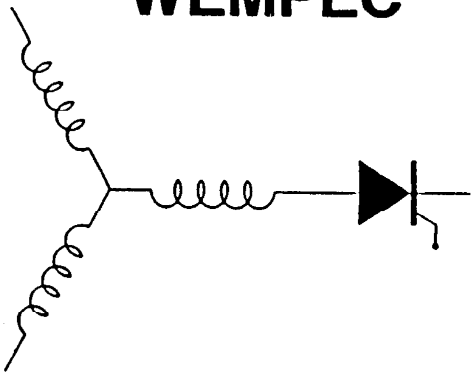

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IMPROVING RELIABILITY OF INDUCTION MOTOR DRIVES BY MEANS OF FAST ACTING CURRENT REGULATION

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I. INTRODUCTION

In the past several decades remarkable progress has been made in the development of AC motor drives using both hard switched dc link and resonant-link schemes which utilize high speed switching devices such as fast recovery bi-polar junction transistors, insulated gate bi-polar transistors (IGBTs) and GTOs. Also, control strategies, particularly field oriented control strategies, have greatly improved the performance of AC motor drives. These control strategies utilize almost exclusively current regulated pulse width modulated (CRPWM) switching strategies that exploit the low switching loss capability of these converters and seek to produce a precisely controlled current to the windings of the motor.

While current regulation and field oriented control has greatly improved the torque response of ac drives, the use of this principle as a means of avoiding problems during system faults is relatively unappreciated. One of the most common types of faults, is the loss of a transistor in one of the legs of the inverter, or alternatively, the loss of one of the phases of the motor. In this case one of the motor phases is suddenly open circuited, essentially single phasing the motor, resulting in a loss of field orientation and in high pulsating torques. Braking of the motor is then typically initiated by using one of the following strategies: 1) friction braking, 2) dc current injection into the stator of the machine, 3) capacitive self-excitation braking or 4) magnetic braking by shorting two or three stator leads [1-3] or combinations of these braking schemes. In all cases, these strategies involve expensive mechanical devices such as friction brakes or mechanical contactors to initiate the braking process. Reliability can also be improved by increasing the number of motor phases [4]. However, the advantages of using improved control strategies with such machines has apparently not been reported.

Another common occurrence is the shorting of one or more turns or coils making up one of the phase within the machine. In this case, the heat generated within the machine rapidly. Detection of this problem becomes the major issue since continued operation under such a situation can rapidly lead to destruction of the machine itself. In this paper several strategies are discussed which could be used to help alleviate these problems.

II. CENTER TAPPED DC LINK

One topology that can eliminate the cost and complications arising during emergency braking due to failure of an inverter switch is shown in Fig. 1 [5]. It can be noted, that this topology differs from the standard ac drive topology only in that the neutral point of the motor is returned to the mid point on the dc voltage link. The mid point is created by simply splitting the capacitor bank into two equal sections. During normal operation the stator current is regulated in normal PWM fashion by the field oriented controller. In this case, the current flowing in the neutral of the machine, connected to the mid point of the dc link, is essentially zero with possibly a very small current flowing due to PWM operation of the inverter. In the event that a transistor fails open in the inverter, however, a new current control strategy can be initiated by the converter which preserves the torque at its original value, or changes the torque to any desired value while eliminating the negative pulsating torque usually associated with operation with an open phase.

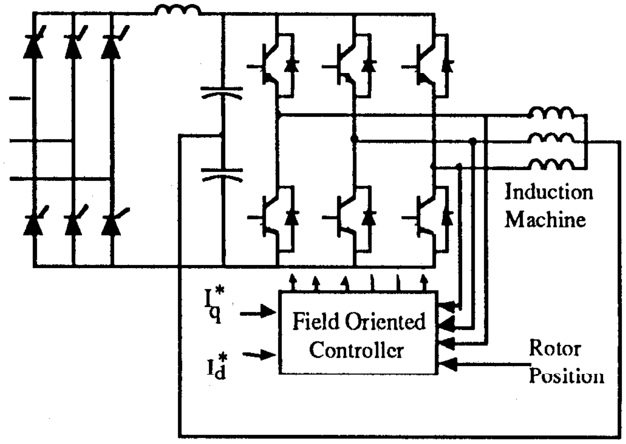


Fig. 1 Induction motor drive with machine neutral fed back to dc bus mid point.

In order to illustrate the concept for control during a single phase open circuit, it is useful to employ the principle of space phasors [6]. Assume that at "t=0⁻" all three phases are excited normally and the current space phasor is located as shown in Fig. 2.

