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Paper Number PCI-77-1

THE NEW BLACK BOX IN CONVENTIONAL MOTOR CONTROL APPLICATIONS

Dr. F. W. Kussy

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Westminster, Maryland

Unitized Combination Starters

Summary

Combination starters have been built for many years as a combination of a circuit breaker or disconnect switch and a separate starter. The disconnect means, especially circuit breakers, usually used components which were originally developed for distribution equipment.

This paper describes two basic kinds of unitized combination starters, each one being one unit which is compatible mechanically and electrically with the requirements for motor controllers. The circuit breaker type unitized combination starter is current limiting. The unique action of such a current limiting combination is described in the second part of this paper.

Historical Development

The combination of fused switches or circuit breakers as disconnect devices and starters for industrial control equipment has been regulated for many years by the National Electrical Code Article 430, UL Standards 508 and 845, the Nema Industrial Control and Systems Standards, and ANSI Standard C19. In looking over the practical design of the disconnect devices, they were usually built for electrical distribution equipment and adapted with some minor changes to the needs for industrial control. Therefore, the compatibility of the disconnect device which was originally created for different purposes with control equipment was mechanically and electrically poor. In 1968 the NEC recognized for the first time the instantaneous trip type circuit breaker as equipment for the protection of motor branch circuits. At this time the instantaneous trip type circuit breaker was already used in the industry for a long time without being recognized. Only the thermo magnetic breaker was permitted by the NEC as a circuit breaker before 1968. Unfortunately, the various types of instantaneous trip type circuit breakers, often called motor circuit protectors, were developed by circuit breaker manufacturers as a by product to the thermomagnetic circuit breakers, using the same mechanism, same arc chutes, same handles, and as many identical parts as possible and having the same dimensions as the thermo-magnetic breakers from the same company. The consequence breaker had some good features but was only to some degree compatible with industrial control equipment. The first truly electrically compatible units were the combination of switches with motor short circuit protectors (MSCP's)[1] which were recognized in the code in 1971 and later the combination of instantaneous trip type circuit breakers with high fault protectors (HFCP's)[2] and starters. These devices insured a compatible system since starters, disconnect devices, MSCP's, or HFCP's were tested and approved together. Mechanical compatibility was lacking. To insure complete electrical and mechanical compatibility, a series of new devices was developed. At the present time there are two new lines of unitized combination starters developed. They are built for Sizes 0, 1, and 2 and besides the unitized combination starters, a new line of instantaneous trip type motor circuit protectors called Amp Cap for Sizes 0, 1, 2, 3, and 4; and a new line of switches which can be used with MSCP's for Sizes 1, 2, and 3.

Mechanical Compatibility

a. The NEC requires a separate disconnect device for each motor starter for nearly all motor branch circuits with the exception for some very small motors. The separate disconnect device must be a fusible switch or a circuit breaker. By combining the switch, the MSCP or fuses, or the instantaneous trip type circuit breaker, the proper handle and the starter with pushbuttons, reset buttons, selector switches, and pilot lights to one unit, considerable space can be gained. (Figures 1 & 2)

