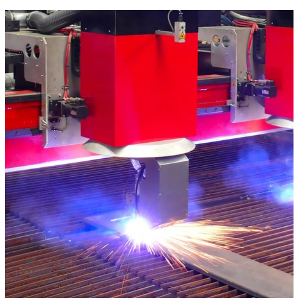

The Inside Story on

Phase Failure Protection

TECH-PHASEFAILURE_v115 01/2015

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Introduction

One of the outstanding features of IEC type overload relays is protection of three phase motors in the event of a single phase condition; otherwise known as “open phase” or “phase failure “ in one of the motor leads. Basic training programs usually deal with this subject in a simplified manner. This white paper will go inside the motor and provide a more detailed look into what happens when one phase of the power supply is lost and how Sprecher + Schuh overload relays handle the phase failure.

Most of the motors that we encounter are delta-connected squirrel cage induction motors. The current (le) flowing thru the outside conductors leading to the motor is in fact of a greater magnitude than the current (Ip) flowing thru the deltaconnected phase windings of the motor. In normal operation (Figure 1) the phase currents (Ip) are 1/ 1.73=0.58 (1 .73) derived from square root of 3) smaller than the currents (Ie) in the outside conductors (Ip = 0.58 Ie). In the event of a phase failure on one leg of the power source (Figure 2) the current in one phase of the motor increases to 2/3 Ie. The two other phases are now connected in series, therefore the current decreases to 1/3 Ie.

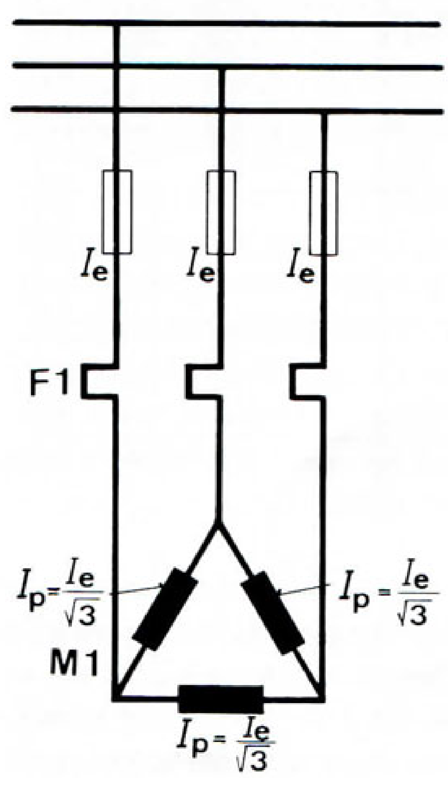

Figure 1

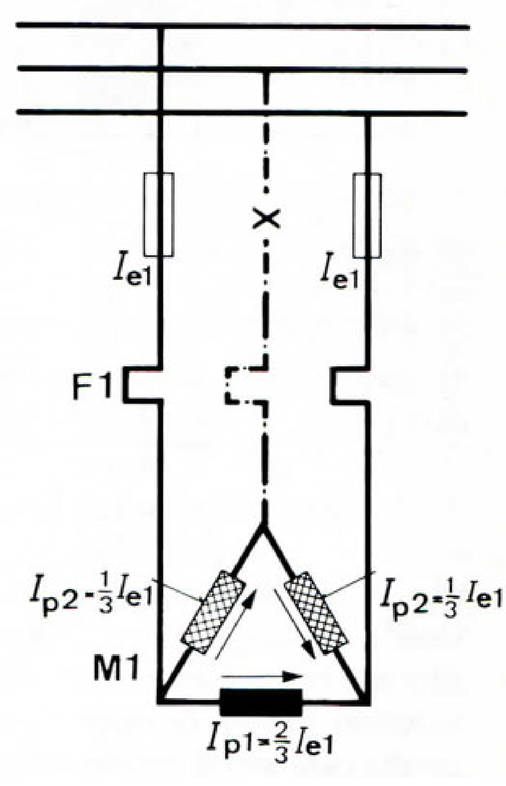

Figure 2

What Happens Inside the Motor

The moving rotor cuts the stator field flux and causes induced voltages and currents in the rotor bars. The rotor currents create a rotor field with poles midway between stator poles. The rotor current will lag nearly 90 degrees; therefore, the rotor and stator are 90 degrees out of phase (similar to a two-phase motor). The following phase currents resulting inside the motor are Ip = 2/3 Ie1 and Ip2 = 1/3 Ie1. If we assume that the current in the outside conductors does not increase Ie1 = Ie, then Ip1 = 1.15 Ip and Ip2 = 0.67 Ip. This would make a nice neat solution except in the real world we cannot make this assumption.