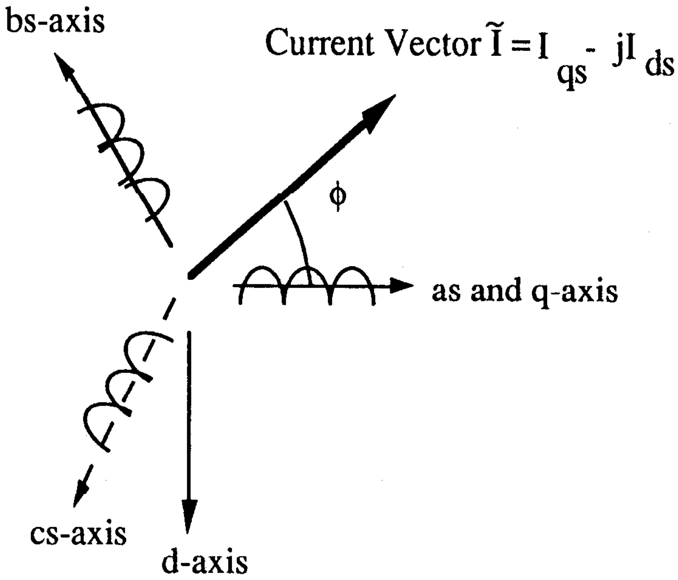


Fig. 2 Orientation of the current space vector just before one phase is open circuited.

It is assumed that before any phase is open circuited, the currents feeding the induction motor are regulated to be three balanced positive sequence sinusoidal currents, i.e.,

$$I_{as} = I \cos(\omega t + \phi)$$

$$I_{bs} = I \cos(\omega t + \phi - 2\pi/3)$$

$$I_{cs} = I \cos(\omega t + \phi + 2\pi/3) \quad (1)$$

The rotating MMF generated by the armature currents is the sum of the MMFs caused by each of the three phases. Based on the three axes shown in Fig. 2, this MMF can be expressed by the complex vector,

$$\begin{aligned} MMF &= MMF_a + MMF_b + MMF_c \\ &= N I_{as} + a N I_{bs} + a^2 N I_{cs} \quad (2) \end{aligned}$$

where $a = 1\angle 120°$ and N is the effective number of stator turns per phase.

For balanced three phase operation

$$\mathrm{MMF} = \frac{3}{2} F e^{j\theta} \tag{3}$$

$$= \frac{3}{2} F (\cos\theta + j \sin\theta) \tag{4}$$

where $F = N I$ and $\theta = (\omega t + \phi)$

Assume that at any time t, the current in phase b suddenly drops to zero. In this case, the rotating MMF will be the sum of MMF_a and MMF_c only, i.e.,

$$\mathrm{MMF}' = N I'_{as} + a^2 N I'_{cs}$$

$$= N I'_{as} + N I'_{cs} \left(-\frac{1}{2} - j\frac{\sqrt{3}}{2}\right) \tag{5}$$

where the prime indicates the new values of each variable after one phase is open circuited.

The same MMF is maintained after phase b is open circuited by setting (4) equal to (5) and then solving for real and imaginary parts separately,

$$\frac{3}{2} F \cos\theta = N I'_{as} - \frac{1}{2} N I'_{cs} \tag{6}$$

$$\frac{3}{2} F \sin\theta = -\frac{\sqrt{3}}{2} N I'_{cs} \tag{7}$$

From these two equations, it can be determined that

or, equivalently,

$$I'_{as} = \sqrt{3}\, I \cos(\omega t + \phi + \pi/6)$$

$$I'_{cs} = \sqrt{3}\, I \cos(\omega t + \phi + \pi/2) \tag{8}$$

Hence, if phase b is open circuited, "disturbanceless" control is possible if phase a current is regulated to jump forward by 30° and phase c current regulated to jump backward 30°. Both phase a and phase c current magnitude must also be increased to $\sqrt{3}$ times their previous value. Figure 3 shows the phasor relationships before and after phase b is suddenly open circuited.

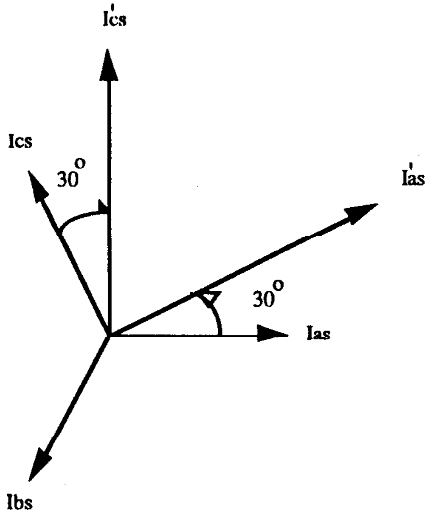


Fig. 3 Phasor relationships before and after phase b is open circuited.

