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Trends in Motor Protection and Recent Advances in Electronic Sensing Systems

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INTRODUCTION

The refrigeration compressor and its associated electric motor present unique problems requiring protective functions and devices especially designed for this service. As refrigeration systems grow more compact and increasingly complex in their operating structure, the need for effective protection becomes even more apparent.

These units normally operate in self-contained environments of refrigerant and oil coupled with high temperatures and pressures. As a consequence, the design engineer is faced with the problem of adequately detecting changes in operational characteristics which lead to performance deterioration and in time, damage to the motor and the sealed system.

We could hardly find a more graphic illustration of the need for refrigeration protection than that provided by a community experience in 1928. As a result of a severe storm, massive power outages were experienced throughout the greater Boston area. When power was restored, the reconnecting of the electrical load resulted in an extremely low voltage condition which lasted a number of hours. Much equipment burned out including a great number of motors in refrigeration compressors. When the electric utility began the analysis of these staggering losses, it was discovered that only one make of refrigerator had escaped damage. These were found to be equipped with inherent thermal protection, i.e., protective devices which were integral with the compressor housing.

The evolution of refrigeration motor protection, reaching back before this event in 1928 is illustrated in Figure 1. Four basic phases of this industry are shown in this diagram. During the early 1920's, motor protection on refrigeration compressors was accomplished by remote over current devices alone. But since motor current approached this problem only from an analog basis, it did not accurately reflect all critical temperature conditions. It became necessary to develop a sensing means which was responsive to temperature as well, and which could be located in close proximity to the heat source. The dome mounted motor protector fulfilled these two requirements. The events in Boston in 1928 graphically verified the validity of this approach.

As electrical insulating materials improved in the years following, refrigeration compressor manufacturers took advantage of these new materials by incorporating motors capable of higher maximum loading capability operating at higher winding temperatures. This narrowed the range between running and stalled conditions and also led to increases in the temperature rise. There
was then a need to design motor protectors with response times matching the accelerated rise in winding temperatures which would also allow the compressor to run at maximum loading conditions. There was also a need to protect motors under all abnormal conditions, and this resulted in moving the protector itself inside the hermetic enclosure.

During the early 1950's the hermetically sealed, line-break motor protector was developed and was successfully applied in direct contact with the motor windings. Because these protectors were responsive to both motor current and temperature, they were capable of being matched to a wide range of motor designs. The "internal protector", as it eventually became known, fulfilled the majority of air conditioning compressor applications from the 1960's to the present.

A wide range of hermetically sealed line-break devices have been produced for many years with typical examples shown in Figure 2. Types shown are suitable for use with single-phase and three-phase motors and from fractional sizes up through 7 1/2 HP. The thermal energy which actuates these devices is obtained in three ways:

1) Directly from the motor winding itself.

2) From heat generated within a bimetal disc by the passage of motor current through it.

3) From an internal auxiliary heating element.

Figure 3 diagramatically illustrates the basic structure of a typical single-phase disc type motor protector. In the sectional drawing, the auxiliary heater is located just below the bimetal disc. This is connected electrically in series with the disc such that all motor current passes through both elements. For those applications where the auxiliary heater is not required, terminals 1 and 2 are used.

In recent years as the larger motor ratings moved toward higher locked rotor temperature rates of rise, the response time for adequate protection was again seriously challenged. The last diagram of Figure 1 illustrates the latest trend in moving the detection system directly in contact with the actual source of heat. Small, rapid response thermal sensors, integrally located within the motor windings, provide the capability to "instantly" sense the true temperature condition of a motor. These sensors, along with their associated electronic circuits, form the basis for the remainder of this discussion.

*Numbers in brackets refer to listings in the References.
A number of thermal sensors have been available over the past several years for a wide range of applications. Not all are suitable for motor protection due to their relative sizes, resistance characteristics, dielectric properties, etc. Before discussing the actual physical configurations, it is necessary to consider their basic electrical characteristics. Figure 4 graphically illustrates the characteristics of three types of resistance varying thermal sensors. The NTC thermistor is perhaps the most familiar and has been associated with temperature detection and control for many years. Its resistance change as a function of temperature approximates 5 to 6% per degree Centigrade. The characteristic shown at the lower part of the graph is a metal wire resistance type sensor. Generally, the resistance change experienced with most metal systems of this type is below 1% per degree Centigrade. The third sensor characteristic illustrated on the right is referred to as steep slope PTC or positive temperature coefficient type. Because of a sharp-breaking anomaly in its resistance curve, this characteristic is sometimes called a switching type PTC. Resistance changes in this steep slope portion fall in the 25 to 150% per degree Centigrade range and for this reason offer excellent properties for precise temperature limitation. The resultant change in resistance can easily extend over five orders of magnitude.

