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## A STRATEGY TO ISOLATE A SWITCHING DEVICE FAULT IN A CURRENT REGULATED MOTOR DRIVE

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**Abstract**— In this paper a new, improved induction motor control topology is proposed which allows for continuous, disturbance-free operation of the drive with a failed short-circuited switch in one leg of the inverter. The analysis of this control strategy and the computer simulation are explored. The experimental results from hardware are attached to verify the simulation results. A complete control strategy combined with short-circuit fault and open-circuit fault is also included.

### I. INTRODUCTION

One of the most common types of drive system faults is a failed short-circuited switch in a leg of the inverter. In this case one of the motor phases is continuously connected to the positive or negative side of the dc bus, resulting in a loss of field orientation and consequent flow of uncontrolled current. One method to isolate a short-circuited switch is to simply shoot-through or short circuit the faulty leg of the inverter by turning on the other switch in the same inverter leg. With this method, two fuses per inverter leg are required. When one of the inverter switches is short-circuited, the other switch in the same leg is intentionally turned on so that the fuses will blow and isolate the short-circuited switch. However, because of the overcurrent limit of the switches and the clearing characteristics of the fuses, a new short-circuited switch may be created even though the original fault has been cleared. In such cases, there is no means to isolate the newly created short-circuited switch. Hence, the motor cannot be operated satisfactorily and must be braked to remove the fault.

Figure 1 shows a new topology, derived from a current regulated pulse width modulated (CRPWM) inverter [1-3], that can solve the problem caused by a short circuited switch. One fuse and the circuit equivalent of a triac (more realistically, a pair of thyristors connected in inverse parallel or a single thyristor connected inside a diode bridge) for each phase are required for this topology. The return lines are connected from each phase to the midpoint of the dc voltage in series with the triac which is controlled to be normally open circuited. Once a failure indicating a short circuit signal is sensed, the other switch in the same leg is blocked and the triac of the appropriate phase is triggered

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on. This results in the short circuit of the capacitor of half of the dc supply. The energy stored in the capacitor will then blow the fast acting fuse and isolate the shorted switch of the inverter. By using this topology, no matter which switch is short circuited, either one of the two switches of an inverter leg can be isolated.

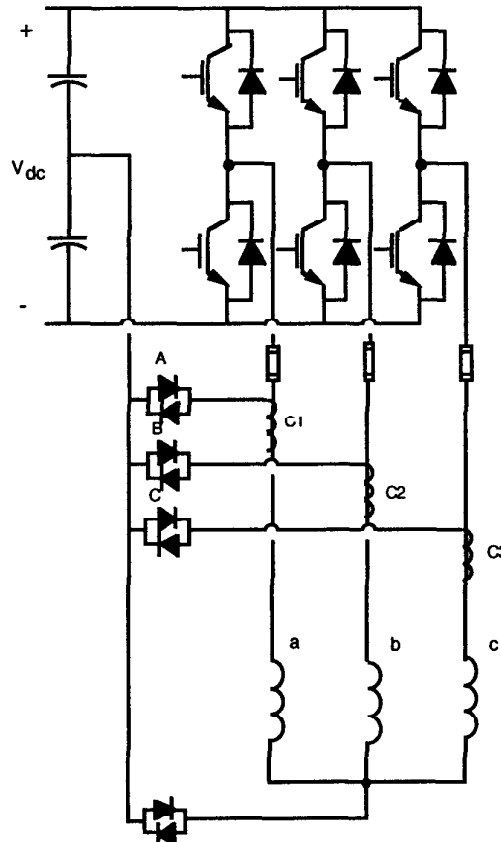


Fig. 1 Topology for isolating a short circuited inverter switch

## II. ANALYSIS

The penalty for using the topology of Fig. 1 for limiting fault current is a reduction of current control capability. Since the winding terminal of the isolated phase is connected to the midpoint of the dc voltage, its phase voltage is determined by the switch positions of the other two phases.