The same analysis can be applied to the cases of phase a or phase b being open circuited. If phase a is open circuited, then control of the remaining two currents after the open circuit should be,

$$I'_{bs} = \sqrt{3}\, I \cos(\omega t + \phi - 5\pi/6) \tag{10}$$

$$I'_{cs} = \sqrt{3}\, I \cos(\omega t + \phi + 5\pi/6) \tag{11}$$

If phase c is open circuited

$$I'_{as} = \sqrt{3}\, I \cos(\omega t + \phi - \pi/6) \tag{12}$$

$$I'_{bs} = \sqrt{3}\, I \cos(\omega t + \phi - \pi/2) \tag{13}$$

To verify the above relationships a suitably modified field oriented controlled induction motor was implemented in hardware. In this model, indirect field orientation was employed based on the slip relationship for field orientation [5]

$$s\,\omega_e = \frac{R_r}{L_r}\frac{I_{qs}}{I_{ds}} \tag{14}$$

A speed control loop with a PI controller is used to control the motor speed. The PI controller compares the preset speed setting to the rotor speed signal and generates a torque command, i.e. I_{qs}*. The flux command I_{ds}* is assumed to be constant in the simulation. The field angle θ_{rf}, which is required to transform the *d-q* axis commands to *a-b-c* axis commands, is generated by summing the rotor position signal and the slip position signal. The rotor position signal is obtained directly from the integration of the rotor speed. Using the calculated value of θ_{rf}, the current commands in the *d-q* axis I_{qs}* and I_{ds}* are transformed to current commands in the *a-b-c* axis I_{as}*, I_{bs}* and I_{cs}*. The commanded currents I_{as}*, I_{bs}* and I_{cs}* are then compared to the motor stator currents I_{as}, I_{bs} and I_{cs} which are generated from the dynamic model of the induction motor. Three current regulated delta modulators operated under a specified sampling frequency are used to generate the switching pattern for each phase. These switching patterns are then used to control the switches of the current regulated PWM inverter. The overall control block diagram is shown in Fig. 4.

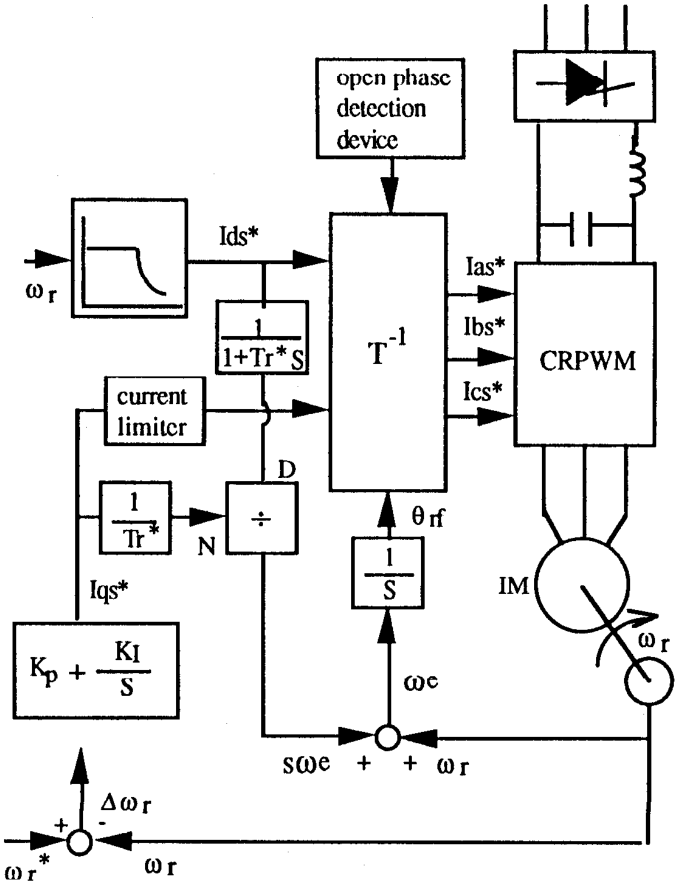


Fig. 4 System control block diagram incorporating open circuit contingency control.

It is clear that the controller of the proposed system can readily take advantage of today's digital signal processing technology. The digital controller and summation provides not only a highly accurate but also drift free control. The three control schemes required for the different open circuit operations can be pre-programmed and stored in the memory of the digital signal processor. The main program is then interrupted to execute the contingency control as soon as an open circuit signal is detected.

For proper two phase operation, it is apparent that the capacitor midpoint voltage should be maintained at one half of the dc bus voltage. To prevent the capacitor midpoint voltage from drifting from this desired voltage, the capacitor neutral point can be regulated as shown in Fig. 5. The resistor placed across the two dc link capacitors are relatively large, having negligible losses and help stabilize drift in the capacitors. They could be omitted with good regulation of the bus capacitors.

