The College of Engineering
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Wisconsin Electric Machines and Power Electronics Consortium

RESEARCH REPORT
91-19

A Strategy for Improving Reliability of Field Oriented Controlled Induction Motor Drives

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Abstract—— **Although design of induction motor drives employing field oriented control has reached a relatively mature state, relatively little effort has been expanded on improving the reliability of these drives In this paper a new, improved induction motor drive topology and control strategy is proposed which allows for continuous, disturbance free operation of the drive even with complete loss of one leg of the inverter or motor phase. A complete analysis and computer simulation of this new control and circuit concept is included.**

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. Switching losses of hard switched converters (dc voltage link converters) have also improved dramatically due to the substantially reduced turn off time of third generation IGBTs. Also, control strategies, particularly field oriented control strategies, have greatly improved the performance of AC motor drives. These control strategies utilize almost exclusively pulse width modulated (PWM) switching strategies which exploit the low switching loss capability of these converters and seek to produce a precisely controlled current to the windings of the motor. In effect, the controller serves to convert the dc/ac inverter from a voltage to a current source thereby overcoming many (but not all) of the inaccuracies involved in induction motor torque control.

While current regulation 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 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.

The cost and complications arising during emergency braking can be eliminated by considering the drive circuit shown in Fig. 1. 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.

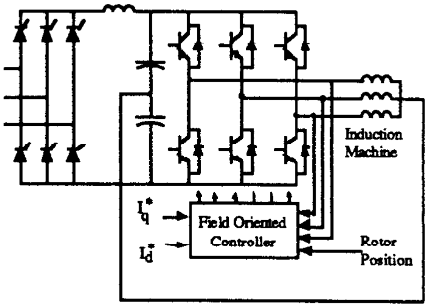


Fig. 1 Induction motor drive with machine neutral fed back to dc bus mid point.

II. ANALYSIS

In order to illustrate the concept for control during a single phase open circuit it is useful to employ the principle of space phasors [4]. In particular, assume that at "t=0⁻" all three phases are excited normally and the current space phasor is located as shown in Fig. 2.

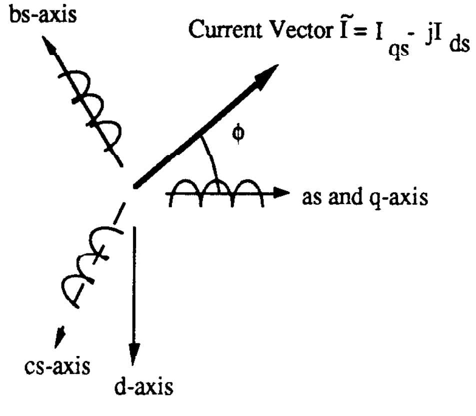


Fig. 2 Orientation of the current space vector just before one phase is open circuited.

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.

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

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

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

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,

$$MMF = MMF_a + MMF_b + MMF_c$$

$$= N I_{as} + a N I_{bs} + a^2 N I_{cs} \qquad (2)$$

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

For balanced three phase operation

$$MMF = \frac{3}{2} F e^{j\theta} \qquad (3)$$

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

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.

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

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

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,

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

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

From these two equations, it can be determined that

$$I'_{cs} = -\sqrt{3}\, I \sin\theta$$

$$I'_{as} = \frac{3}{2} I \left(\cos\theta - \frac{1}{\sqrt{3}} \sin\theta\right) \qquad (8)$$

or, equivalently.

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

$$I'_{cs} = \sqrt{3}\, I \cos(\omega t + \phi + \pi/2) \qquad (9)$$

Hence, if phase b is open circuited, "bumpless" 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.