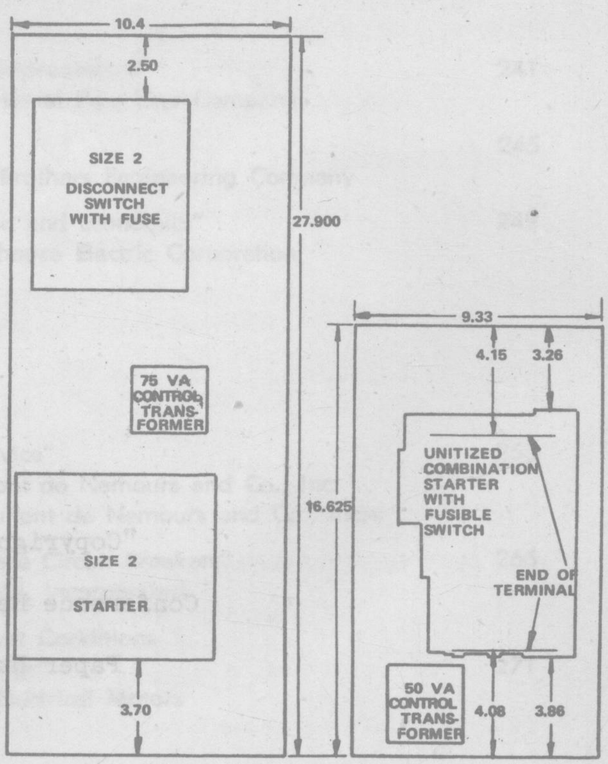


FIGURE 1

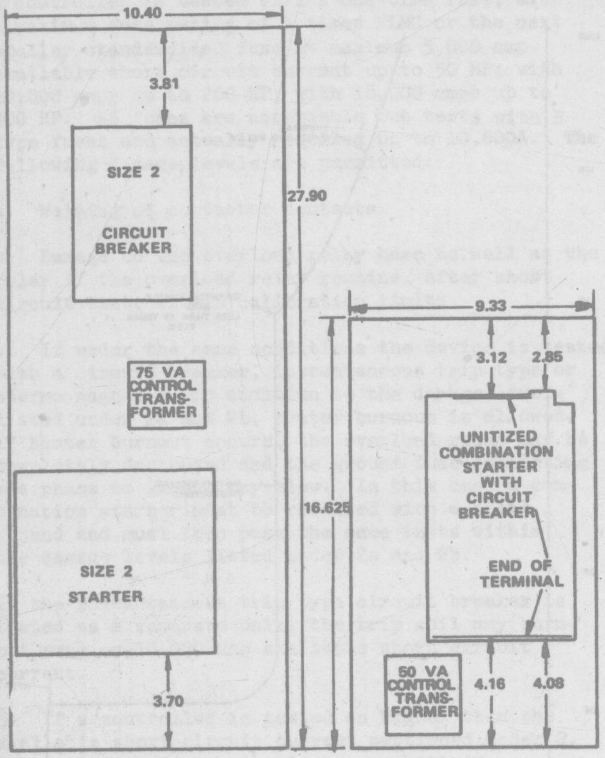


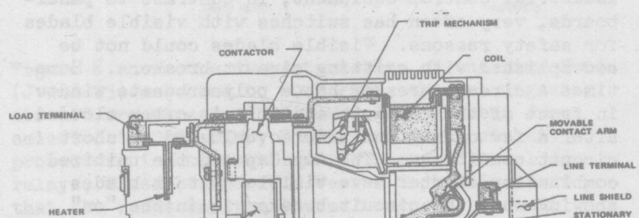
FIGURE 2

We see an enclosed Size 2 unitized combination starter which is approximately 10" shorter than a combination starter having separate units in spite of having more gutter space. Figure 1 shows the comparable size and space of a Nema 2 enclosed unitized combination starter of the fusible disconnect switch type using fuses or MSCP's with respect to a standard combination starter with a fused switch. Figure 2 shows the comparable size and space of a Nema 2 enclosed unitized combination starter of the Amp Cap motor circuit protector type with respect to a standard combination starter with separate motor circuit protector. The covers are omitted. Such a unit can be more easily installed than several incompatible units. The switch with the MSCP's has a normally closed auxiliary contact which opens when an MSCP blows and disconnects the control circuit of the contactor.

b. Most of the molded case circuit breakers used in distribution equipment have a toggle handle which is most suitable for panelboards. A series of complicated linkages which in most cases exclude trip indication, were developed to convert this toggle handle movement to a handle which is usually used in motor control centers and combination starters. Such a handle must be all the time in control of the disconnect device. Further, it must insure that the disconnect device cannot be energized when the door is open and the door may not be opened when the disconnect device is closed. Both of these features must be defeatable by an expert. The enclosure door must be latchable and must be able to be prevented from opening with a padlock. The disconnect device may not be allowed to be closed when locked in the open position with one, two, or three padlocks. In some cases, a lock-on condition must be provided. Since circuit breakers already have a complex mechanism, a device having two mechanisms, one to move a toggle handle and the other to convert the toggle handle mechanism to such as described here, may easily cause problems especially since control devices are very often used in special enclosures which are not highly tooled. It is quite time consuming to punch holes and to attach levers and stationary parts to the housing or door which interface with the handle. In order to insure mechanical compatibility, all necessary interlocks are part of a mass produced handle or platform including the pushbuttons, pilot lights, and reset buttons so that the user has only to install one unit and to punch one hole in the cover.

c. All presently existing instantaneous trip type circuit breakers, especially for smaller sizes up to Size 4 which represent more than 95% of the industrial control equipment, do not have interchangeable trip units. Approximately seven different instantaneous trip type circuit breakers or MCP's must be selected by the electrician for the Size 1 or 2 combination starter. The electrician is accustomed to choose the proper heater for his overload relay very late, usually after he knows the exact motor data from the motor nameplate including the full load motor current. To each heater belongs a particular motor short circuit protector to form a protective system. If the preselected protector was not quite correct, the electrician must remove the protector from the combination starter, motor control center, or special panel, and then install a new one.

Mechanically compatible equipment should have interchangeable trip units which could be installed and changed in the field like heaters in overload relays. One block contains the three molded coils and yokes of the tripping magnet. This block has fins for better heat dissipation. Terminals mechanically and electrically connect the trip coils to the breaker. Figure 3 shows the principle of a unitized circuit breaker of the motor circuit protector type having exchangeable trip coils.



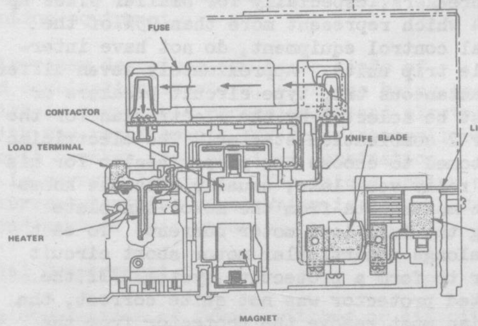
UNITIZED COMBINATION STARTER W/AMP. CAP FIGURE 3

The electrician who installs industrial control equipment is accustomed that pilot lights and various auxiliary switches can be easily attached to the starter in the field. All existing instantaneous trip type circuit breakers must be taken apart in order to attach such devices as alarm switches, interlocks, or shunt trips. That is completely sufficient for distribution equipment but is definitely not compatible with the requirements in the industrial control field. An alarm switch and an electrical auxiliary switch may be attached similar to auxiliary switches on controllers. It must be just as easy to attach an auxiliary switch to a disconnect switch.