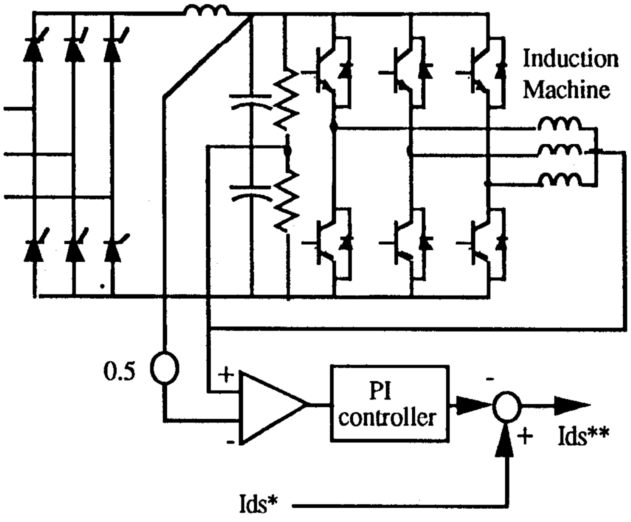
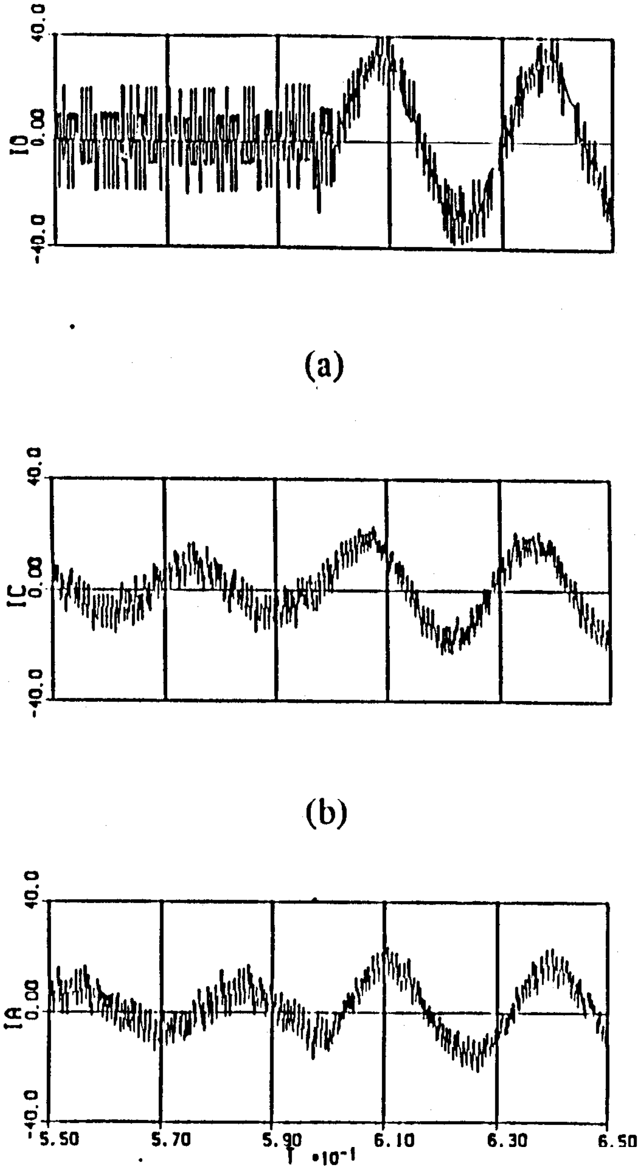


Fig. 5 Flux command control method.

Both the simulation and actual hardware tests of sudden open circuits have been implemented. In all cases, one phase current is assumed to drop to zero suddenly while the remaining two phases are regulated to the new magnitude and phase angles which are required to maintain the MMF as unaffected as discussed in section II. Figures 6 and 7 are the simulation results for the case where phase b is suddenly open circuited.



(a)

(b)

(c)

Fig. 6 Computer simulation of current variation after phase b is open circuited (a) neutral current I_{os}, (b) phase c current I_{cs}, (c) phase a current I_{as}.