An additional feature of the steep slope PTC sensor is its use in a self-heated active mode as well as the normal passive sensing mode. With appropriate circuitry, both of these characteristics can be used simultaneously for additional system flexibility, such as providing greater trip/reset differential. This is made possible by its unique self-regulating temperature characteristics upon application of electrical power.

**STEEP SLOPE PTC TEMPERATURE COEFFICIENT AND ANOMALY TEMPERATURE**

The temperature coefficient of resistance and its dramatic change at a given temperature, characterize these PTC sensors as previously noted. [2][3] Figure 5 provides a graphic illustration of a typical barium titanate sensor exhibiting its resistance vs temperature characteristics. The point at which the temperature coefficient suddenly increases is termed the anomaly temperature (TA). This anomalous behavior is caused by a change in the crystal structure of the doped barium titanate based ceramic. The characteristic anomaly temperature and resultant temperature coefficient are determined by the chemical composition of the barium titanate. Material with the anomaly occurring at 120°C has the largest coefficient, typically +150%/°C. at TA. By comparison, a 65°C material has a temperature coefficient of +25%/°C. at TA.
Although many applications occur normally in the 120°C range, there are numerous others which require temperatures above or below this value. For this reason, processing techniques have been developed to provide an essentially continuous range of temperatures as shown in Figure 6. In these specific instances, specific quantities of various doping agents are compounded with the basic material to shift the anomaly temperature either above or below the 120°C point. This processing flexibility provides a broad range of individual sensors for application to the different motor insulation classes.

| Temperature °C | Resistivity | | | | |
|----------------|-------------|-------------|-------------|-------------|
| -200           | 10^2        | 10^3        | 10^4        | 10^5        |
| -100           | 10^6        | 10^7        | 10^8        | 10^9        |
| 0              | 10^10       | 10^11       | 10^12       | 10^13       |
| 100            | 10^14       | 10^15       | 10^16       | 10^17       |
| 200            | 10^18       | 10^19       | 10^20       | 10^21       |
| 300            | 10^22       | 10^23       | 10^24       | 10^25       |

Fig.6 Individual PTC Resistivity Characteristics

SENSOR APPLICATIONS TO ELECTRICAL MOTORS

Because these characteristics are fixed by the sensor's chemical composition, very stable operating points are maintained over the life of the system. This means that a specific sensor can be applied to a given motor at the time of manufacture based on the particular wire insulation class used. By having this temperature limitation fixed by the motor manufacturer, he has a higher degree of confidence that the motor will not be exercised beyond its safe limits. In addition, because the system does not provide for field adjustment, the possibilities for tampering are greatly minimized.

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<th>Probe Resisitance</th>
<th>Effectivc Path of Series Combination</th>
<th>Error Produced By Series Combination</th>
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<tr>
<td>Sensor temperature</td>
<td>Sensor resistance</td>
<td>Desired Trip Temperature</td>
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Fig.7 Advantage of Steep Sloped Sensors

If steep sloped PTC sensors are employed in the same fashion, virtually no temperature error results whether one sensor is used alone or three in series. Although a composite addition of all sensor resistances results as in the previous example, it occurs in regions which are of no consequence to the protection of the motor. It will be noted when examining this example in Figure 7 that there is essentially no lateral shift in the steep slope portion of the characteristic where temperature sensing occurs. Therefore, increases in composite resistance above or below this anomaly point do not affect the system's ability to limit winding temperature to the desired value.

An additional advantage resulting from this steep sloped characteristic is that insertion resistances up to several hundred ohms can be tolerated without materially affecting the trip temperature. This could occur, for example, where motors are located at remote distances.
from the protection and control circuits. For this same reason, moderate variations in the trip and reset resistance levels of a protection circuit will have little noticeable affect on performance. The latter is especially important when considering the variations in supply voltage and temperature extremes to which these circuits are exposed in actual application.

**THERMAL RESPONSE OF SENSING SYSTEM**

As noted earlier, the trend toward motor designs having higher temperature rates of rise demands a sensing system capable of following these accelerated conditions. Simple on-winding thermostats are not capable of following rapid temperature changes due to their relatively large thermal masses. An obvious alternative is to reduce the size of the ultimate sensing system and place it as close as possible to the heat source. The development of PTC thermal sensors like those shown in Figure 8 have made this possible.

![Fig. 8 PTC Barium Titanate Thermal Sensors](image)

Both units shown use a very small barium titanate ceramic pill to which electrical leads have been securely attached. The smaller of the two configurations is called a "bead sensor" and finds general application in the medium to low response ranges. Because of its small size it can also be easily retrofitted to the outside of existing varnish dipped and baked motors.