Shunt trip including its cut off switch must be easily attached to the circuit breaker without taking the unit apart in the field.

Figure 4 shows the principle of a unitized combination starter of the disconnect switch type.

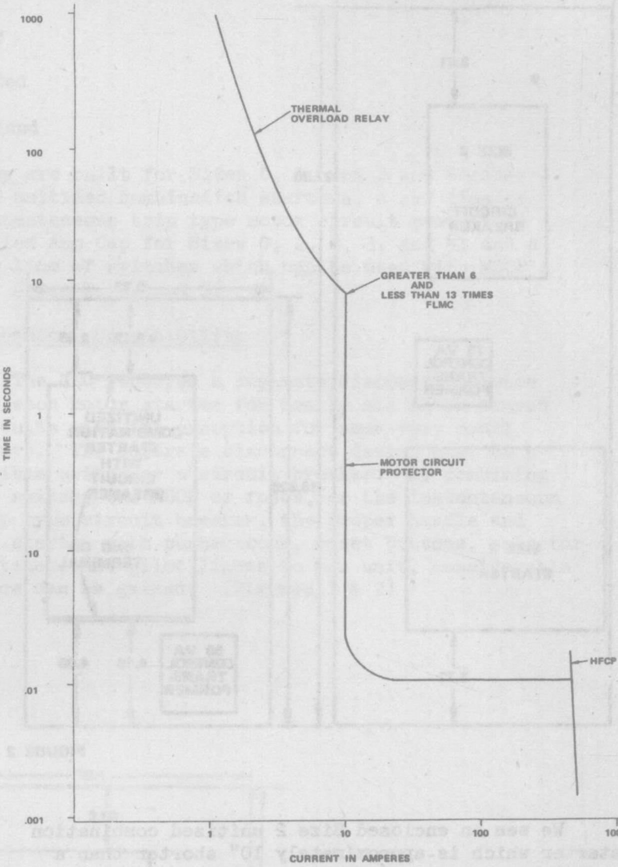
FIGURE 4



Industrial control equipment, in contrast to panelboards, very often has switches with visible blades for safety reasons. Visible blades could not be accomplished with existing circuit breakers. Sometimes a circuit breaker has a polycarbonate window in front of the contacts and this is often clouded after a few operations under overloaded or short circuit conditions. The Amp Cap and the unitized combination starter have visible contact blades, showing when the circuit breaker is in the "on" or "off" position. The circuit breaker for panelboards had no room for the line shield, therefore, it did not exist for control equipment. A compatible device has a line shield.

Electrical Compatibility

Still more important than the mechanical compatibility is the electrical compatibility of the equipment. The electrical compatibility of an instantaneous trip type circuit breaker with an HFCP was obtained in the following manner: The overload relay is self-protecting up to the cross over point where the time current characteristics of the starter and the circuit breaker are crossing. (Figure 5)



PRINCIPLE OF COMBINATION HFCP / CIRCUIT BREAKER STARTER

FIGURE 5

This current is higher than the locked rotor current (usually 6 times full load motor current) and less than 13 times FLMC as required by the NEC. The cross over point between the circuit breaker and the HFCP (high fault protector) is below the current on which the I^2t of the system is equal to the I^2t of the heater or of the contactor or the wires, whichever is the weakest link. In order to insure electrical compatibility within defined limits of a combination motor controller without an HFCP, an electro-energy limiting instantaneous trip type circuit breaker has been developed, either separate or as a part of the unitized combination starter. The let through energy must be smaller than the withstandability of the weakest link of the system. In order to determine what the I^2t withstandability of the weakest link is, we must investigate the various damage levels.

Permissible Damage Level of Combination Starters

1. Practically no damage to any component is permitted with the exception of slight pitting of contacts. At the present time there is no standard which requires that the controller must function without being damaged after a short circuit.

2. Damage Levels Permitted by American Standards. UL has several standards in order to obtain approval.

A controller is tested with a one time fuse, with a maximum fuse rating of 4 times FLMC or the next smaller standardized fuse at maximum 5,000 amp. available short circuit current up to 50 HP; with 10,000 amps up to 200 HP; with 18,000 amps up to 400 HP. K5 fuses are acceptable but tests with H type fuses are actually required up to 10,000A. The following damage levels are permitted:

a. Welding of contactor contacts

b. Damage to the overload relay base as well as the relay if the overload relay remains, after short circuit test, within calibration limits.

c. If under the same conditions the device is tested with a circuit breaker, instantaneous trip type or thermo magnetic, in addition to the damage levels listed under 2a and 2b, heater burnout is allowed. If heater burnout occurs, the overload relay may be completely destroyed and the ground fuse connecting one phase to ground may blow. In this case a combination starter must be retested with a solid ground and must then pass the same tests within the damage levels listed under 2a and 2b.