Figure 2 shows the four possible configurations which can exist when one of the switches in phase *b* fails in a short-circuited mode and is cleared by the topology described in Fig. 1. Note that in this case, terminal *b* is always connected to the midpoint of the dc voltage and the current magnitude in phase *b* is equal to  $-(I_a + I_c)$ . In Fig. 2(b), both the phase *a* and phase *c* currents are lower than the current commands. Hence the switches of phase *a* and phase *c* are both switched to the positive dc bus, the terminal voltages for phase *a* and phase *c* are both equal to  $(1/6)V_{dc}$  while the voltage for phase *b* winding becomes  $-(1/3)V_{dc}$ . In Fig. 2-(b), phase *a* current is lower than the current command, while phase *c* current is higher than the current command. Hence the phase *a* switch should be switched to the positive dc bus, and the phase *c* switch switched to the negative dc bus. This configuration results in the terminal voltages for phase *a* being  $(1/2)V_{dc}$  and

the terminal voltage for phase  $c$  becomes  $-(1/2)V_{dc}$ . The voltage across the phase  $b$  terminal in this case is zero. Figures 2-(c) and 2-(d) show the motor terminal voltages for the two other possible configurations.

Current control utilizing CRPWM can still be accomplished by manipulation of the terminal voltages. By using only two-phase control, the available driving terminal voltages are reduced. This causes the rate of the current change to also be reduced. However, as long as the desired current can be maintained, satisfactory performance can be expected.

### III. SIMULATION RESULTS

As soon as a short-circuited switch is sensed, an inhibiting signal must be issued to block the other switch in the same leg so that a shoot-through fault will be prevented. After the fuse successfully isolates the short-circuited switch, the current in the isolated phase becomes, in essence, the negative sum of the other two phases. By using CRPWM, balanced three-phase currents are presumed. As long as the current control capability is maintained in the two healthy phases, a sinusoidal current in the isolated phase can continue to be maintained. Figure 3 shows a computer simulation for a control scheme change from three-phase control to two-phase control at  $t = 0.5$  sec. Under the two-phase control topology, the current in phase  $b$  is not controlled. The currents in the three stator windings are determined by the terminal voltage through the induction motor model. It can be noted that the stator currents have less harmonics under two-phase control because of the lower driving voltages as described in Section II. It is also noticed that the stator currents are still maintained to be a positive sequence. Since the currents in the three phases are not changed, no torque or speed changes will, in principle, occur.

### IV. EXPERIMENTAL RESULTS

#### A FUSE SELECTION

In this study the criterion used to select the fuse was taken as the time

integral of current squared,  $\int i^2 dt$ , which is normally identified (somewhat incorrectly) as

$I^2t$ . This criterion can be conveniently used to evaluate the aggregate effect of a particular short-time current, no matter whether it is a thermal effect or a mechanical effect or a combination of the two. To isolate the failed switch, the fuse described in Section II was connected in series with the triac and served as a current interrupting device. The resulting current pulse due to a capacitor short circuit discharge tends to quickly reach a peak value and then decay exponentially as the charge on the capacitor is dissipated. In this case, the principle for choosing the isolating fuse is that the fuse let-through  $I^2t$  should not exceed the  $I^2t$  withstand value of the triac.

Hence, the criteria for fuse selection is given below:

- (1) The fuse melts, i.e. opens, only when an isolating command is actuated.
- (2) The fuse must open from the energy stored in the capacitor.
- (3) The  $I^2t$  of the fuse must be less than the  $I^2t$  withstand value of the inverse-parallel switch pair (i.e. the "triac").

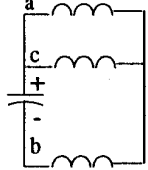
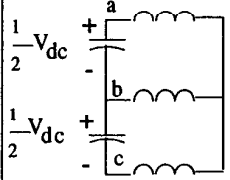
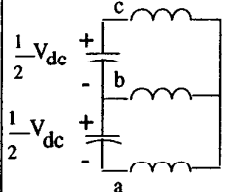
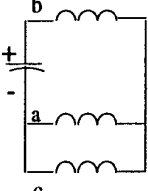
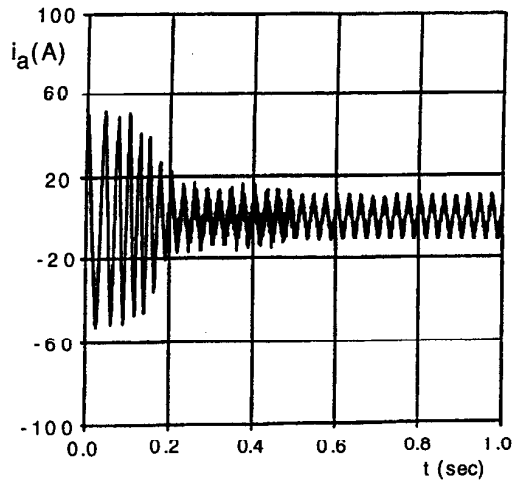
	Switches	Configurations	Terminal Voltages
(a)	A+ on C+ on		$V_a = V_c = \frac{1}{6}V_{dc}$ $V_b = -\frac{1}{3}V_{dc}$
(b)	A+ on C- on		$V_a = \frac{1}{2}V_{dc}$ $V_c = -\frac{1}{2}V_{dc}$ $V_b = 0$
(c)	A- on C+ on		$V_a = \frac{1}{2}V_{dc}$ $V_c = -\frac{1}{2}V_{dc}$ $V_b = 0$
(d)	A- on C- on		$V_a = V_c = \frac{1}{6}V_{dc}$ $V_b = -\frac{1}{3}V_{dc}$