For applications requiring faster response times, the oval-shaped "foil sensor" is used. Although larger in size, its thermal response time is approximately half that of the bead sensor. This improved characteristic results from the two thin metallic heat absorbers inside the foil covering which provide greater thermal contact with the motor winding. The approximate upper response limits of the bead and foil types are 15°C/second and 30°C/second respectively.

A comparison of the thermal response times of a thermomechanical and solid state system is shown in Figure 9. Here the motor winding temperature is depicted as the upper line, increasing in a linear fashion under a locked rotor condition. The response curve of the thermomechanical protector is shown in the lower trace as considerably lagging the temperature of the motor winding. At the point where this thermostat eventually trips, the winding temperature has exceeded the safe operating limit. To overcome this problem an external supplementary overload device must be used to provide additional protection.

![Fig. 9 Comparison of Solid State and Thermomechanical Sensing](image)

The much faster thermal response of the solid state sensor tracks the temperature rise of the motor windings more accurately as shown by the middle trace. Even though a small overshoot occurs at the trip point, the magnitude is considerably reduced over that shown by the larger thermomechanical device. Characteristically this overshoot is greatest on the first cycle when beginning from a cold start. Subsequent overshoots are always lower due to gradual heating of the stator iron and motor housing. Protection systems using the bead sensor have been in refrigeration compressor service since the fall of 1963.

The relatively small size of these sensors offers advantages to the refrigeration compressor designer in several other ways. Besides limiting the temperature of the motor windings, thermal sensing in the compressor head or on the discharge tube can provide rapid shut down in the event a
system becomes overloaded or otherwise malfunctions. Overheated bearings can also be detected by similar applications of these sensors. Due to its small size, the bead sensor can be inserted in areas normally too restricted for other thermal sensing devices. Since proper lubrication is a vital aspect to all mechanisms of this type, suitable oil level and/or oil flow detection is easily obtained by using the PTC sensor in a self-heated or active mode. Under this condition the sensor remains essentially at the temperature of the lubricant while immersed. However, if the oil level drops, or if oil flow ceases such that the sensor becomes exposed, its temperature increases rapidly to the anomaly point. This causes the sensor's resistance to increase and provides a rapid change in signal level for alarm or shut down purposes. It is apparent from these examples that the areas of application are limited only by the imagination of the designer.

ELECTRONIC PROTECTION MODULES

To complete this form of protection system, an electronic circuit or module is needed which is responsive to changes in sensor resistance. It is desirable when selecting this to incorporate as many additional operational features as possible within a given cost frame. The ability at a future date to expand a protection system to include other options is a distinct advantage to both the designer and the end user. With electronics, certain design flexibilities are available which are more difficult if not impossible to obtain with thermomechanical devices.

Those features which may be considered more important in the selection of a protection system are:

1) Long life in terms of cycle requirements.
2) Reliable operation over voltage and temperature extremes.
3) Voltage transient immunity.
4) Tamper-proof design and construction.
5) Future system expansion at low add-on cost per function.
6) Reduced module inventory.
7) Sealed construction for contamination protection.
8) Integral transformer to minimize field wiring.
9) Shock and vibration resistance.

Many of these features may not seem important until it is realized that most modules are mounted directly on or near the compressor enclosure. This subjects them to a wide range of temperature, vibration and other environmental factors not necessarily associated with remote panel mounted controls.

Figure 10 shows typical examples of three types of electronic modules which can be used with the PTC sensing devices just described. Both types of thermal sensors are shown in the foreground. On the extreme left is a general purpose protection system with up to three sensor input channels designed for a broad class of refrigeration compressors. A companion model (not shown) incorporates a timer for special application use where oil level sensing is required. The small unit in the center is a single channel, all solid state version, principally used where a 24 volt system is already available and where series sensors are desired. The larger module to the right, along with its associated plug-on head, is an advanced version intended for use on higher HP compressor units where more complex functions are encountered. An advantage of this module is the ability to easily expand its basic circuitry to include future options. Various types of plug-on heads allow the designer to tailor the system to his specific needs.

Fig.10 Electronic Protection Systems

Multifunction capability in any control or protection system is desirable if the options are economically feasible. Two of the modules described here have been designed to provide for certain modification contingencies. Figure 11 pictorially illustrates some of the possible options which could be included in addition to basic motor winding and bearing protection. With steep slope PTC sensors, it is possible to connect them to any module input either individually or in series, without sacrifice in performance. A number of
additional possibilities are shown but should not be considered as limiting the scope of application.

![Diagram of current sensing, alarm indication, combination motor starting and protection, manual or automatic reset, pressure high and low limit, differential, overheat protection, 6 channels, 6 parallel sensors or 3 series sensors per channel, liquid level.]