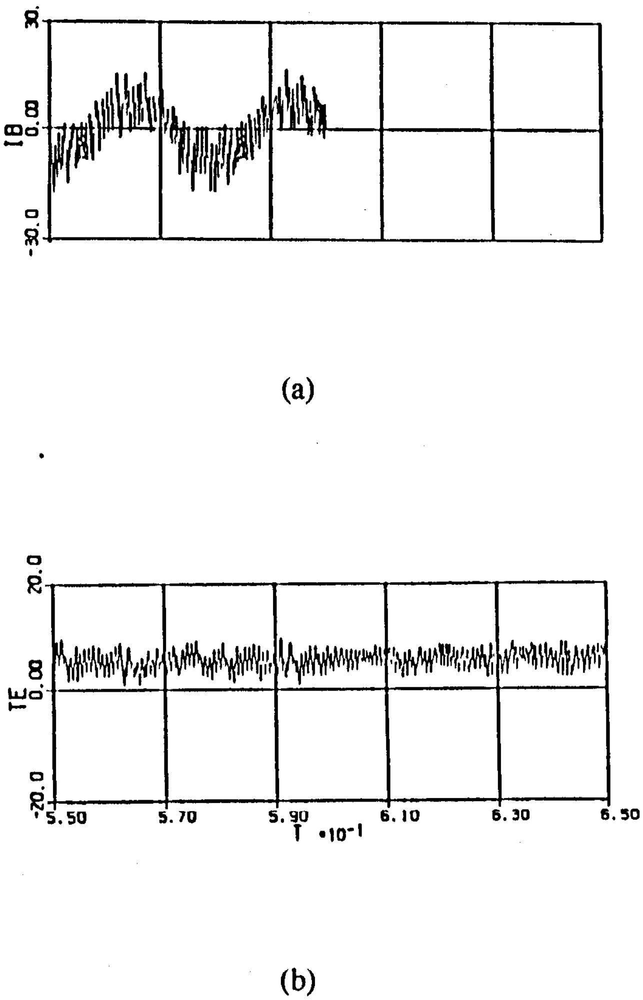


Fig. 7 Computer simulation of torque variation after phase b is open circuited, (a) phase b current I_{bs} (b) Electromagnetic Torque.

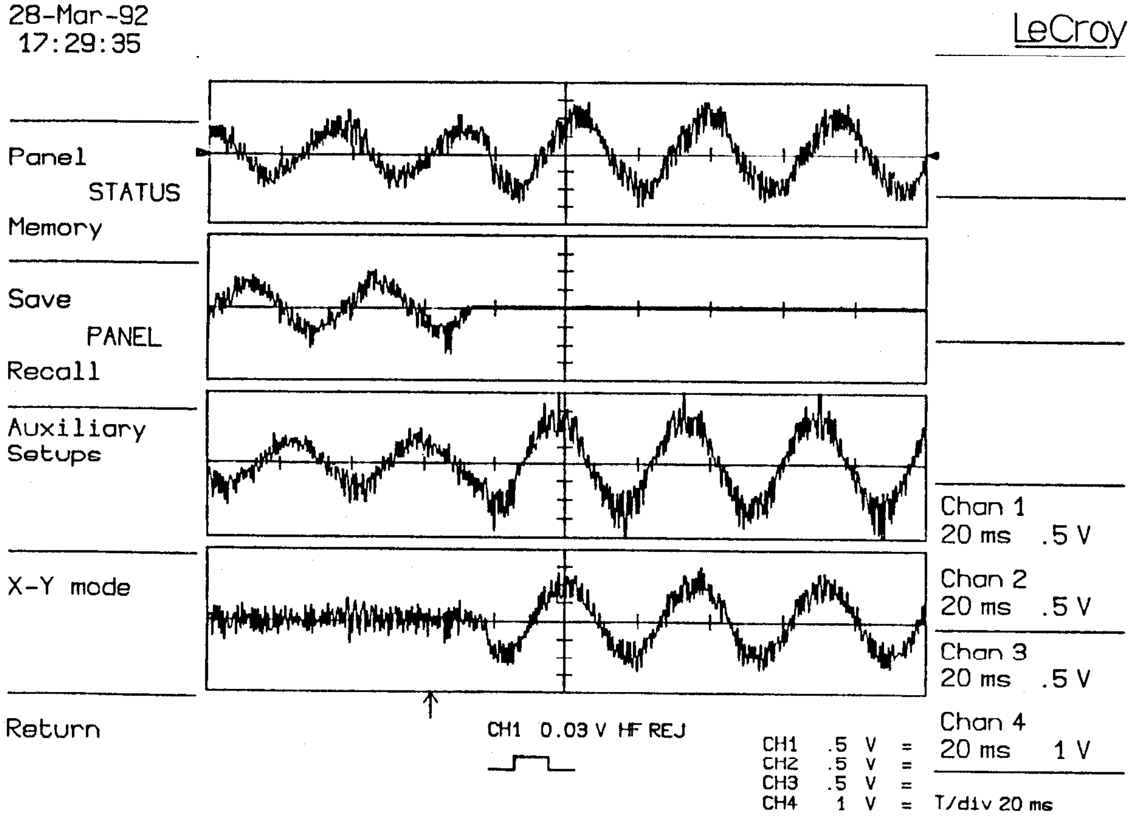


Fig. 8 Current waveforms of actual system during loss of a phase. a) phase current a, b) phase current b, c) phase current c, d) motor neutral current.