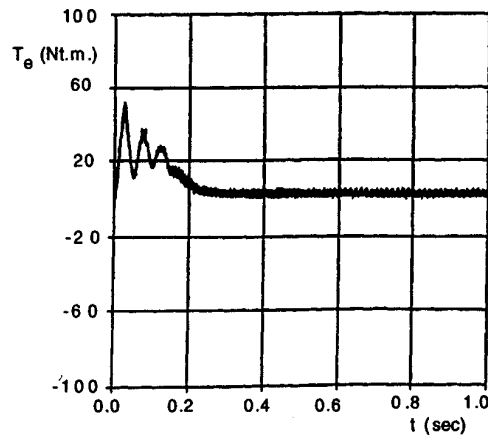
Fig. 2 Terminal voltages for two-phase control topology

**B FUSE INTERRUPTION TEST**

In the initial portion of the experimental study a test of the selected fuse was conducted to verify that the capacitor has sufficient energy stored to blow the isolating fuse. The motor and inverter was a General Electric 7.5 HP induction motor, and a 7.5 HP Toshiba Model 130H1 PWM inverter respectively. The inverter was modified to incorporate 10,000  $\mu\text{f}$  in the DC link. A Motorola DSP 56000 Application Development System was used to implement the control. A pair of back-to-back SCRs were used as the short-circuit switching device. To comply with the fuse selection criteria summarized above, a Gould Shawmut semiconductor fuse, A50P60-4, was selected as the isolating fuse. The A50P60-4 has a rated voltage and rated current of 500 Vac and 60 Amps (RMS) respectively. The  $I^2t$  data of the fuse and the SCR used in this experiment are compared in Table 1. Figure 4 shows the results of the fuse test. It can be noted that the fuse opens the circuit in about 500 microseconds.



(a)

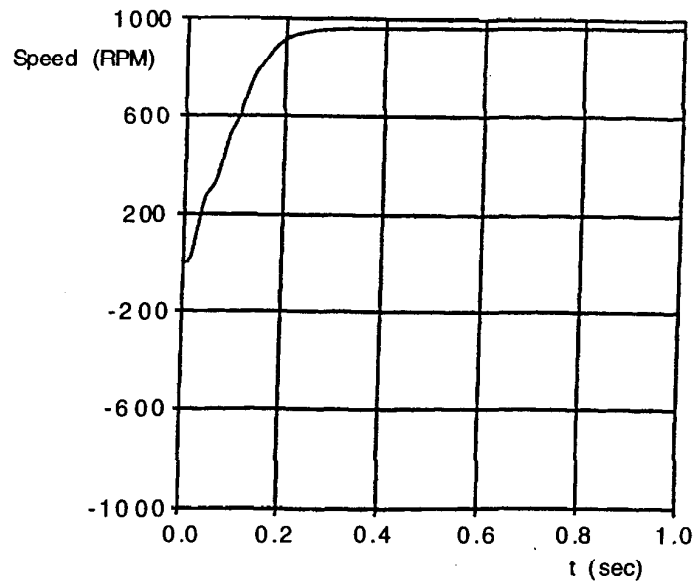


(b)

Fig. 3 (a),(b) Computer simulation for a change in control from three-phase control to two-phase control at  $t = 0.5$  sec. (a) phase c current  $I_c$ , (b) torque

### C CONTROL SCHEME CHANGE FROM THREE-PHASE TO TWO-PHASE CONTROL

To simulate the failed short-circuited condition of the switching device in the inverter, a bypassing triac or its equivalent can be connected across one of the switches as shown in Fig. 5. A triac short-circuit command can be issued through an interactive communication program between a digital signal processor (DSP) and a personal computer. When the DSP detects the short-circuit command, it isolates both switching devices of the appropriate inverter leg before sending the short-circuit signal to the SCRs.