**Fig.11** Multifunction Capability With Electronic Systems

**SPECIAL CIRCUIT CONSIDERATIONS**

When combining solid state sensing devices with a companion electronic module, certain basic considerations may dictate the selection. The low coefficient resistance characteristic shown in Figure 12 illustrates some of the difficulties encountered with this type sensor. Consider, for example, the requirement to protect three different motors, each at a different winding temperature. In this instance, a user has to:

1) Stock three separate modules, each individually calibrated to different fixed resistance trip points, or
2) Stock one module which has provision for separate adjustable calibration over the entire range.

The first alternative requires maintaining an inventory which includes three different modules. The latter choice encourages tampering with the set points once installed in the field. In both cases, any module calibrated to one set of conditions may not necessarily be usable for another.

Since the module is intended for a wide variety of applications, it should not be saddled with the temperature constraints which tie it to one specific use. For this reason the sensor approach shown in Figure 13 offers a better solution to the above set of conditions. In this instance as before, the requirement is to protect three different motors, each at a different winding temperature limit. However, a single module having only one fixed resistance trip level is used instead. Since each motor is categorized according to its own unique winding insulation class, specific sensors can be selected and installed by the manufacturer to match these requirements. This has the added advantage of being unalterable in the field. What essentially is demonstrated is that any properly equipped motor can be connected to any of the available channels of any module and be protected to the temperature limits selected by the manufacturer. This feature also allows motors and modules to be interchanged at will without affecting established protection limits.

**Fig.12** Shallow Sloped PTC Characteristic

**Fig.13** Steep Sloped PTC Characteristic
ENVIRONMENTAL AND VOLTAGE STABILITY

The ultra steep slopes of these PTC sensors have the additional advantage of contributing to the inherent stability of their companion electronic module. Rather substantial resistance changes can be tolerated in the module's operating characteristics without materially affecting the temperature limit of a given application. To indicate the stability of this type system, Figure 14 shows the actual trip temperature of a protected system when the module was exposed to wide extremes in ambient temperature and supply voltage. The upper graph shows virtually no change in protection performance when the module was cycled through ambient temperatures ranging from -40°F to +160°F. In the lower graph a similar plot depicts equally stable conditions over a supply voltage excursion of 90 to 132 volts a-c. These characteristics provide advantages in applications where the ambient conditions cannot be fully controlled.

The motor stator was equipped with 95°C foil sensors in each of its phases which operated into an electronic module. Reading from right to left, the upper trace shows a first cycle peak temperature of 110°C which subsequently stabilized after approximately 45 minutes to a maximum of 104°C. Before the test was completed, a temporary shut down in the plant's power facility required a restart of the system occurring at the 11,776th locked rotor cycle. When compared to the original first cycle, very little difference is noted in the maximum temperature limit. The final temperature trace, at the lower right, shows the 16,250th cycle. Again, little change is noticed when comparing it with the stabilized condition of the first few cycles occurring eight months earlier. At this point the test was arbitrarily terminated since it was concluded that adequate protection stability had been demonstrated.

APPLICATION EFFECTIVENESS

Generally speaking, it is the aim of the designer in all applications to provide and promote the most effective use of his system. With motor trends moving toward smaller frame sizes and higher operating temperatures, the need to obtain maximum safe power utilization is paramount. It has been the purpose of this discussion to illustrate the protection means by which these goals may be safely attained. Greatly reducing the size of the thermal sensing device and placing it in the closest possible proximity to the heat source eliminates reliance on the current-temperature analog, a major source of protection inaccuracy. More accurate protection means the motor can be worked to its full capacity without danger of thermal damage. This when contrasted to the motor protection means first available in the early 1920's, indicates the growth which this technology has made possible. These concepts have been well summarized by Veinott *below.

"Thermal protector compared with overcurrent device"

"An external overcurrent device operates on the theory that the winding temperature depends upon only the motor current, so it is set to operate at a certain current, usually of the order of 115 to 125 percent of full-load current. Now, it is not over-current that damages the windings, but over-temperature. Many factors other than current can elevate the winding temperature: location of the motor in a high ambient, as sometimes occurs in appliances; partial or complete blocking of the supply of ventilating air; dust or dirt accumulations on the windings themselves, or in air passages; proximity to hot surfaces or bodies; operation on overvoltage, etc. The thermal protector, located inside the motor,
operates on motor temperature as well as motor current. It protects against dangerous temperatures at small currents, where an overcurrent protector would not trip, and permits the motor to carry more overload at low ambient temperatures, which it can safely do without overheating. In short, a properly applied thermal protector affords more positive protection, and permits fuller utilization of overload capabilities of the motor, than does the remote overcurrent protector."


The systems described here provide the compressor designer and the end user the tools to develop a broad range of new functional applications. By taking advantage of advanced sensing technology, the scope of these applications is limited only by the imagination of the user.

Fig.15 Eight Month Locked Rotor Test on 30 HP Compressor Motor

REFERENCES