Note from Fig. 6 that under this type of unbalanced operation, the neutral current I_{os} is no longer zero. Instead, it becomes the sum of I_{as} and I_{cs} and is 3 times the value of the original line current which existed before the open circuit. From Fig. 7 it can be noted that although the phase b current drops to zero at t = 0.6 sec the torque remains almost unaffected.

In order to verify the theory associated with operation with an open phase, the control strategy outlined in Figs. 4 and 5 has also been implemented in hardware. Figure 8 shows the results for the experimental system in which phase b is suddenly open circuited by suddenly turning off the switches of the phase. As substantial flow of high frequency current in the motor neutral can be observed before the open circuit occurs. Clearly, this current can be reduced by either increasing the modulation frequency or by increased the zero sequence inductance either by motor design or by physically inserting a small inductor in the motor neutral. In the practical system, the PWM frequency was limited at about 5 kHz.

The problem of additional motor losses due to neutral current under normal operation can be essentially eliminated by alternatively connecting a triac (or its equivalent) between capacitor midpoint and the motor neutral point. During normal operation, the triac is blocked, so no current will flow to unbalance the charge to the capacitors. The triac is only triggered "on" when a one phase open signal is detected and two phase operation is required. Figure 9 shows a sketch of this control method.

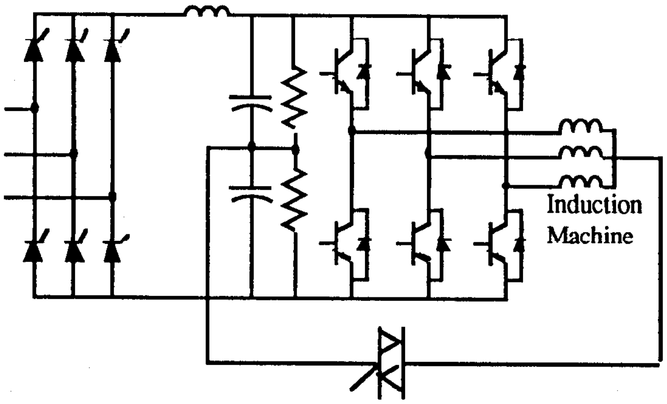


Fig. 9 Use of a triac to block the neutral current during normal operation.

III. FIVE PHASE INDUCTION MOTOR DRIVE

The problems associated with operating with an open phase can also be addressed by considering a machine with a number of phases greater than three. Figure 10 shows an example of an induction motor drive in which the machine has five rather than three phases. In this case the MMF in the machine can be depicted by the equation

$$MMF = NI_a + aNI_b + a^2NI_c + a^3NI_d + a^4NI_e \tag{15}$$

where, in this case $a = 1\angle 72°$. It is readily shown that if the five currents form a balanced, positively rotating set then, under normal balanced operation

$$\mathrm{MMF} = \frac{5NI}{2} e^{j\theta} \tag{16}$$

where $\theta = \omega t + \phi$. Assuming that phase a suddenly becomes open circuited, then after the open circuit the real and imaginary parts of Eq. 16 are

$$\frac{5NI}{2} \cos\theta = N(I_b' + I_e') \cos 72° - N(I_c' + I_d') \cos 36° \tag{17}$$

$$\frac{5NI}{2} \sin\theta = N(I_b' - I_e') \sin 72° + N(I_c' - I_d') \sin 36° \tag{18}$$

In order to eliminate the two degrees of freedom remaining in Eqs. 17 and 18 it is useful to assume that

$$I_b' = -I_d' \tag{19}$$

$$I_c' = -I_e' \tag{20}$$

whereupon, it can be determined that

$$I_b' = -I_d' = \frac{5I}{4}\left(\frac{\sin\theta}{\sin 72° + \sin 36°} + \frac{\cos\theta}{\cos 72° + \cos 36°}\right)$$

$$= 1.38I \cos(\omega t + \phi + 36°) \tag{21}$$

$$I_c' = -I_e' = \frac{5I}{4}\left(\frac{\sin\theta}{\sin 72° + \sin 36°} - \frac{\cos\theta}{\cos 72° + \cos 36°}\right)$$

$$= 1.38I \cos(\omega t + \phi - 36°) \tag{22}$$

Hence, if an open circuit occurs with a five phase machine the current in the remaining four phases can be used to control the torque the machine without the presence of a negative sequence or zero sequence current. In this case the current amplitude of the healthy phases need be increased to a value only 38% greater than when all five phases are functional. Similar control algorithms can be readily worked out for an open circuit in any of the other four motor phases or for the case of a six, seven, eight, etc. phase machine.

