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Low Voltage Motor Control Centers Utilizing Microprocessor Technology

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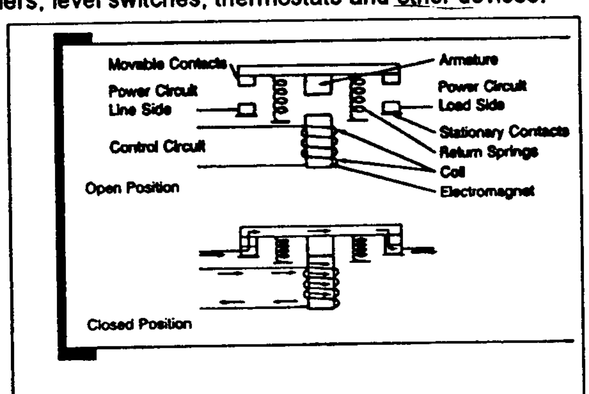
Abstract - Low voltage squirrel cage induction motors are used in cement mill conveyors, dust collectors, crushers, mills, separators and fans. There are many types of starters used to control these motors, including manual, magnetic, solid state and adjustable frequency. However, most motors in the 10 to 400 hp range use magnetic contactors with thermal overload relays. Recently, a new type of magnetic starter was invented that includes a built-in microprocessor. This paper describes the design of this starter and how this new design is able to solve a variety of problems inherent with conventional magnetic motor starters.

I. INTRODUCTION

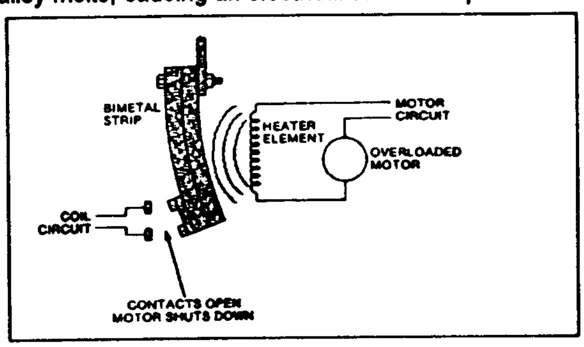
The magnetic motor starter was developed to allow remote control of a motor. The basic operation of a motor starter is simple. The motor starter closes a set of contacts whenever a voltage is applied to the starter coil. These contacts, in turn, transfer power to the electric motor. When the control voltage is present, the contacts close and the motor starts. When the control voltage is removed, the contacts open and the motor coasts to a stop. This control voltage can be applied by pushbuttons, timers, programmable controllers, level switches, thermostats and other devices.



Motor Contactor Functional Schematic
Figure 1

In addition to energizing and deenergizing a motor, the starter also attempts to protect a motor from overload. By measuring the current flowing to the motor through the starter, the starter can decide when the current level is unsafe and deenergize the motor.

Most motor starters do not measure current directly. Rather, current is determined by measuring the heat produced from a calibrated shunt (heater). Motor current is passed through this shunt. During overload conditions, the heat produced from this shunt builds until a thermostat trips or a specially formulated metal alloy melts, causing an electrical switch to open.



Thermal Overload Relay Schematic (Bimetallic Type)
Figure 2

II. TYPES OF STARTER FAILURES

The previous discussion described normal operation for a magnetic motor starter. Unfortunately, a starter can malfunction for a variety of reasons such as:

1. Starter contacts opening during a fault, exceeding the interrupting rating of the starter.
2. Contacts that have been eroded little by little until there is insufficient material to conduct the motor current adequately.
3. Contacts that have been welded shut, preventing the motor starter from deenergizing the motor.

4. Starter coils that have burned out, preventing the contacts from closing under automatic control.

5. Insufficient overload accuracy resulting in either tripping too soon (nuisance trip) or too late (motor burn-out occurring).

6. The overload relay becoming uncalibrated after a large overcurrent damages the current shunt (heater).

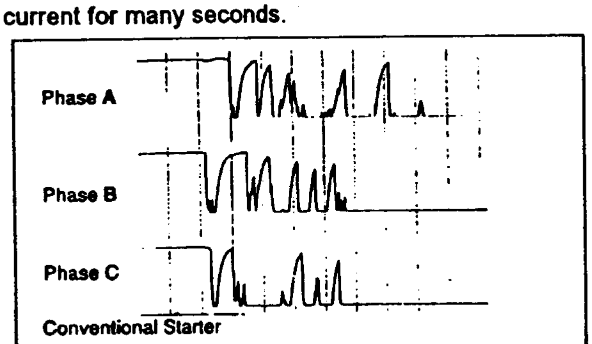
Depending on which problem occurs, the results could be catastrophic. Because of the cost of downtime and safety concerns of unscheduled motor shutdowns due to starter failures, a design program was undertaken to learn the reasons for starter failure.

III. REASONS FOR STARTER FAILURE

A. Starter Opening During Fault
All magnetic starters have an interrupting rating. When a starter opens while carrying excessive current, the magnetic forces that form between the contacts may produce sufficient force to damage the starter. In addition, the heating resulting from this arc can be damaging.

A conventional starter does not prevent the main contacts from opening during an excessive overcurrent condition. With a conventional starter, whenever coil power is removed, the starter contacts open without regard to whether it is safe to do so. Opening a starter's contacts while high current is flowing through the starter can cause serious damage to the starter.

B. Contact Erosion
High speed analysis of a starter closing operation shows that contacts bounce for a short time after closing. At each bounce, an arc is drawn and a portion of the contact material is vaporized. Note that this bounce occurs at the worst possible time since a motor draws inrush current immediately after being energized. This inrush current is typically 13 times full load current for one-half cycle, followed by 6 times full load current for many seconds.



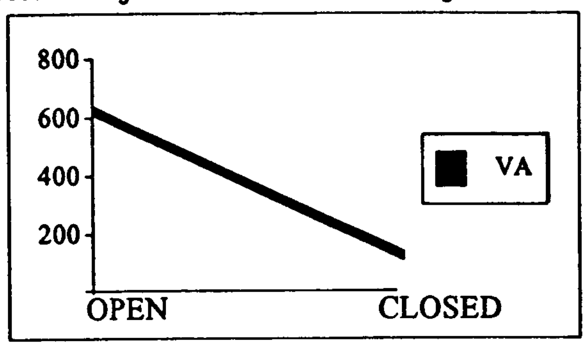
Contact Bounce following energization
Figure 3

Studies show that conventional starter contacts bounce from 10 to 40 times after coil energization.

C. Welded Contacts
Welding occurs when hot molten contacts are brought in contact with each other and then cooled. Contacts can be heated to melting by the arcing of normal closing, but typically the extreme heat necessary to melt contacts occurs only when the arcing occurs for an extended period. Some reasons for extended arcing include:

- Low or intermittent coil power causing the contacts to bounce open and closed repeatedly.
- Jogging or plug reversing a motor.

D. Coil Burn-Out
An AC coil draws current inversely proportional to its impedance. When the coil impedance is low, the current flowing to the coil is high. With a magnetic motor starter, the coil impedance is low when the starter contacts are open. As the contacts close the coil impedance begins to rise and the current begins to fall.



NEMA Size 4 Coil Volt-Amps vs. Contact Position
Figure 4

The starter coil is not designed to carry "open starter" current continuously. The coil current must drop to the "closed starter" current within a few seconds. If the starter is prevented from closing, and the coil voltage continues to be applied, the coil may burn out.

E. Overload Accuracy
Strictly speaking, conventional overload relays (bimetallic or eutectic alloy) do not measure current, they measure the heating of a temperature sensor because of current flowing through a calibrated shunt (heater). The more current flowing, the more heat given off by the shunt and the sensor reaches its preset trip level faster. When the temperature sensor reaches a preset level, the overload relay opens a set of contacts. When these contacts open, power is removed from the starter coil and the motor coasts to a stop, thus preventing a motor burn-out. Since the time to trip is a function of heat transference between a heater

and a temperature sensor, contaminants, such as dust and dirt, can affect the accuracy of the overload relay.

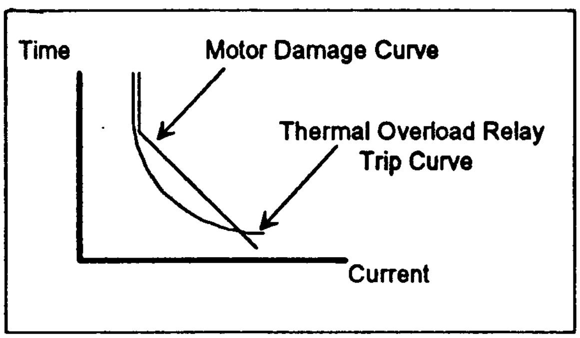
Also, it has been shown that the time-current trip curve for a thermal overload relay is only an approximation of the actual heating that occurs in a motor. Typically the heating in a motor is defined by the following equation:

$$\text{Motor Heating} = KI^2t + K_nI_n^2t + K_0I_0^2$$

Nomenclature

- K Positive sequence scaling factor
- I Positive sequence current
- t Time (seconds)
- I_n Negative sequence current
- K_n Negative sequence scaling factor
- I_0 Zero sequence (ground) current
- K_0 Zero sequence scaling factor

The amount of heat necessary to damage a motor is defined by the motor damage curve. Currents persisting for greater than the time defined by the motor damage curve will result in motor damage. Often, the motor damage curve follows a constant I^2t curve. The thermal overload relay does not. Note that motor heating is proportional to the square of the current. Plotted on log-log paper, the heating as a function of current and time is a straight line. Superimposing the motor damage curve with the typical overload trip curve looks like this:



Thermal Overload Tracking of Motor Damage Curve
Figure 5

Near the top of the motor damage curve, the thermal overload relay typically under-protects the motor, since it trips too slowly to protect the motor from damage.

At other points along the curve, the thermal relay trips too soon. This is termed "overprotection." Overprotection by an overload relay may prevent a motor from starting a high inertia load, even if the motor is designed to handle the load.

F. Overload Relay Damage Due To Faults
As with the contactor, there is a maximum instantaneous current and I^2t rating of the overload relay. Exceeding either of these values can result in damage to the overload relay. In extreme cases, fault currents can burn out heater elements, resulting in a single phase condition. In a less severe case, the heater element characteristics may change because of the fault, resulting in impaired operation.

IV. PREVENTION OF STARTER FAILURE

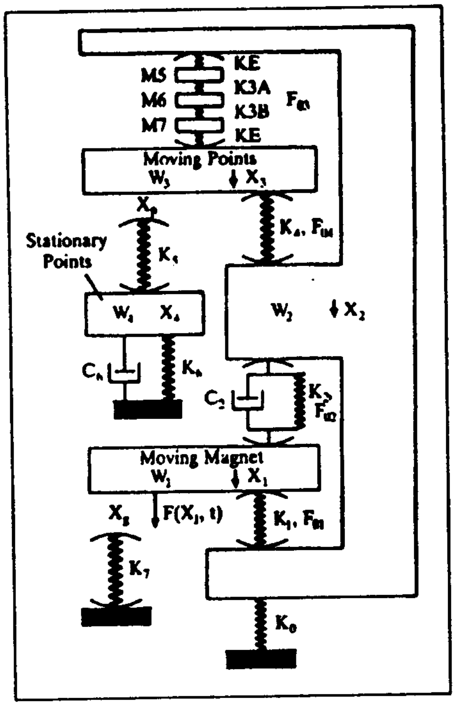
After analysis of the failures mentioned in the previous section, various solutions were proposed. The next section of this paper describes those solutions and how those solutions were incorporated in a new starter design.

A. Do Not Open Contacts During High Overload
One method for preventing the starter from opening during an excessive overload is to monitor the current flowing through the starter, and prevent the starter from opening if the current is too great. This is precisely the method used by this new starter design. Using built-in current sensing, the starter compares the current flowing through the overload relay with the pre-programmed interrupting rating of the starter. If the instantaneous current flowing through the overload relay exceeds the interrupting rating of the starter, the external stop signal or overload trip signal is temporarily ignored. This gives the upstream short circuit protection sufficient time to clear the fault.

Attempting to interrupt a fault with a starter can result in damage to the starter, sometimes with spectacular results. Always use the short circuit protection, such as a breaker or fuse, to clear such a fault. However, for those extraordinary situations that require it, the starter can be told to open despite the magnitude of current flowing through it.

B. Reducing Contactor Bounce
Several years ago, it was recognized that by reducing the amount of contact bounce, the contacts would last longer. One way of reducing contact bounce would be to choose springs that precisely dampen the bounce. After all, in its simplest form, motor starter contacts can be viewed as a mass suspended by a spring and acted upon by a force (starter coil).

1) Mathematical model development
To analyze if it would be possible to develop a bounceless contactor, a mathematical model of a contactor was developed. After completing the model, an attempt was made to find the optimal tuning of spring constants, mass and coil force necessary to minimize contact bounce.



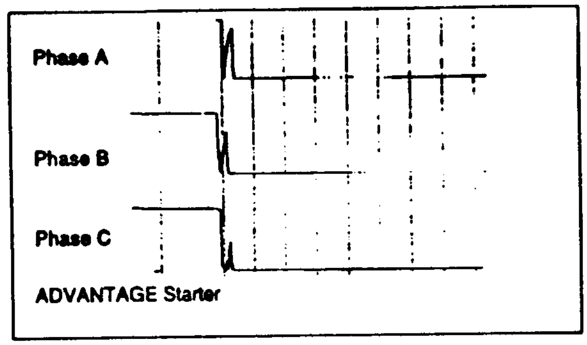
Mathematic Model of Magnetic Contactor
Figure 6

After completing the analysis, it was discovered that it was possible to tune the springs for minimum bounce, but the optimal spring constants would be valid for one and only one value of force exerted by the coil. Unfortunately, the coil force varied both as the coil voltage varied and on something more difficult to control. This second, more difficult item was phase angle. Since coil force is based on instantaneous coil voltage, and since a sine wave's instantaneous voltage varies with time, coil force becomes a function of where on the sine wave voltage is first applied to the coil.

The solution was to control the magnitude and duration of voltage applied to the coil. By triggering the coil for portions of AC half cycles, but always triggering at 0°, the force provided by the coil can be precisely controlled.

An analogy of how a conventional contactor closes would be like driving your car into your garage with your foot on the gas and only removing your foot from the gas when you crash into the back wall. Using an energy balance contactor, you would accelerate, then coast to a stop against the back wall.

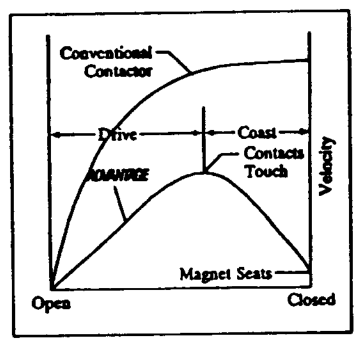
Experiments have shown that this new starter consistently bounces from 0 to 4 times before seating. This compares very favorably with the 10 to 40 bounces of a conventional starter. This reduced bouncing results in improved contact life.



Coil Controller Reduces Contact Bounce
Figure 6

2) Recipe selection

The secret in supplying the precise amount of force is to look up a "closing profile" from a table of possible choices, before telling the starter to close. The microprocessor selects this profile based on coil current. In other words, to select this profile, the microprocessor pulses a known voltage across the starter coil and measures the amount of current flowing. Based on the current value, a "closing profile" is selected. A closing profile defines how much voltage will be applied to the coil and for how long. For example, a typical profile might be 100% voltage for one-half cycle followed by 80% voltage for another half-cycle, 60% voltage for another half cycle and so on until the contacts close. The result is an "energy balanced close."



Energy Balanced Contactor "Coasts" Closed
Figure 7

Note that the energy balanced contactor closes at a lower velocity than the conventional starter.

Another benefit of having a smart coil controller is that the controller allows the starter to operate over a wide control voltage range. For example, using a 120 Vac rated coil, experiments have shown that this new starter can achieve the specified 0 to 4 bounces over an input voltage range of 78 to 144 Vac (65 - 120% of nominal coil voltage).

Many conventional starters only meet the NEMA Standard ICS 2-110 that requires a starter coil operate "without damage" from 85 - 110% of their rated voltage. However, at these voltage extremes, the bounce performance of the conventional starter is significantly degraded.

C. Preventing Welded Contacts
Welding typically occurs when the contacts are exposed to prolonged arcing while in the "kiss" position. This prolonged arcing can be the result of intermittent or low control voltage. This low or intermittent control voltage causes the contacts to chatter resulting in excessive arcing and contact heating.

To prevent intermittent or low control voltage from damaging the contacts, this new starter monitors input voltage and only commands the starter to energize if the voltage exceeds a preset amount for a preset time. These values have been chosen as 78 Vac for 1/20th of a second.

Once the starter contacts are closed, the input voltage must drop below 60 Vac (50% of nominal) before the microprocessor commands the starter to deenergize. To provide additional protection for the contacts, a built-in backspin timer is included. This timer prevents the starter from being energized within 1/2 second from when it was last deenergized.

D. Solving Coil Problems
Besides controlling the amount of energy needed for a "zero bounce" close, a microprocessor also can be programmed to guard against conditions that could damage the coil.

In a conventional starter, a voltage can be applied to the coil that is too low to seat the contacts properly, but high enough to allow the contacts to begin to close. The result can be a light closing force called "kiss." If the kiss contact position is allowed to persist, contact arcing, chattering and accelerated erosion can result. Also, since the coil current draw is high until the contacts seat, the coil will begin to overheat. The result can be coil burnout.

One way of solving the coil burnout problem would be to program the coil controller to verify:

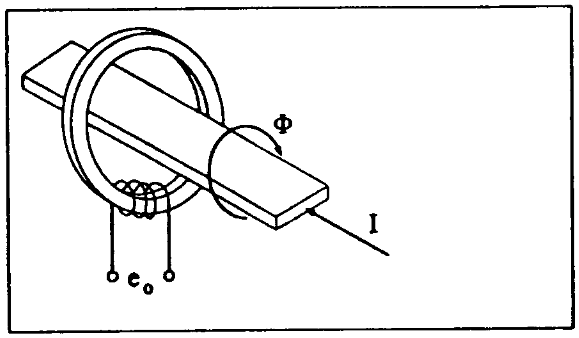
- If sufficient control voltage is available.
- If sufficient "power" is available from the control voltage source.
- If the control voltage is a transient, or if it is a real closing voltage signal.

Note that the coil controller must differentiate between sufficient *voltage* and sufficient *power*. Situations where sufficient voltage is available but sufficient power is not include:

- Undersized control power transformer.
- Defective control power transformer.
- Corroded or loose control wiring.
- Overheated starter coil.

By monitoring these conditions, this new starter reduces the likelihood of a coil burnout.

E. Improving the Overload Relay
Instead of measuring heat as a byproduct of motor current flowing through a shunt, an improved overload relay should measure current directly. Then, this current should be used in the I^2t equation of the overload relay to decide if the motor is overloaded. In the past, electronic overload relays have been available that do just that. However, older electronic overload relays used conventional current transformers (CT). These CT's were used to reduce the current level passing through the overload to a manageable value that can be monitored by the electronic circuit. A weakness of this design is that during fault conditions, the current output from the CT can be quite large. This excessive current level can damage the circuitry of the electronic overload. To overcome this problem, a new type of current sensor was developed.



Current Sensor
Figure 8

This sensor saturates during periods of excessive overcurrents, thus limiting the amount of energy transferred to the electronic circuit. Also, this current sensor outputs a voltage instead of a current. Specifically, the output voltage of the sensor is proportional to the change of current flowing through it. The accuracy of this device has enabled the new starter to calculate motor current with a 2% accuracy over the entire range of 20% to 600% of the rated full load amperes of the starter.

An additional benefit is the elimination of heaters. The user selects a full load current and overload class by setting a DIP switch. Class 10, 20 or 30 overload protection may be selected. The ability to select multiple overload classes on the same relay allows the engineer to provide accurate protection for a variety of loads, without changing the overload. Inventory can be reduced since heaters and different class overload relays are not required.

F. Overload Damage After a Fault
Since this sensor saturates at high current levels, much higher fault current withstand ratings are provided when compared with either conventional overload relays or electronic overload relays that use CTs.

V. OTHER BENEFITS

Up to this point, the main enhancements described have been in the form of improved starter life. However, other problems exist with the conventional magnetic starter.

A. Starters Generate Heat
The new starter design reduces heat generation three ways:

1. Contact force is greater, thereby reducing heating losses across the contacts. In conventional starter designs, there is a trade-off between contact force and low bounce. In a conventional starter, increasing the coil force increases the contact bounce. With the new starter, the combination of powerful contact over-travel springs and microprocessor based coil controller results in low bounce but high contact force.

2. No heaters are used. Heaters generate waste heat as a byproduct of the current flowing through them. By eliminating this heat generation and instead measuring current directly, less heat is produced.

3. More efficient coil design. The coil uses less power for two reasons. One, the coil is a DC coil rather than an AC coil, so shading coil and eddy current losses are not a factor. Second, by using a coil controller, only the required amount of energy is supplied to the coil. Compared to our previous design, these savings amount to a 30% reduction in watts dissipation.

B. Monitoring of Phase Unbalance and Ground Fault
Unbalanced phase currents can cause the motor to overheat more rapidly than with balanced currents, risking a motor burnout before the overload trips. Also, ground currents could suggest a safety problem, in that one phase within the motor has been inadvertently grounded.

To solve both problems, the microprocessor was programmed to test for these conditions and trip if either a Class II ground fault or a 30% or greater phase unbalance persists for more than a preset time. Built-in start delays reduce nuisance tripping.

C. Reduced Inventory
Since heaters are not required, inventory can be reduced.

D. Balanced Contact Wear
A particular problem occurs when a conventional starter is controlled by a programmable controller or other solid state output. Since the solid state output always shuts off current during a current zero, the starter will always be told to open during the same phase sequence. Over time, this causes unbalanced contact wear. This unbalanced wear may require that the contacts be changed more frequently.

With the new starter design, the starter remembers the order in which the phases were last opened. The starter will then rotate the sequence so that the phase sequence is different each time the contacts open.

E. Smaller Size
By building the overload relay into the starter, instead of adding one on, the new starter design is more compact. Even compared to IEC, this NEMA rated starter may be 50% smaller. For example, using the new design, a NEMA size 4 combination starter can now be built in a 2X motor control center bucket. Compared to our previous MCC design, this is a 33% space savings.

VI. COMMUNICATIONS

Another advantage of placing a microprocessor within a motor starter is that data can be read from the starter. This microprocessor can be programmed to monitor and record:

- Individual Phase Currents
- Ground Current
- Control Voltage
- Contactor status (Open/Closed)
- Overload status (Normal/Tripped)
- Type of Trip (overcurrent, ground, phase fail, etc.)
- Overload Settings (FLA, Class, Manual/Auto reset)

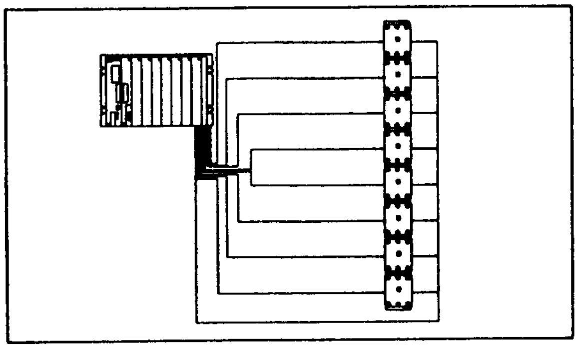
With this new starter, this information is available via a twisted pair network that connects up to 1000 of these devices on up to 7500 feet of cable. Using a plug in card, this data can be brought to a computer or programmable controller. Using a separate interface, this signal can be converted to RS-232 and sent to more remote sites via modems.

Some possible ways of connecting to this network include:

A. Connecting To Programmable Controllers (PLCs)
In a conventional motor starter, a programmable controller output module must be wired to provide voltage to the starter. When the programmable controller pro-

gram decides to energize the starter, the output module sends the necessary voltage.

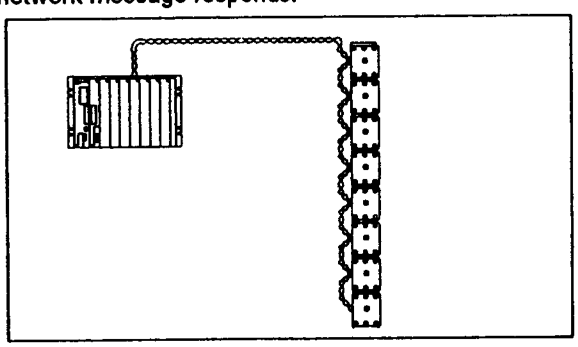
If two starters are to be controlled from the PLC, then two outputs from the programmable controller must be wired. If two hundred starters are to be controlled, then two hundred points on the programmable controller must be wired between the programmable controller and the starters.



Conventional Starter to PLC Wiring
Figure 9

This new starter can be wired just like a conventional starter. However, since the new starter has a microprocessor, a unique layout is possible.

Using the microprocessor within the starter, each starter can be given a unique network address. In this manner, the same wire can be connected to each starter, but only the starter whose address matches the network message responds.



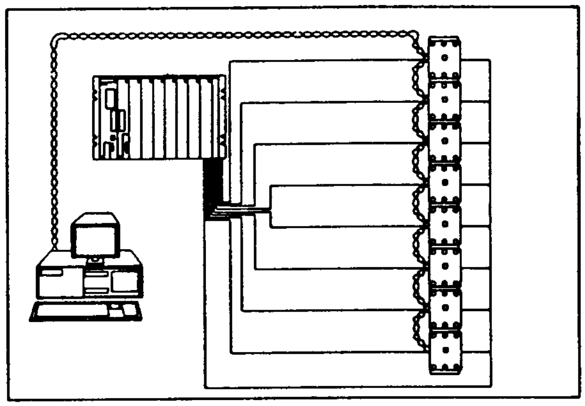
New Starter Connects Directly to PLC with single pair
Figure 10

One benefit is that the corresponding output and input modules in the PLC I/O racks are not required. Another benefit is the ability to monitor status information from each starter. For example, not only is it desirable to know if the starter is closed, opened or tripped, but other information that is available at the starter may be useful such as:

- Why did the starter trip? Was it a ground fault / phase unbalance / overcurrent trip? What was the magnitude of the ground fault / phase unbalance / overcurrent at the time of the trip?
- Does the starter show that sufficient control voltage and/or control power is available to energize?
- What is the present value of phase current flowing in each of the three motor phases?

All of this information is available at the PLC without the PLC requiring either digital or analog I/O modules. And as additional starters are added to the network, no additional I/O modules must be purchased.

B. Connecting To Computers
As with programmable controllers, the twisted pair network can be brought to a computer. Using either a plug in board or the RS-232 port, messages can be sent from the computer to control and/or monitor the starter. One possible variation is to have both a PLC and a computer connected to the same starter. Connect the PLC output modules to the input terminals of the starter and connect the twisted pair network to the computer.



PLC and Computer Connected To New Starter
Figure 11

VII. CONCLUSION

Using the microprocessor, the AC motor starter can now:

- Perform an "inrush make / full load break" (AC3) test for twice as many operations as the next best starter tested.
- Operate reliably without nuisance coil burn-outs during low or fluttering control voltage
- Include an overload relay that provides 2% metering accuracy as well as ground fault and phase failure protection.
- Communicate with other automation.

VIII. REFERENCES

"Advantage Reference Guide," Westinghouse Electric Corporation