If the instantaneous trip type circuit breaker is tested as a separate unit, the trip coil may burn-out even on 10,000 amp available short circuit current.

3. If a controller is tested on higher than the available short circuit current mentioned under 2, the following damage levels are permitted:

a. Complete disintegration of contacts

b. The device may not be operative after test as long as no parts are discharged from the enclosure.

c. The enclosure may be deformed as long as the door of the enclosure is not blown open.

d. The ground fuse may blow if heater burnout occurs. Then the tests must be repeated with a solid ground connector. This repetition is not required by Nema Standards for motor control centers.

e. The breakage of the insulation is permitted as long as the integrity of the mounting of live parts is not impaired.

f. The dielectric withstand level on the line side of the disconnect device may be lowered to 900 volts or to twice the rated voltage after the short circuit test.

4. The IEC Standards have similar degrees of damage levels. In Type a, any damage to the starter is allowed as long as the enclosure remains externally undamaged. In damage level Type b, the characteristics of the overload relay of the starter may be permanently altered, no other damage shall occur except that light contact burning is allowed and the risk of welding of contacts is accepted. In damage level Type c, only welding of the contacts is permitted.[3]

Comparison of Characteristics of Protective Means

A great shortcoming of all Nema, UL, and IEC Standards is that testing under low fault conditions is not required. The only exceptions are the tests with instantaneous trip type circuit breaker plus HFCP's and switches with MSCP's.

That is, a test on currents above the locked rotor current of the motor[4] up to short circuit currents below the bolted fault current.

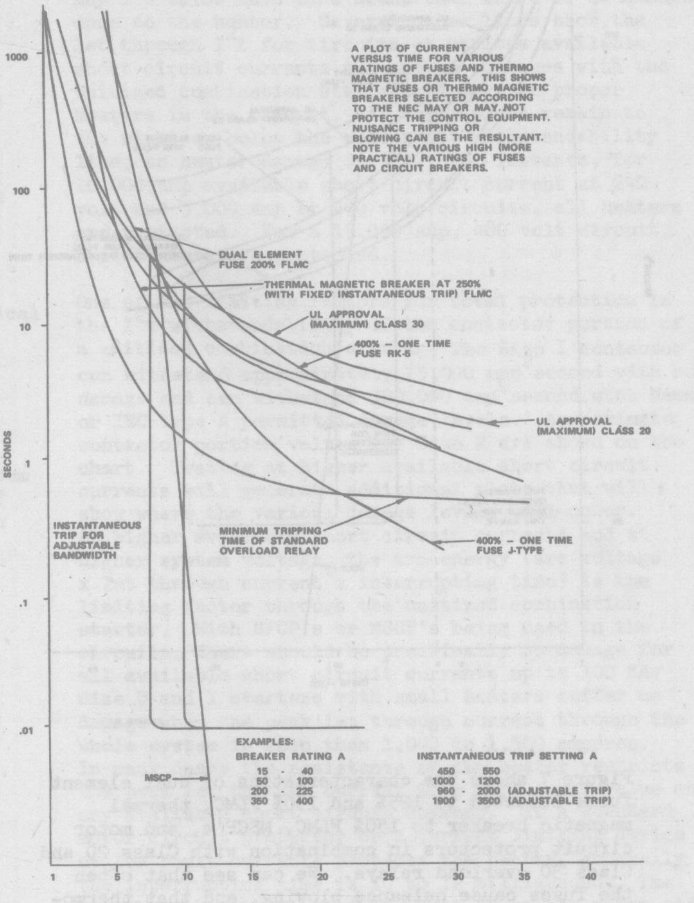


FIGURE 6

Figure 6 shows the characteristics of one time fuses (J and K5) selected to 400% FLMC, thermal magnetic circuit breakers to 250% FLMC, dual element fuses selected to 200% FLMC, MSCP's and motor circuit protectors in combination with standard overload relays, Class 30 and 20. We see from this chart that the fuses and the thermal magnetic circuit breaker are much slower than many overload relays at currents 25 or even more than 40 times FLMC. That means starters must protect the branch circuit components and themselves for much higher currents than the currents for which they are being tested. Therefore, these components do frequently neither protect the wire nor the starters on low level faults with the exception of the motor circuit protector and the disconnect switch with MSCP. Figure 6 shows the superiority of the motor circuit protector and the MSCP. These elements cross the overload relay characteristics very steeply between 6 and 13 times FLMC.