In the real world, the motor shaft power output normally remains constant. This means that the magnitude of current in the two outside conductors (Ie1) and the resulting motor phase currents (Ip1, Ip2) become greater by a factor that depends on the motor load. The old rule of thumb that the current of the outside conductors increases by 1.73 (173%) is a simplification and is only true at 75% load. We can see from the graph in Figure 3 that the resulting currents from various (P/ Pe) load factors are not a straight-line function.

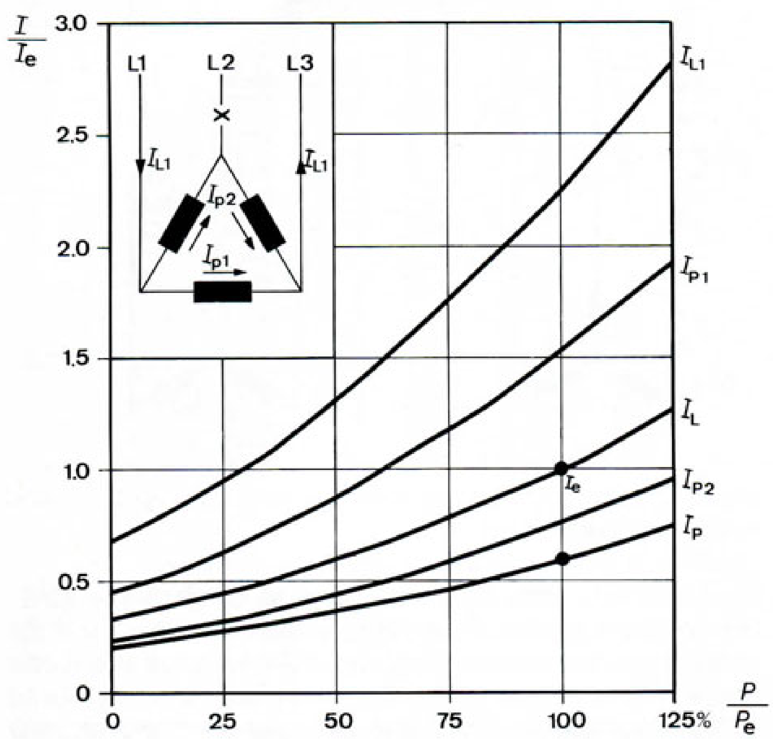

Figure 3

Since Ie represents rated outside conductor currents (FLA) at 100% load in normal operation we shall pick this point to start our explanation. Under 100% undisturbed operational load, when a loss of phase is experienced the outside conductor current (IL1) in the two remaining legs will rise approximately 225% of rated FLA (Ie). The thermal overload relay in the starter circuit would be monitoring this current increase. Currents within the phases of the motor would follow the formulas expressed earlier:

$Ip = 1/1.73\ IL = 0.58$

$Ip1 = 2/3\ IL1 = .67 \times 2.25 = 1.51$

$Ip2 = 1/3\ IL1 = 0.33 \times 2.25 = .74$

We noted earlier that at 75% load IL1 would be approximately 173% of FLA and at 50% load IL1 would be approximately 132%. Finally, at 25% load IL1 would be less than FLA but still more than IL, the outside current in normal 25% operation. All these values can be picked off the graph in Figure 3.

We have thus far only addressed what happens to currents during running conditions because most experts agree that a three-phase motor will not start with an open phase. Some reference books suggest that the motor may start in the reverse direction under an open phase. This means that at the least locked rotor amperes would be experienced and most motor manufacturers tell us that a T-frame motor will experience failure under locked rotor (6 X FLA) in approximately 15 seconds . A class 10 differential overload relay would trip in 6 seconds if single-phase were present at start up. During stead state running mode, if a phase loss occurs, then we expect tripping to occur within 45 seconds with a thermal overload device, and within 3 seconds with a solid state overload device.

The heat buildup in a winding is proportional to the square of the current due to heat exchange among the windings, as well as between the windings and the adjacent metal. The heat produced in the entire stator is proportional to the sum of the losses in all three phases. The critical squirrel cage motor rotor design characteristics are the mechanical stresses caused by heat. Excess heat may result in desoldering of the rotor bars. In general, the rotor losses resulting from an unbalanced current flow (phase failure) are substantially higher than in normal operation. Increased losses mean the rotor will be additionally heated. The aging of insulation material (like that used in the stator windings) is a chemical process that is rapidly accelerated by temperature in excess of the class rating. It is generally accepted that a continuous winding temperature 10 degrees above the class rating limit will halve the service life each time it occurs. All of this information leads us to conclude that the real issue is determining what happens to operating temperature under a single phase condition. This can be seen in Figure 4.

Heat Build-up in the Motor

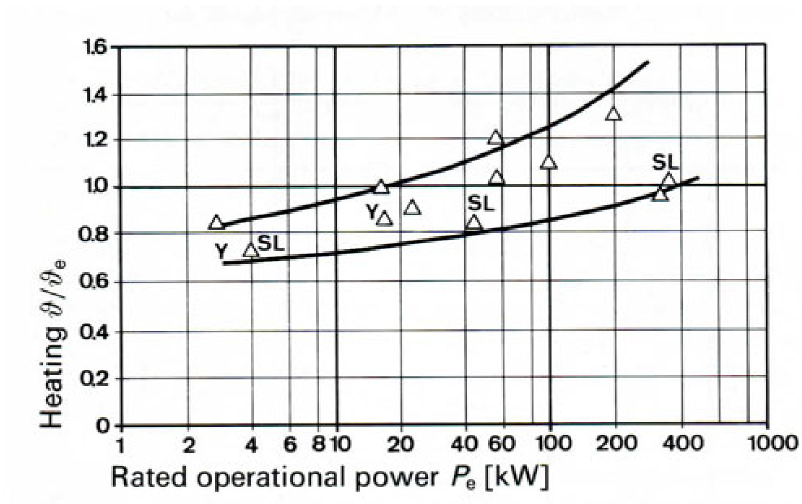

Figure 4

In Figure 4, the X-axis is the rated operational power in kilowatts of various motors. The Y-axis is a ratio of the temperature measured in the phase failure mode over the temperature in the rated three-phase operating mode. There are various ratings, designs and rotor types represented in the graph.

Δ Stator winding, delta-connected
Y Stator winding, wye-connected
SL Slip-ring motor

Note that we are currently discussing delta connected stator windings. Since squirrel cage motors are considered "rotor-critical" motors, we are primarily concerned with worst case scenarios, which is the upper range of the plots. Note also that the loads were selected such that the outside conductor currents in the open phase mode were of the same magnitude as the operating currents of the motors in three-phase operation. This data shows that motors 10KW or less develop less heat under single phase condition than under normal three-phase operation. This means that no special phase failure protection need be provided for motors 10KW or less.

HP = KW/746 if efficiency = 1
HP = 10/0.746 = 13 or 10 HP motors

We may also note that wye-connected motors are not endangered by phase failure conditions. This should be expected since in a wye connection under phase failure, the currentless third winding is a sink for excess heat. Delta-connected motors rated higher than 10KW need additional phase-failure protection in the form of motor overload detection. Two types of overload relays used to detect phase failure are thermal bi-metallic relays using differential tripping, and electronic overload relays using micro-electronics to measure current directly.

Thermal Overload Relay "Differential Tripping"

Similar to their NEMA counterpart, IEC overload relays pass the running current through a set of three bimetallic heaters. The heat generated by the current causes the bimetal to bend at a proportional rate. Under a symmetrical three-phase overload, the bending bimetal pushes against a tripping mechanism, which opens a normally closed contact in the control circuit. This in turn de-energizes the coil and opens the main power contacts.

The primary difference between IEC style thermal overload relays and NEMA style overload relays is the double slide bar tripping mechanism (Figure 5). This mechanism is at the heart of the IEC "Differential Tripping" concept. Slide Bar I is spring loaded to the right while Slide Bar II is spring loaded to the left. Hinge points connect the two slide bars to the tripping lever.

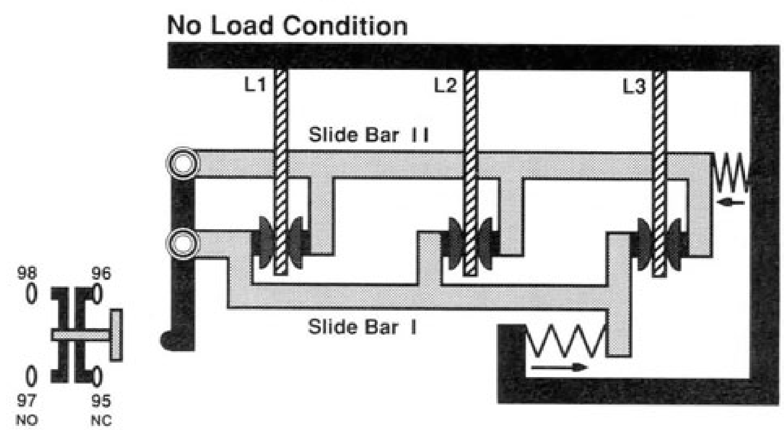

Figure 5

Under any three-phase symmetrical load, the two slide bars act like a single slide bar. When current heats the three bimetals they push against Slide Bar I. Slide Bar II follows at the same rate due to spring tension. Any normal three phase symmetrical running load (less than FLA) would position the tripping lever short of tripping the normally closed contacts (Figure 6). A three phase symmetrical overload (greater than FLA) would bend the bimetals even more, shifting the slide bars and the tripping lever (all at the same rate) over an additional distance. This additional movement would cause the tripping lever to open the normally closed contacts (95 & 96).

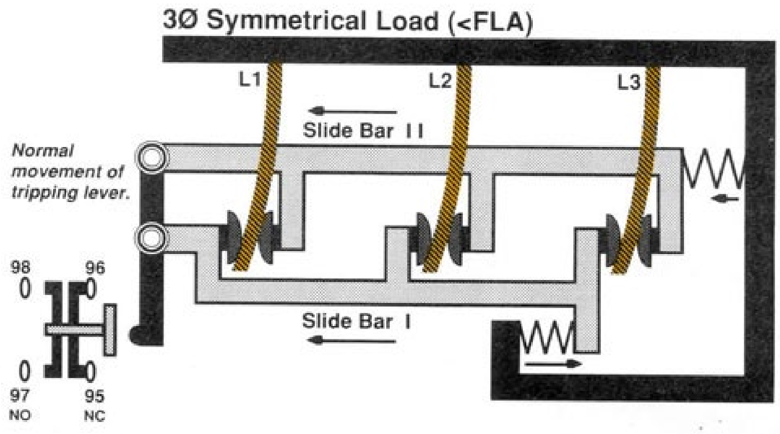

Figure 6

The purpose of the two individual slide bars becomes quite evident during a phase failure condition. In Figure 7, when one of the phases are lost (L3 in this example), the cold bimetal heater would hold Slide Bar II in the original position while the additional current passing thru the two remaining bimetal heaters would shift Slide Bar I. This action produces an accelerated movement of the tripping lever, causing the normally closed contacts to open. It is important to note, that any unbalanced loading of one or more of the three bimetal heaters would cause a differential shift of Slide Bar I relative to Slide Bar II; thus the name "Differential Tripping".

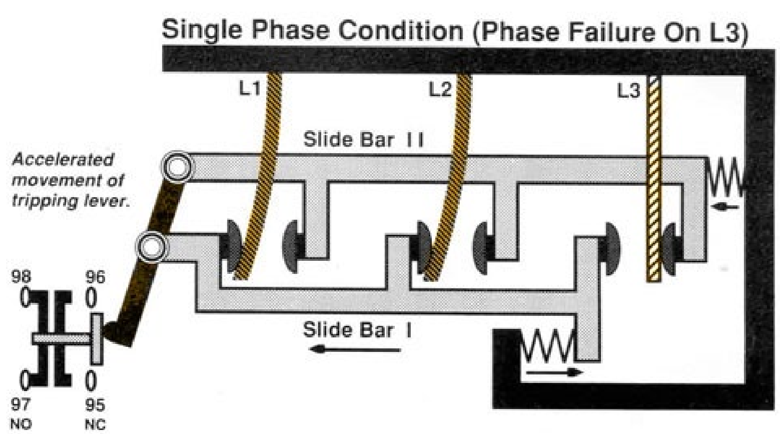

Figure 7

Electronic Overload Relays use "ASIC"