(c)

Fig. 3 (c) Computer simulation for a change in control from three-phase control to two-phase control at  $t = 0.5$  sec. (c) speed

To protect the DSP from damage caused by the power circuit, optical transmitters and receivers were used to isolate the control signal between the DSP and the power circuit.

Table 1  $I^2t$  comparison for A50P60-4 fuse and SKKT71 SCR

	Fuse(A50P60-4)	SCR(SKKT71)
Rated Voltage	500VAC	600V( $V_{RRM}$ )
Rated Current	60A(RMS)	70A( $T_{case}=85C$ )
$I^2t$	360 $A^2s$ (melting) 2900 $A^2s$ (clearing)	13000 $A^2s$

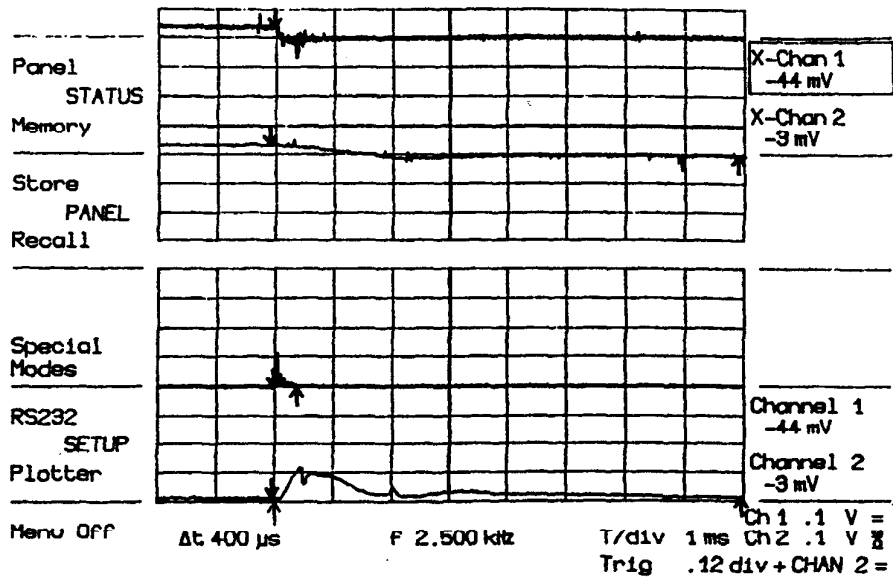


Fig. 4 Experimental results from fuse test. Traces from top to bottom are: (a) voltage across the capacitor, 50 v/div., 1 ms/div. (b) voltage across the capacitor, 50 v/div., 50 μs/div. (c) current through the fuse, 500 A/div., 1 ms/div. (d) current through the fuse, 500 A/div., 50 μs/div.

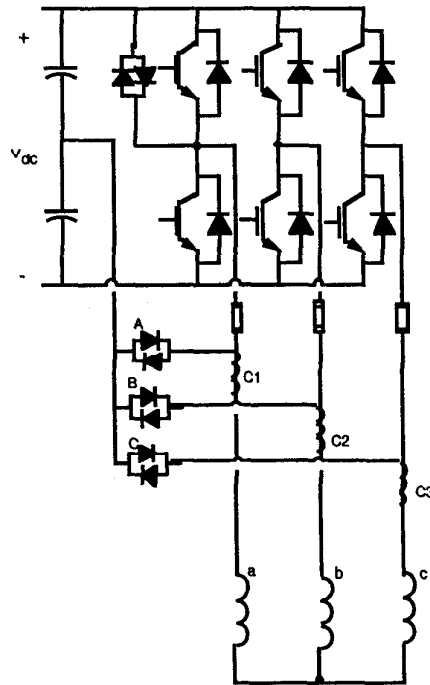


Fig. 5 Schematic diagram for short-circuited switch experiment

In these figures, switch 1 in phase  $a$  is assumed to be a failed short-circuited switch. Hence a bypassing triac is connected across switch 1. After the faulty switch is successfully isolated, the terminal of phase  $a$  winding is connected to the mid-point of dc voltage through triac  $A$ . As previously mentioned, the controls in phase  $b$  and  $c$  currents need not be changed.

Figures 6 and 7 show experimental results for a control scheme change from three-phase current control to two-phase control. Since the inverter is protected by an overcurrent protection circuit, a short circuit of the capacitor resulted in an isolation of all switches in the inverter. Hence, it should be noted that the experimental results were taken without causing a short circuit of the capacitor. To accomplish this condition, both switches 1 and 4 must be isolated first, then triac  $A$  is turned on. After triac  $A$  is turned on, the current in phase  $a$  is no longer controlled. Phase  $a$  current now is the negative sum of phase  $b$  and phase  $c$  currents.

From Fig. 6 top trace, it can be seen that there is no current flowing through the mid-point of the two capacitors during three phase balanced operation. After the motor is under two-phase control, all the current in phase  $a$  flows through the mid-point of the capacitors. It can be seen that although the current in phase  $a$  is no longer controlled, it is still maintained as a satisfactory sinusoidal waveform by controlling the currents of phases  $b$  and  $c$ .

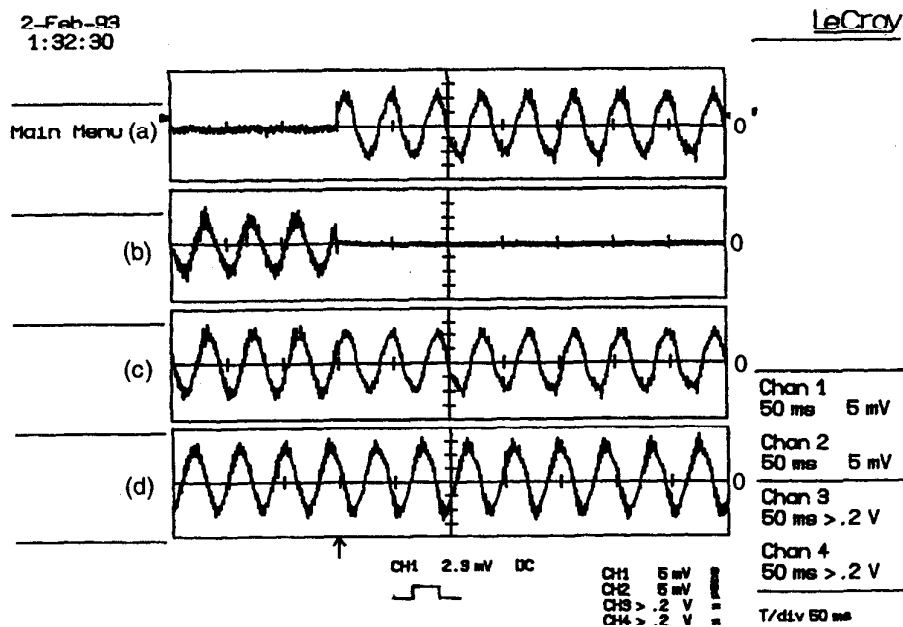


Fig. 6 Experimental results for control scheme change from three-phase control to two-phase control at  $\omega = 80$  radians per sec. Traces from top to bottom are: (a) phase  $a$  current flowing through the mid-point of the two capacitors, (b) phase  $a$  current flowing through the inverter leg, (c) phase  $a$  current flowing through the motor winding, (d) phase  $c$  current. The scales for all traces are 2A/div. and 50 ms/div.



Since the available driving terminal voltages are reduced during two-phase control, the capability of current regulation is also reduced. From Fig. 7 it can be noted that when motor speed is increased, it becomes more difficult to maintain the currents of phase *b* and phase *c* at the required values.

### V. LOGIC DIAGRAM

To further increase the reliability of the system, a combined control scheme which has both the characteristics of short circuit isolation and open circuit operation can be implemented. Figure 8 shows the ladder diagram of the overall control scheme [4] Although the control scheme recommended in this paper is implemented by DSP, nevertheless, a ladder diagram can be used to conveniently represent the control logic in the program. A ladder diagram consists of symbols representing coils and contacts arranged to provide relay logic. Once the program execution begins, the entire ladder diagram is continuously scanned in the DSP to reflect the latest logic status.

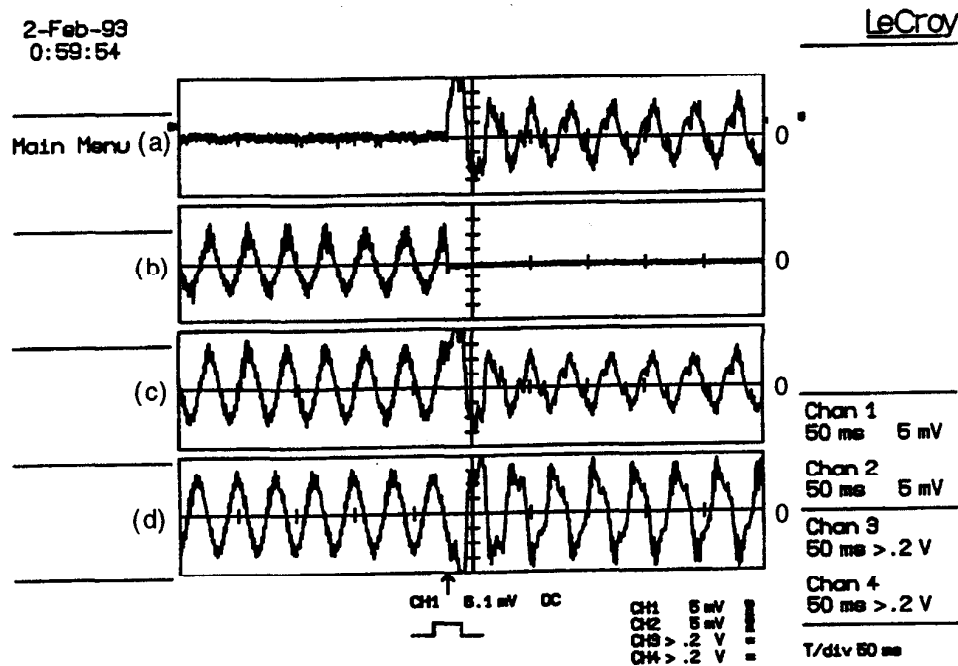


Fig. 7 Experimental results for a control scheme change from three-phase control to two-phase control at  $\omega = 100$  radians per sec. Traces from top to bottom are: (a) phase *a* current flowing through the mid-point of the two capacitors, (b) phase *a* current flowing through the inverter, (c) phase *a* current flowing through the motor winding, (d) phase *c* current. The scales for all traces are 2A/div. and 50 ms/div.

In this application sensing circuits to detect an open circuit failure or short circuited failure of the switching devices are clearly required. The two phase control topology is, in this case, the first choice after an open or short circuit failure of a switch is detected. If the current sensor still does not sense any current after a certain time delay, then the triac in the neutral line will be triggered and an open phase control strategy can be applied as illustrated in Ref. 5.

## VI. ACKNOWLEDGMENTS

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## VI. CONCLUSION

This paper has presented a new approach to faulty switch isolation in modern solid state inverter drives. The approach utilizes low cost thyristor/fuse technology to isolate the shorted switch thereby permitting continued operation either by connecting the phase previously experiencing the fault back to the center point of the dc bus or, when insufficient voltage is available, by connecting the neutral back to the center point of the dc bus and simply operating with the two healthy phases. This method could prove to be an important innovation to those applications requiring a high degree of fail-safe protection such as nuclear pumps, aerospace applications, military applications, and the like.

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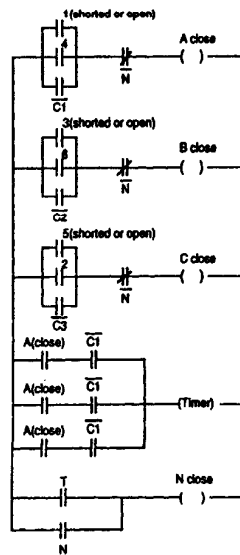


Fig. 8 Ladder diagram of combined control scheme. Symbols refer to components of Fig. 1.