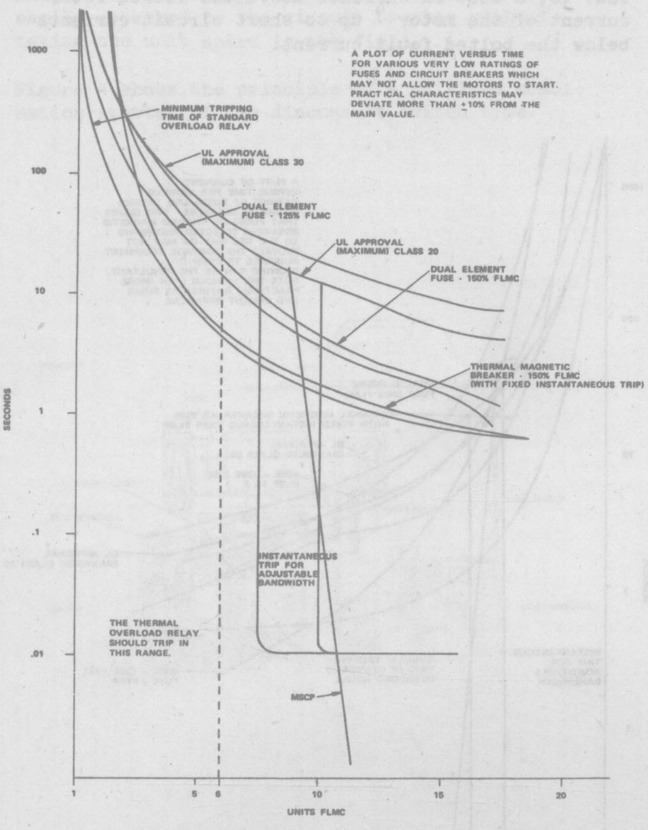


FIGURE 7

Figure 7 shows the characteristics of dual element fuses selected to 125% and 150% FLMC, thermal magnetic breaker to 150% FLMC, MSCP's, and motor circuit protectors in combination with Class 20 and Class 30 overload relays. We can see that often the fuses cause nuisance blowing, and that thermo-magnetic breakers would not allow the motor to start, besides they are only available in certain distinct ratings. Only motor circuit protectors and the MSCP secure that nuisance tripping or blowing may not occur and the branch circuit components are always protected.

The Meaning of I^2t

Excessive damage, even if permissible under fault conditions up to 100 KA available short circuit current, can be avoided if the I^2t limit of the protective device is lower than the weakest part of the system. It is generally quite difficult to define the requirement in I^2t for the protective device in order to satisfy the various permitted damage levels. Only approximations are possible and therefore tests on specific equipment must be conducted in order to insure complete electrical compatibility. If no damage to the control equipment at low rated currents, approximately 10 amps maximum (this number varies slightly), is permitted, we must look at the heaters. It was proved[2] that the heaters for these FLMC's are the most vulnerable part of the motor brancy circuit. In order to study what I^2t values heaters of various ratings can withstand, various methods can be applied. The simplest method is by computation.

a. The following formula can be developed:

The maximum allowable let through withstandability is:

$$I^2t = \frac{\Theta CW}{R}\ \text{Amp}^2\text{Sec}$$

Where

Θ = Maximum permitted temperature rise (for Nichrome it is 1350°C, a material which may often be used for heaters)

C = Specific heat of heater element material For Nichrome V C = 0.420 watt sec/g°C

W = Weight in grams of resistance material of the heater

R = Resistance of heater in ohms

Other materials change the resistance with the temperature. Then multiply the left side with a factor k expressing the average resistance change between the room and melting temperature.

b. Another way would be to check starters with oversized MSCP's since MSCP's have defined characteristics and I^2t values. Tests show which MSCP could be used on high fault currents without damaging the heater.

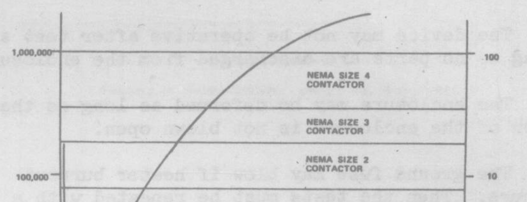


FIGURE 8

Figure 8 shows the approximate values for the withstandability and resistance of the heater. The resistance value is determined by the maximum permitted wattloss of the heater. We know from experience that the "no damage" level to contactors is very much dependent on the construction, the contact material, arc chamber, etc. Again, we can apply oversized MSCP's and see which MSCP doesn't cause any damage. Generally contactors are not damaged by comparatively fast interrupting RK5 fuses of 4 times FLMC rating at 5,000 amp available short circuit current for Size 1 and 2 contactors. Figure 8 shows also a minimum I^2t value at which contactors usually are not damaged. Tests for specific equipment are necessary. Generally we can assume that the damage level remains within Nema limitations under high fault conditions if tested with umbrella values of RK5 fuses at 175% of FLMC.

If overload relay burnout is permitted, the electrical withstandability through the whole system can be increased to its value in amp^2sec of contactors. This is especially important for small heaters. Attention must be paid that after heater burnout, a short circuit may be established. Then the electro energy through the system increases. Also the withstandability of the wire, especially aluminum wire, must be compared with the withstandability of the protective device. In nearly all cases we can assume that the contactor contacts lift off due to electro dynamic forces. Only very small heaters prevent lift off under short circuit conditions (bolted faults).