Unlike bimetallic relays that use heater elements, Electronic Overload Relays run current through microelectronics to measure motor current directly through integrated current transformers. The transformers, in turn, create a magnetic field that induces DC voltage onto the Application Specific Integrated Circuit board (ASIC). The electronics identify excessive current or loss of phase more accurately, and react to the condition with greater speed and reliability than bimetallic overload relays. Electronic overload relays use the on-board electronics to monitor all three phases of the current. If the ASIC senses that one phase is missing during a steady state running condition, it will trip in 3 seconds when running under full load. This trip time is 15 times faster than the 45 seconds of a thermal bimetallic overload relay. In addition, CEP7 overload relays detect a 50% phase imbalance in the same way as a phase loss if the load is at least 65% of the dial setting.

To gain a better understanding, look at the sine wave of the currents flowing through the overload. Figure 8 illustrates three individual AC sine waves, which are 120 degrees out of sync. The negative halves of the sine waves are flipped (inverted) to the positive side. The three phases, now shown as six curves, are summarized by an algorithm via the microelectronics and monitored by the overload as DC current.

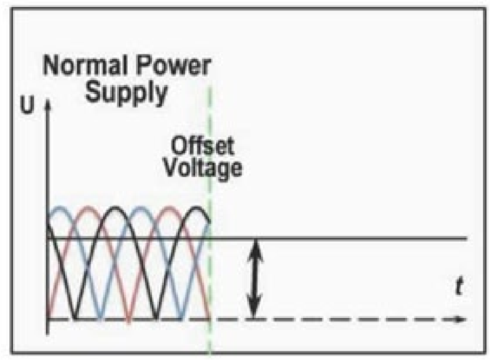

Figure 8

When one of the phases is not present, or "drops out", the DC voltage increases, thus increasing the two remaining phases (Figure 9), now shown as four curves. The phase shift algorithm identifies the increase in the DC voltage average and signals the overload to trip. The CEP7 does not need to wait for the current to increase in the two remaining phases, or to cause the heater element to reach a certain temperature. This is why ASIC solid state overload relays trip much faster than a thermal "differential tripping" overload relay when detecting a phase loss condition.

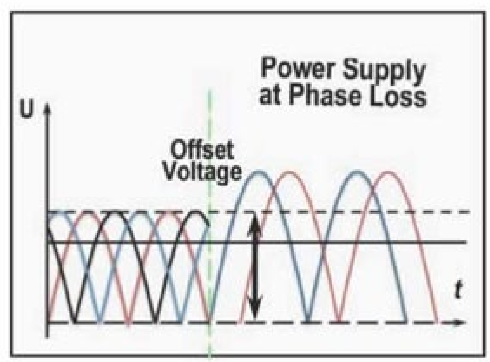

Figure 9

Summary

In summary, phase failure can burn up the rotors of a motor in as little as 15 seconds, even at less than full load amps. Overload and phase loss detection are key elements in protecting against costly motor replacement. Overload relays that include and protect against phase loss can help reduce your operating costs by preventing a costly motor repair or replacement.

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Technical Paper

TECH-PHASEFAILURE_v115 01/2015

Sprecher + Schuh has provided reliable control and protection solutions for its customers since 1903.

Today, Sprecher + Schuh offers a wide range of low-voltage industrial control products, including contactors, a variety of relays, starters, push buttons, switches, terminals and controllers, to name a few. All of our products are crafted with precision and tested rigorously for performance — far exceeding industry standards. Moving forward, we continue along the path of constantly seeking innovative ways to provide solutions for our customers. It is by this philosophy that Sprecher + Schuh has come to be the industrial control manufacturer of choice for many customers around the globe seeking quality, reliability, and a name they can trust.