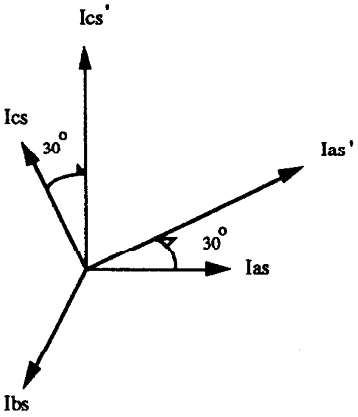


Fig. 3 Phasor relationships before and after phase b is open circuited

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,

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

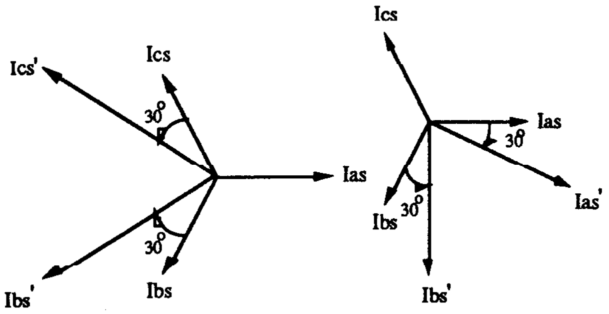
$$I'_{cs} = \sqrt{3}\, I \cos(\omega t + \phi + 5\pi/6) \qquad (11)$$

If phase c is open circuited

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

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

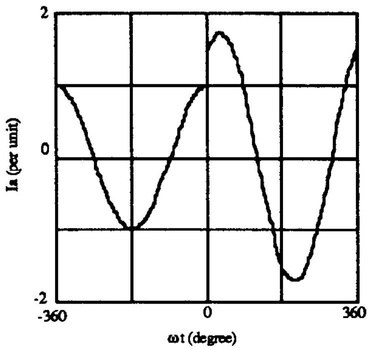
Figure 4 shows the phasor relationship before and after phases a and c are open circuited. In any of the above three cases, it is noted that after opening of one phases the remaining two phases should be regulated to a magnitude of $\sqrt{3}$ times of their original value and phase shifted 60 degrees with respect to each other. The new phase angle is accomplished by regulating one phase to jump forward 30° and the other phase jump backward 30° with respect to their positions before the open circuit.

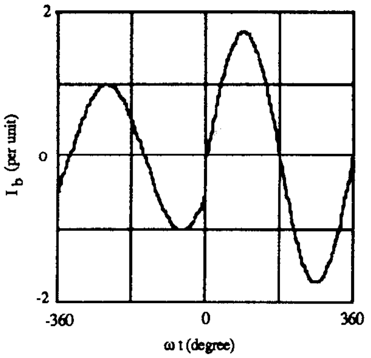


(a) Phase a open circuited (b) Phase c open circuited

Fig. 4 Phasor relationships required for a unaffected operation when (a) phase a is open circuited (b) phase c is open circuited

Figure 5 shows an idealized example of a typical scenario in which the motor phase *c* is open circuited at t=0 for the special case in which $\phi = 0$. The only torque transient to be expected is the result of the di/dt limit of the inverter imposed by the maximum dc link voltage.





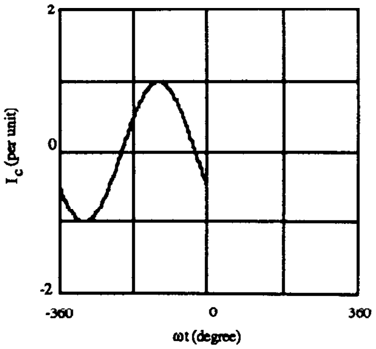


Fig. 5 Phase currents before and after a sudden open circuit of phase *c* which results in the same instantaneous torque and no torque transient.

III. COMPUTER SIMULATION

A. *Simulation Model*

To verify the principles aforementioned, a simple computer model for field oriented controlled induction motor was established. In this model, indirect field orientation was implemented based on the slip relationship for field orientation [5]

$$s\,\omega_e = \frac{R_r I_{qs}}{L_r I_{ds}} \qquad (14)$$

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 following motor parameters are used in the simulation:

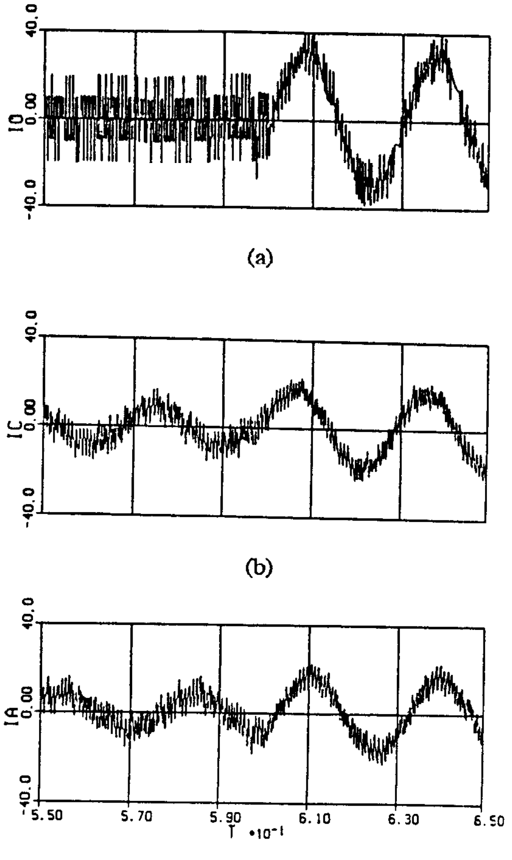
L_s = 0.07131 h, L_r = 0.07131 h, L_m = 0.06931 h, R_s = 0.435 Ω, R_r = 0.816 Ω, V_{dc} = 198 V, K_I = 0.01, K_P = 0.1, Commanded speed = 1000 rpm, Switching frequency = 5 KHz

The dynamic model of the induction motor is based on Stanley's equations. In general, the simulation of one phase open circuited condition can be achieved by two means. The first method employs the use of the induced voltage in the open winding [6]. The voltage appears across the open winding can be determined by the mutual inductance, rotor leakage inductance and the rotor rotating flux. The other method assumes zero current in the open phase as a constraint. Substituting this constraint into Stanley's equations, a second set of dynamic equation dedicated to one phase open circuit operation can be derived.

B. *Simulation Results*

Both the simulation of motor starting and normal operation with and without load 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.

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 operating line current 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 is almost unaffected

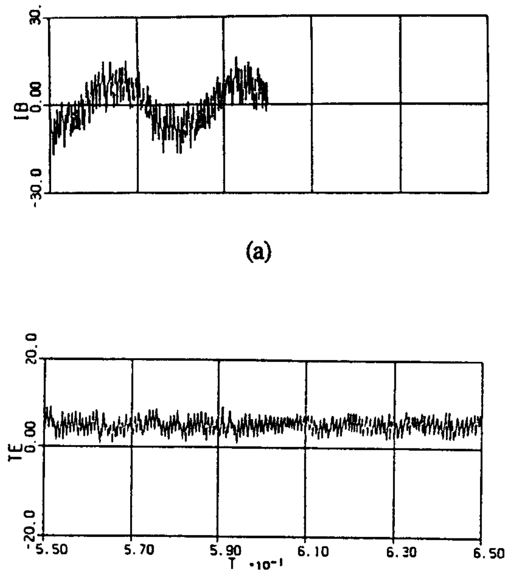


(a)

(b)

(c)

Fig. 6 Current variation after phase b is open circuited (a) I_{os}, (b) I_{cs}, (c) I_{as}.



(a)

(b)

Fig. 7 Torque variation after phase b is open circuited(a) I_{bs} (b) Torque.

IV. CONTROL SYSTEM BLOCK DIAGRAM

The system of Fig. 8 shows one method for implementing the modifying the indirect field orineted control strategy. The basic concept is same as the simulation model described in section III A. In addition, a device to sense the operating condition is required in order to implement a control scheme change. This device should have the ability not only to detect the open circuit but also to identify the different phases so that the system can switch to the appropriate control scheme accordingly. The a-b-c axis current commands are obtained from the d-q to a-b-c axis transformation. For example, for normal operation, the current commands are

$$I_{as}^* = I_{qs}^* \cos\theta + I_{ds}^* \sin\theta \qquad (15)$$

$$I_{bs}^* = I_{qs}^* \cos(\theta - 2\pi/3) + I_{ds}^* \sin(\theta - 2\pi/3) \qquad (16)$$

$$I_{cs}^* = I_{qs}^* \cos(\theta + 2\pi/3) + I_{ds}^* \sin(\theta + 2\pi/3) \qquad (17)$$

when phase b is open, the current commands should become

$$I_{as}^* = \sqrt{3}\,[\, I_{qs}^* \cos(\theta + \pi/6) + I_{ds}^* \sin(\theta + \pi/6)\,] \qquad (18)$$

$$I_{cs}^* = \sqrt{3}\,[\, - I_{qs}^* \sin\theta + I_{ds}^* \cos\theta\,] \qquad (19)$$

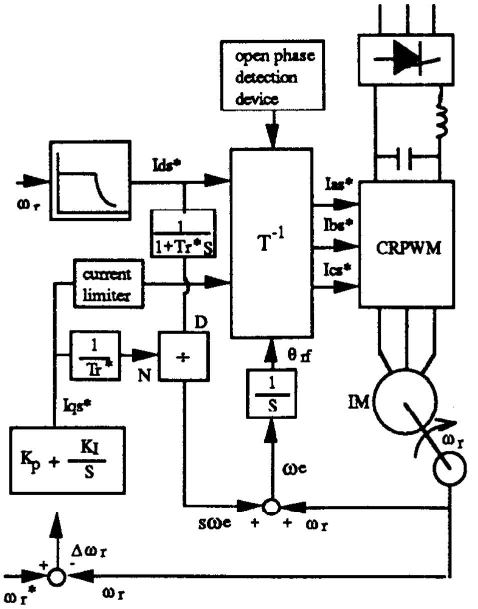


Fig. 8 System control block diagram incorporating open circuit contingency control

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 scheme 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 following three control methods can be considered:

(a) Use a triac connected 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 one phase open signal is detected and a two phase operation is required. Figure 9 shows a sketch of this control method.

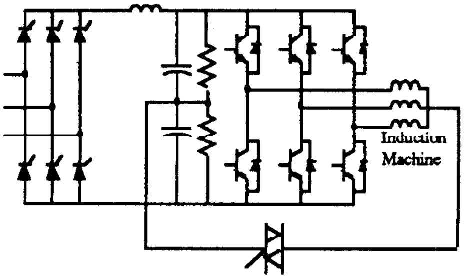


Fig. 9 Use of a triac to block the neutral current during normal operation

(b) Use a pair of small resistors to help stabilize the drift as shown in Fig. 10. In this case some extra losses are clearly incurred. However, in most cases the added losses can be considered as negligible.

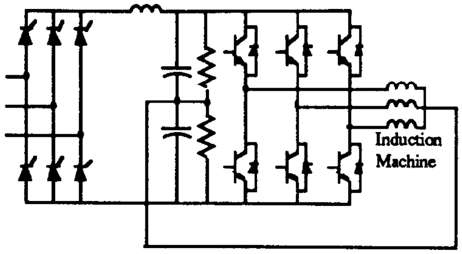


Fig. 10 Use of a pair of resistors to force voltage sharing across the dc link capacitors

(c) Introduce a flux or torque command regulator to manipulate the motor current commands so that the capacitor midpoint voltage will be regulated and will not deviate much from the desired value. Figure 11 shows the control block diagram of this method using flux as the correting signal. The variation of the flux command may result in the torque variation. However, this variation is considered not to be significant. The speed change as a result of flux command change will finally be compensated through the speed feed back control loop.

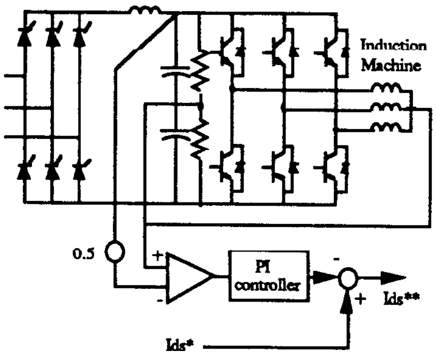


Fig. 11 Flux command control method

V. DISCUSSION

One of the important factors in the practical implementation of this control strategy is the selection of the capacitor size. Under unbalanced two phase operation, the neutral current becomes 3 times that of the line current required for normal operation so that the link voltage could be sujected to severe pulsations in amplitude. To simplify the evaluation, it is assumed that stator currents are regulated exactly to be a sinusoidal waveform so that the neutral current can be considered as a current source charging the capacitors. The voltage variation across the capacitors is estimated as

$$\Delta V = \frac{I_{os}}{2j\omega_e C} \qquad (20)$$

where I_{OS} is the neutral current

ω_e is the electrical frequency

C is the dc link capacitance

Hence, the capacitor selection strongly depend on the operating current, frequency and the voltage variation tolerance. A rough estimate for the case simulated in this paper, to keep the voltage variation less than 10 % of the dc voltage, a capacitor of about 0.004 Farad is required. However, for higher load operation or more strict voltage variation tolerance, a higher capacitor size is required accordingly.

Figure 12 shows a modified simulation in which the effects of the finite link capacitor are incorporated into the computer model. In particular, the value of the dc link capacitance was chosen as 10000 μf. Method (a), above, was used to prevent link voltage drift. That is, a triac is triggered to tie the motor neutral back to the dc voltage midpoint only when an open circuit is detected. Note that the dc link voltage now sustains a moderate ripple voltage. However, examination of the motor torque verifies that the control is not affected.

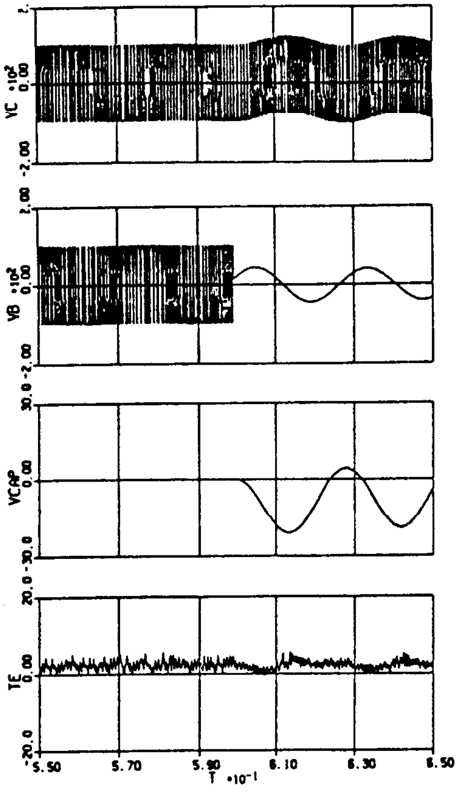


Fig. 12 Opening of phase b using the circuit of Fig. 9. Traces from top to bottom are: Phase c voltage; phase b voltage; dc link midpoint voltage; electromagnetic torque.

In Fig. 13 and Fig.14, operations with the resistive damping circuit and with the flux command regulator are portrayed by means of simulation. Values of 1000 Ω was used for the two damping resistors. Again it can be noted that the currents are well regulated and that drift of the dc link midpoint voltage is well damped both before and after the open circuit occurs.

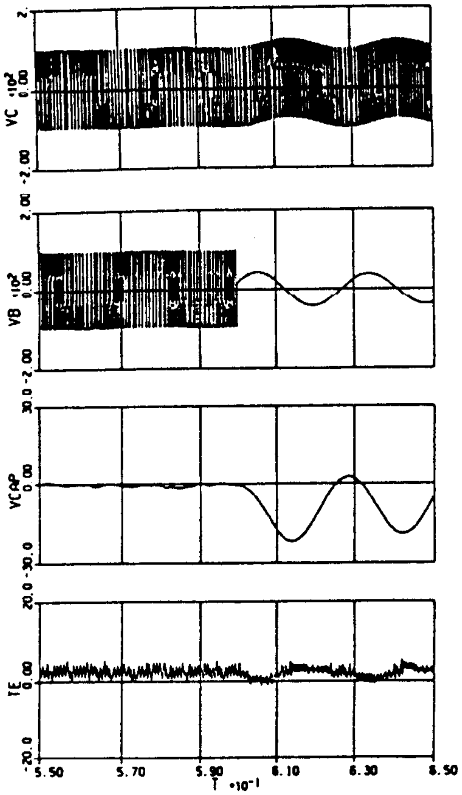


Fig. 13 Opening of phase b using the circuit of Fig. 10. Traces from top to bottom are: phase c voltage, phase b voltage, dc link midpoint voltage, electromagnetic torque.

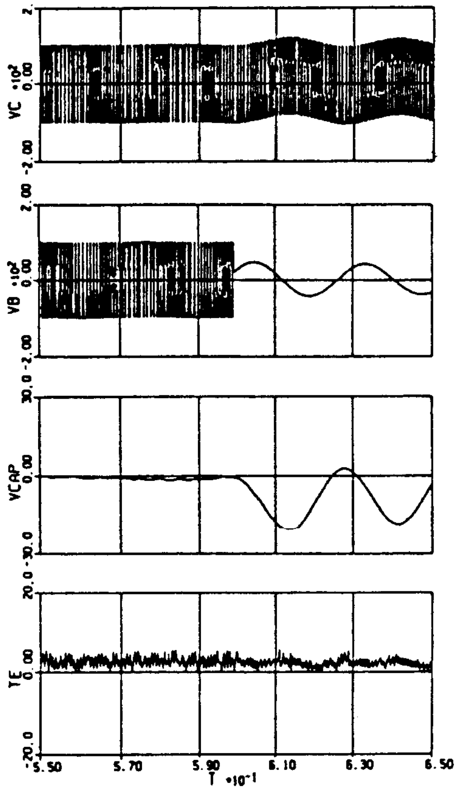


Fig. 14 Opening of phase b using the circuit of Fig. 11. Traces from top to bottom are: phase c voltage, phase b voltage, dc link midpoint voltage, electromagnetic torque.

VI. CONCLUSION

This paper has reported the theory concerning a new principle of protection as well as the possibility of continuous operation under conditions where one phase is open circuited. In particular, this paper introduces a new control strategy to implement this principle. A detailed digital computer simulation is used to verify the correctness of the theory. The limitations imposed by center tapping the dc link supply are discussed and the potential impact on capacitor selection due to the ac currents which now must flow in the link capacitors is evaluated. A proposed control scheme to implement this control strategy was also presented.

It is important to emphasize that *no negative sequence currents are produced by this choice of stator currents*, Hence, there are *no pulsating torques created* and the torque is *undisturbed* even though the current in one of the phases has been interrupted. Clearly, this control strategy not only allows for "bumpless" operation of the motor but affords a significant cost reduction compared to previous schemes which used contactors, extra capacitors and friction brakes to obtain the same degree of protection. It is important to also note that the machine remains completely *field oriented* and that the motor can continue to operate on only *two 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. In contrast to previous schemes using a dc current or with shorted windings, in which the braking torque strategy was to "take what ever you can get", this braking action is done under precise field oriented control.

It can be readily shown that the stator copper loss is unfortunately doubled under unbalanced two phase operation (rotor copper loss is unaffected). However, it is apparent that the motor can continue to operate indefinitely with one-half of rated torque. This may be useful for completing, for example, a machining operation under a lower feed rate than normal before shutting down for repair. Furthermore, shut down is accomplished under field oriented control in which the braking torque can be carefully regulated, eliminating the possibility of broken tools, shafts, etc. Conversely, the motor and converter can be sized to accommodate the extra losses incurred by unbalanced two phase operation so that the motor and converter can then operate indefinitely under full load if the inverter frequency is sufficiently high to limit the ripple current to an acceptable value. Such considerations could be extremely important in the case of critical loads such as a cooling pump in a nuclear power plant. If continuous two phase operation is attempted it should be cautioned, however, that the unsymmetrical concentration of heat around the stator periphery could cause distortion of the stator laminations without proper attention to bracing. Finally, perhaps it is also useful to mention that this new control strategy can be implemented for *any* type of ac drive including induction, wound field synchronous, synchronous reluctance and permanent magnet motor drives.

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