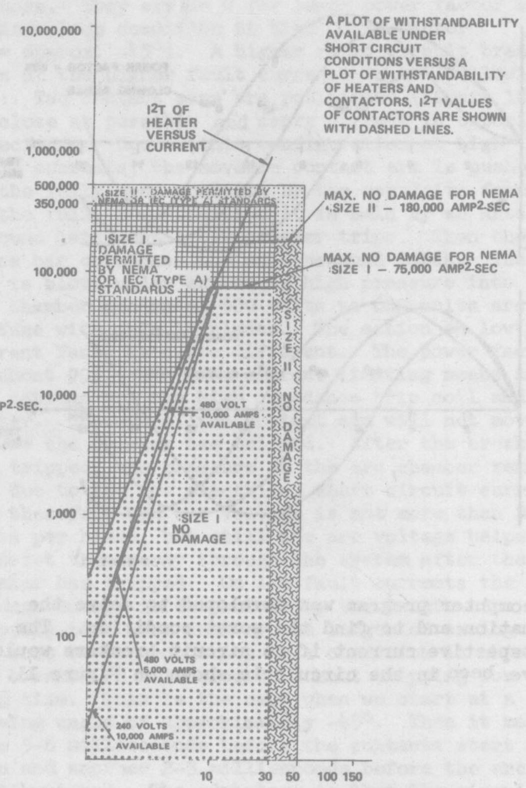


FIGURE 9

Figure 9 shows a basic chart of several plots of I^2t withstandability versus rated current of heaters for a unitized combination starter of the Amp Cap protector type. One line shown on the chart plots the I^2t withstandability of the various heaters in relationship to their current ratings. For any given heater, any I^2t below this line means that there is no damage done to the heater. Several other lines show the let through I^2t for circuits at various available short circuit currents and system voltages with the unitized combination starters having the proper heaters in the circuit. If these plots remain to the right or below the heater I^2t withstandability line, no heater damage occurs. For instance, for 10,000 amp available short circuit current at 240 volt and 5,000 amp at 480 volt circuits, all heaters are protected. For a 10,000 amp, 480 volt circuit, most heaters are protected.

One of the limiting factors for total protection is the I^2t withstandability of the contactor portion of a unitized combination starter. The Size 1 contactor can withstand approximately 75,000 amp^2second with no damage and can withstand 300,000 amp^2second with Nema or IEC Type A permitted damage levels. Approximate contactor portion values for Size 2 are shown on the chart. Testing at higher available short circuit currents will generate additional plots that will show where the various damage levels will occur. At higher available short circuit currents and at higher system voltage, the arc energy (arc voltage x let through current x interrupting time) is the limiting factor through the unitized combination starter. With HFCP's or MSCP's being used in the circuits, there should be practically no damage for all available short circuit currents up to 100 KA. Size 0 and 1 starters with small heaters suffer no damage when the peak let through current through the whole system is less than 1,000 to 1,500 amperes. In many cases the resistance of the heater restricts the peak let through current to a much lower value on any available short circuit current. If a standard motor circuit protector or a current limiting device at low fault currents protects the heater, generally the interrupting time is 10 to 12 milliseconds. The let through withstandability must be on the right side of I^2t curve of the heater. If protected by an HFCP, an MSCP, or fuse, the protective device must at approximately 800 amp RMS have less let through I^2t than $\frac{800^2 \times 10}{1000} = 6400$ amp^2sec. Contacts of Size 1 contactors lift off at approximately 1000 to 1200 amp instantaneous current, that means at approximately 800 amps RMS short circuit current. Due to the repulsive forces at the contactor contacts, the arc chamber and the contact material of the contactor becomes the determining factors for the contactor withstandability. The maximum peak let through current in the system under short circuit conditions usually is not so important. The peak let through current becomes important in defining how well conductors have to be supported and for the design of a disconnect switch with blow on contacts because a disconnect switch must close against the peak let through current under high fault conditions. The electrically compatible unitized combination starter with switch must close at available short circuit currents under fault condition, also with the largest placeable K5 fuses up to 100 KA and naturally with the MSCP or J fuses. If tested under high fault conditions, the withstandability of a combination controller is also dependent on the enclosure design if the equipment can withstand short circuits within the damage levels permitted by the standard.

UL approval was previously granted for combination controllers at available short circuits up to 100,000 amperes if protected by MSCP's or instantaneous trip type circuit breakers with HFCP's. In these cases the combination controller and other parts of the branch circuits in case of a fault are not damaged or suffer only insignificant damage.

Principle of Current Limiting Action Under Fault Conditions

Now let us investigate the difference between an instantaneous trip type circuit breaker and the Amp Cap or unitized combination starter. The Amp Cap or unitized combination starter, circuit breaker type, is current limiting. The existing current limiting circuit breakers were not built for industrial control purposes and usually do not limit the energy to a level to protect the down stream electrical equipment.