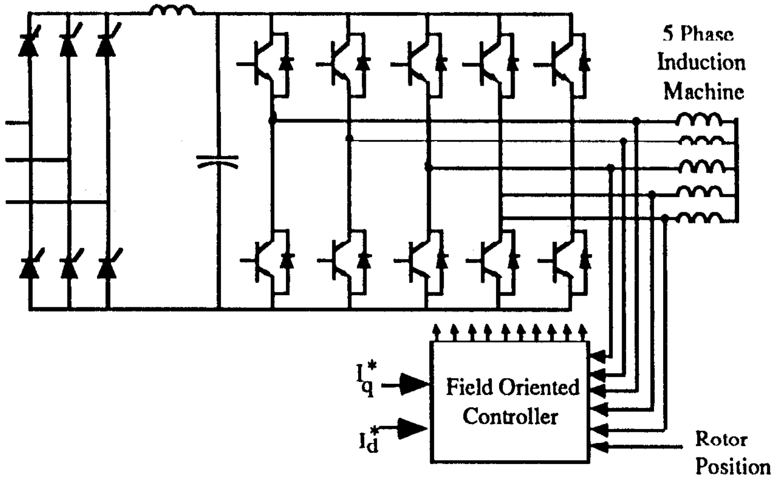


Fig. 10 Five phase current regulated PWM inverter drive.

IV DETECTION OF A PARTIALLY SHORT CIRCUITED MOTOR PHASE

While the problem of open circuits occurs more frequently, short circuits also occur with regularity. Since short circuits are destructive in nature, a rapid method of detection and scheme for corrective action is necessary. When short circuits of the inverter occur, failure to interrupt the current in a few milliseconds results in subsequent short circuit of an inverter leg which quickly produces an open circuit of one motor phase by destruction of the two switching devices in the leg. As described previously, operation can then continue indefinitely on the remaining phases with proper control.

The problem of short circuits in the motor windings is much more difficult from the point of view of protection. Clearly when an entire motor phase is shorted, the rapid increase in current in the guilty phase can be readily detected if the motor is fed from a voltage controlled PWM. However, when current regulation is being utilized for field oriented control the current will remain equal to the commanded values which could now cause potentially destructive torque pulsations. In this case the line to line voltages can be monitored to readily determine the presence of such a short circuit.

Internal faults within the motor, however, occur with the same frequency and are much more difficult to detect. These faults generally begin as turn to turn failures which generate a destructive amount of localized heat and therefore slowly degenerate into the failure of a complete coil or even a phase belt. The same method can be used to determine the presence of such failures however, the detection using phase voltages is much more difficult.

Figure 11 shows a new approach to detecting motor short circuits in which the motor phases are briefly open circuited during each zero crossing. In this case the open circuit voltage representing the induced emf in the phase is monitored and slight unbalances between phases reported to the master controller. Figure 12 shows simulation traces illustrating the concept. In Fig. 12a the current in one of the motor phase is shown and it can be noted that a small zero current interval is provided by simply delaying the arrival of the firing pulse to the reverse conduction transistor by several electrical degrees. At this instant, the voltage across the motor phase is sampled as shown in Fig. 12b. It is important to note that the emf voltage detected remains essentially sinusoidal due to the damping effect of the squirrel cage rotor currents. In practice, it is clear that the detection scheme need operated only periodically (e.g. every few minutes) so that the long term losses in the machine will not be substantially affected.

While Fig. 12 illustrates detection of the fault using line to neutral voltages, equivalent information can clearly be obtained by sensing the voltages across the inverter switches. In some cases this method may be preferred since the motor neutral is often not available (e.g. in a delta connected machine). However, this approach requires additional processing of the data. Since unbalances of only a few percent can be readily determined, detection of the short of a single turn is possible for most machines having a single series circuit connection. However, the detection of machine having several parallel circuits is clearly more difficult and research is continuing on detection schemes for such connections.

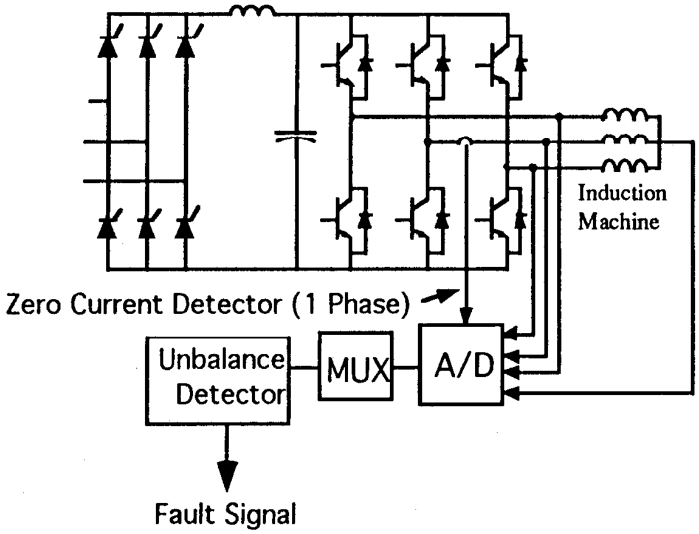
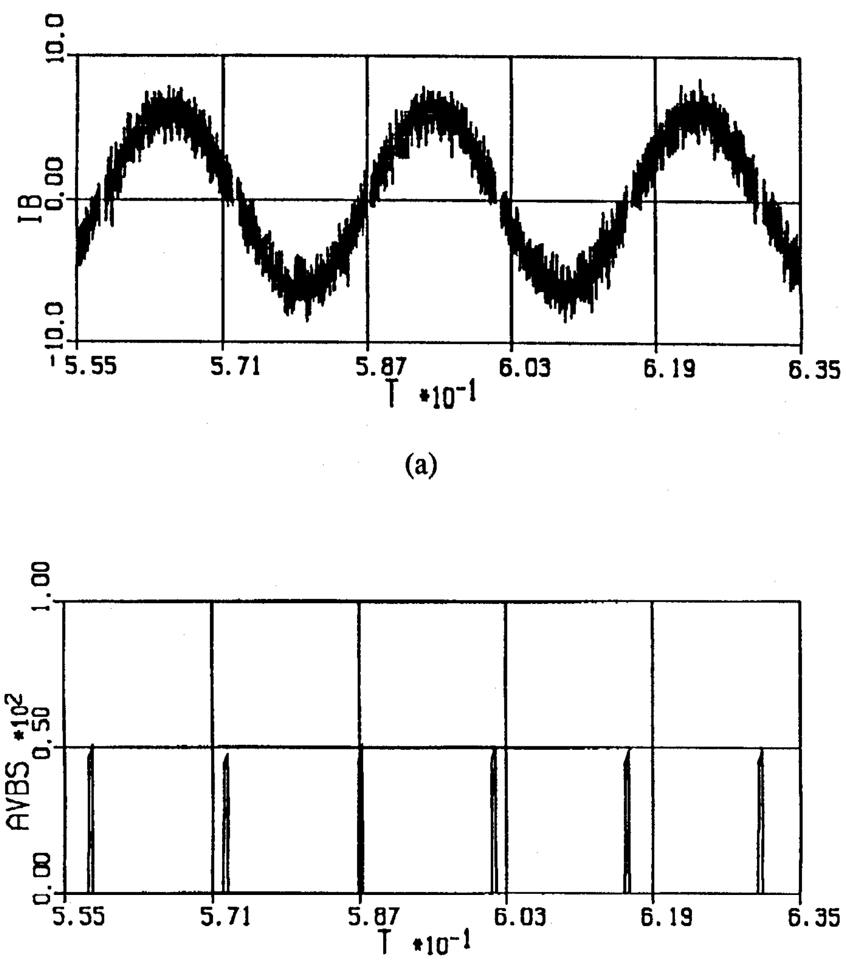


Fig. 11 Motor winding short circuit detection scheme.



(a)

(b)

Fig. 12 Simulation traces showing detection of emf during scheduled open circuit of motor phases. Motor frequency = 30 Hz, open circuit interval = 6°. a) Phase b motor current, b) Absolute value of emf induced in phase b during the open circuit.

V. CONCLUSION

This paper has presented several innovative techniques for reliability enhancement of solid state inverter drives when operating under field oriented control. The theory concerning a new principle of protection as well as the possibility of continuous operation under conditions where one phase is open circuited has been presented. In particular, this paper introduces a new control strategy to implement this principle which utilizes a five phase motor/converter. Computer simulations and experimental approaches were used to verify the correctness of the theory.

It is important to emphasize that *no negative sequence currents are produced by the choice of stator currents* selected for either the three phase or five phase connection Hence, there are *no pulsating torques created* and the torque is *undisturbed* even though the current in one of the phases has been interrupted. It is important to also note that the machine remains completely *field oriented* and that the motor can continue to operate on the remaining phases as long as necessary to complete a required operation or can immediately enter the regenerative mode for the purpose of stopping the motor as quickly as possible.

Methods for protection against short circuit failures have also been presented. In this case, detection is the main issue since continued operation at any current level could result in destruction of the machine. Finally, perhaps it is also useful to mention that these new control strategies can be implemented for *any* type of ac drive including induction, wound field synchronous, synchronous reluctance and permanent magnet motor drives.

VII. REFERENCES

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