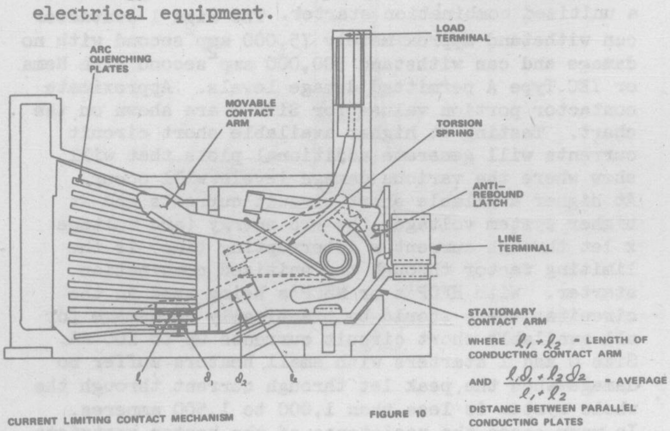


FIGURE 10

Figure 10 shows the principle of an Amp Cap, that means instantaneous trip type current limiting breaker. In contrast to other current limiting breakers for distribution equipment, a small physical size is required. Most standard current limiting breakers use either two arc chambers per pole or other complex physically large current limiting means. They limit the current under high available short circuit conditions for higher rated current devices, but not enough for lower current rated devices. Current limiting instantaneous trip type circuit breakers do not exist.

Heaters for small motor ratings can best be protected by high impedance interchangeable magnet coils. Short circuits for industrial control equipment rated 10 amperes or less have a power factor of 90% or more regardless of the available short circuit current since the resistance of the trip coil and the heater determines the power factor. The power factor for short circuits for industrial control equipment having a higher current rating is dependent on the available short circuit current which means it is usually 50% or less for available short circuit currents up to 10,000 amperes; 30% or less for available test circuit current of 20,000 amperes; 20% or less on higher available short circuit currents. In order to test the system, we have to find the worst closing angle. The equation for currents under high fault conditions is:

$$i/I_{max} = \sin(\omega t + \psi - \theta) - \sin(\psi - \theta)e^{\frac{-Rt}{L}}$$

i = current

θ = angle factor, $\cos\theta$ = power factor

f = frequency, $\omega = 2\pi f$

R = resistance

L = reactance of the circuit

$I_{max} = \sqrt{2}\, I_{RMS}$ = maximum available symmetrical short circuit current

ψ = closing angle of the driving voltage

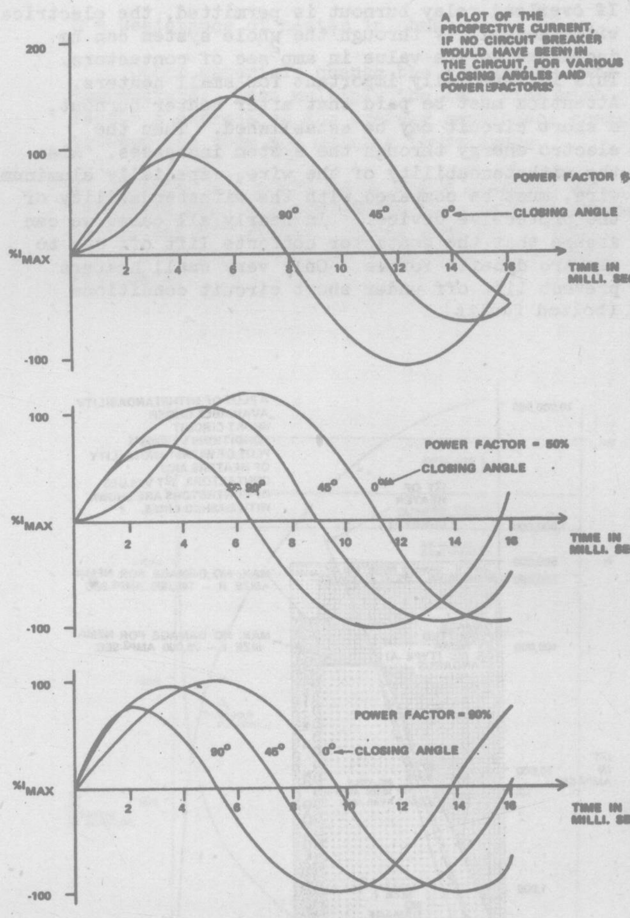


FIGURE 11

A computer program was developed to solve the equation and to find the worst condition. The prospective current if no circuit breakers would have been in the circuit is shown on Figure 11.

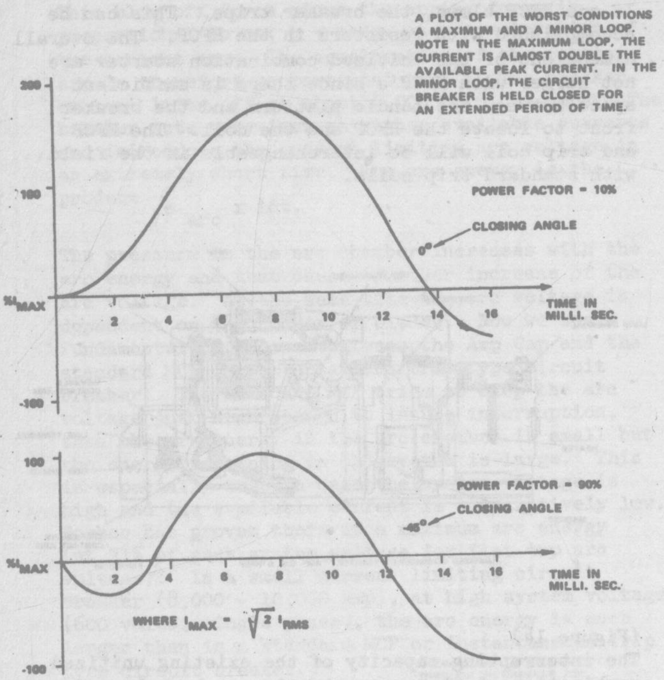


FIGURE 12

Figure 12 shows the worst condition (maximum energy to the down stream equipment) for various power factors. They are $\psi = 0$ for lower power factor and a minor loop condition at high power factor (ψ = approx. -45°). A higher rated circuit breaker acts at the higher fault currents in the following way: Two contact arms are positioned (Figure 10) as close as possible and carry current in opposite directions. Due to this configuration at high fault currents, the movable contact arm is pushed to the fully open position by the repulsive forces. In the fully open position it is held by an anti-rebound latch until the breaker trips. Then the cross bar unlatches the anti-rebound latch. The arc is blown under extremely high pressure into the arc chamber producing 500 volts to 600 volts arc voltage with only 12 blades. The action on low current fault is quite different. The power factor is about 90%. The main current limiting means at low ratings are the high impedance trip coil and heater. Therefore, the contact arm will not move before the breaker has tripped. After the breaker has tripped, the pressure in the arc chamber remains low due to the low electrical short circuit current and therefore the arc voltage is not more than 25-30 volts per blade, but still the arc voltage helps to restrict the energy through the system after the breaker has tripped. On low fault currents the let through energy is determined by the length of tripping time more than by the length of arcing time. The most severe condition is a condition in which the breaker is held closed without tripping for a long time. This is the case when we start at a closing angle of approximately -45°. Then it may take 5-6 milliseconds before the contacts start to open and another 2-3 milliseconds before the arc is distinguished. The advantage is that the circuit has a high power factor. Therefore, it can be easily interrupted. We can now develop the I^2t values for interrupting low fault currents. Let us now look at high fault currents:

For breakers having high rated current ($\gtrsim$ 10 amps), the principle changes. The maximum peak let through current of a current limiting breaker is then reached when:

$$L\frac{di}{dt} = e_{sys} - e_{arc} = 0, \text{ that means } \frac{di}{dt} = 0$$

The resistance can be neglected especially on higher fault currents.

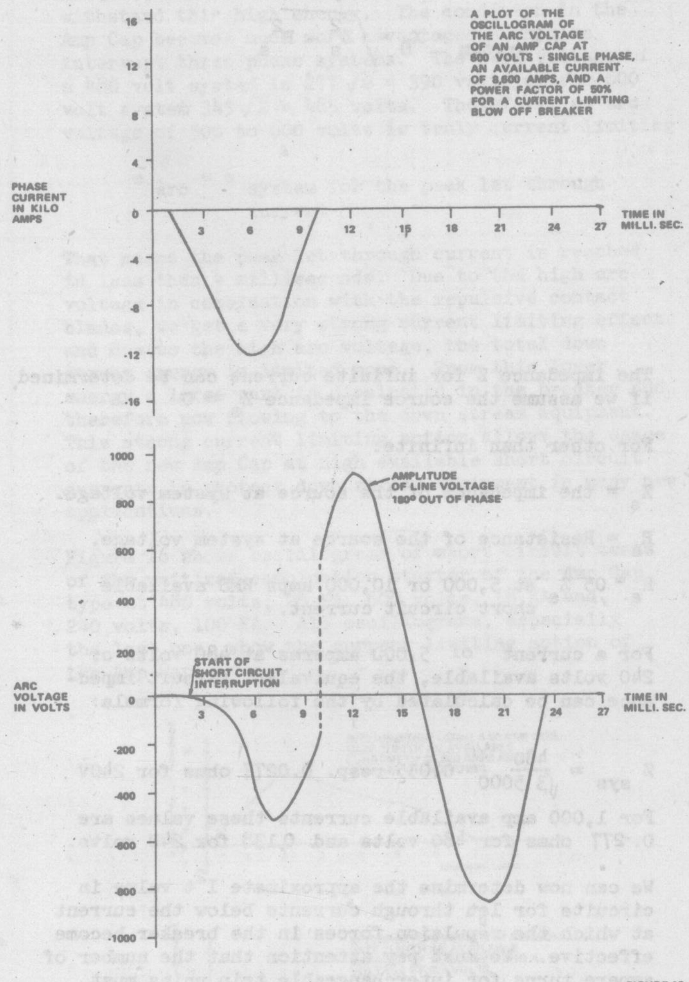


FIGURE 13

Figure 13 shows the oscillogram of the arc voltage, line voltage, and the current at 600 volt AC at the worst closing angle at 8660 amp RMS available short circuit current through the breaker contacts. For lower rated current (high impedance circuit) the I^2t through the breaker can be calculated for the time until the breaker trips and the time during which the breaker interrupts. We determine $e_{system} - e_{arc} = e$. e is practically in phase with the current and the total I^2t is calculated by the following formula, now the reactance can be neglected: