# Optimizing Plant Production and Operation Through Motor Protection

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## Overview

Conventional motor protection techniques are reactive in nature. In order for protective devices to work, faults and failures must first occur in the motor.

Modern electronic motor protection permits the detection of abnormal operating conditions or faults in the motor at an early stage. This makes it possible to minimize shut-downs by initiating preventive measures prior to tripping. Additionally, under normal operating conditions, the data available from the protective device can be used for optimizing motor performance and contributing to plant operation efficiencies.

By integrating state-of-the-art protection into a total control solution, motor and plant control can be improved, and unwanted and unnecessary down-times can be minimized. This results in early payback on motor protection devices, making them a valuable component of modern automation systems.

## Introduction

When analyzing the role of protective devices in the design and operation of motors and plants, both plant management and motor requirements must be taken into consideration. These requirements must be met by those involved in the design of the motor, the protection equipment and the plant control system.

New technologies evolve into improved and even completely new solutions. These solutions lead to overall system improvements. Protective devices can provide control functions and even provide data required to improve these systems.

## Plant Management Requirements for Motor Protection

In today’s economy, plants must able to produce quality products at desired costs. Costs can be broken down into the following categories:

- Investment costs
- Maintenance and repair costs
- Operational costs
- Lost production costs due to down time

It is possible to minimize these costs by proper selection and application of motor protective equipment. Close coordination of the motor, the load and protection avoids the need for oversized motors. This reduces the investment costs and energy consumption since the motors run at a higher efficiency level.

The early detection of faults can reduce repair costs. Pre-warning and start prevention can reduce plant downtime. If pre-warning alarms are available to alert personnel of impending motor failure, the system can be shut down in a planned, orderly fashion. Once shut down, preventive maintenance can occur, possibly eliminating the need for costly repair or replacement.

## Types of Motor Failure and Protective Features

There are a number of factors which cause motor failure. The most common are:

- Bearing failure
- Voltage unbalance
- Voltage too high/low
- Rapid duty cycle
- Overload
- Single phasing
- Restricted ventilation
- Moisture and vibration

If mechanical failures are eliminated, protecting the motor windings from over temperature is the prime function of motor protection.

But even bearing failures can result in motor winding failure if not detected in time.

There are a number of ways that motors can be protected with respect to the needs of *plant management*. Table 1 below classifies these functions.

**Table 1.**

| Task | Purpose | Example |
|---|---|---|
| Prevent starting | - Avoid damage<br>- Avoid unsuccessful start | - Incorrect phase sequence<br>- Insufficient thermal reserve<br>- Defective insulation |
| Disconnect rapidly | - Avoid damage<br>- Keep damage low | - Ground (earth) faults on grounded system<br>- High over temperatures<br>- Stalling |
| Pre-warning | - Avoid stop by preventive measures<br>- Switch off at convenient time | - Ground (earth) on isolated system<br>- Failures in cooling system<br>- Unbalanced supply<br>- Slight or increasing winding temperature |
| Availability of operational data | - Optimization of process | - Motor temperature used to control loading |

There is no substitute for the proper application of motors or proper maintenance. However, protective devices can help you to use the motor to its optimum limits.

## Functions and Operational Principles of Motor Protection Relays

This section provides fundamental information on the thermal activity inside of an AC squirrel cage induction motor, various thermal protective sensors, how they work and the types of protection provided by motor protection relays.

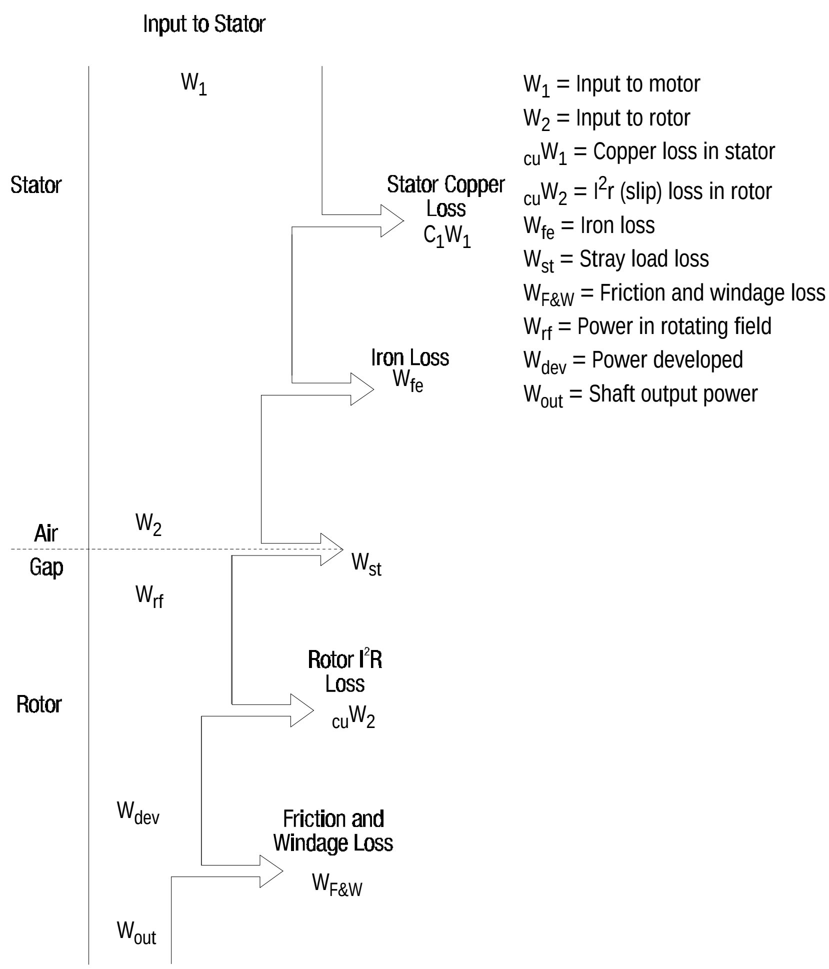
### Thermal Protection

In order to understand how motor protection devices work, the concepts relating to thermal conditions in a motor at rest and during various stages of operation must be understood. Additionally, how various protection devices measure and act on these thermal conditions must be understood.

What happens in the motor?

Squirrel cage induction motors are the most commonly used motors and discussions here will center on them. To better understand motor protection, you must understand what happens inside the motor. The motor basically changes electrical power into mechanical power. Since it is not 100% efficient there are losses inside the motor as seen in Figure 1.

**Figure 1. Power Flow in Motor**



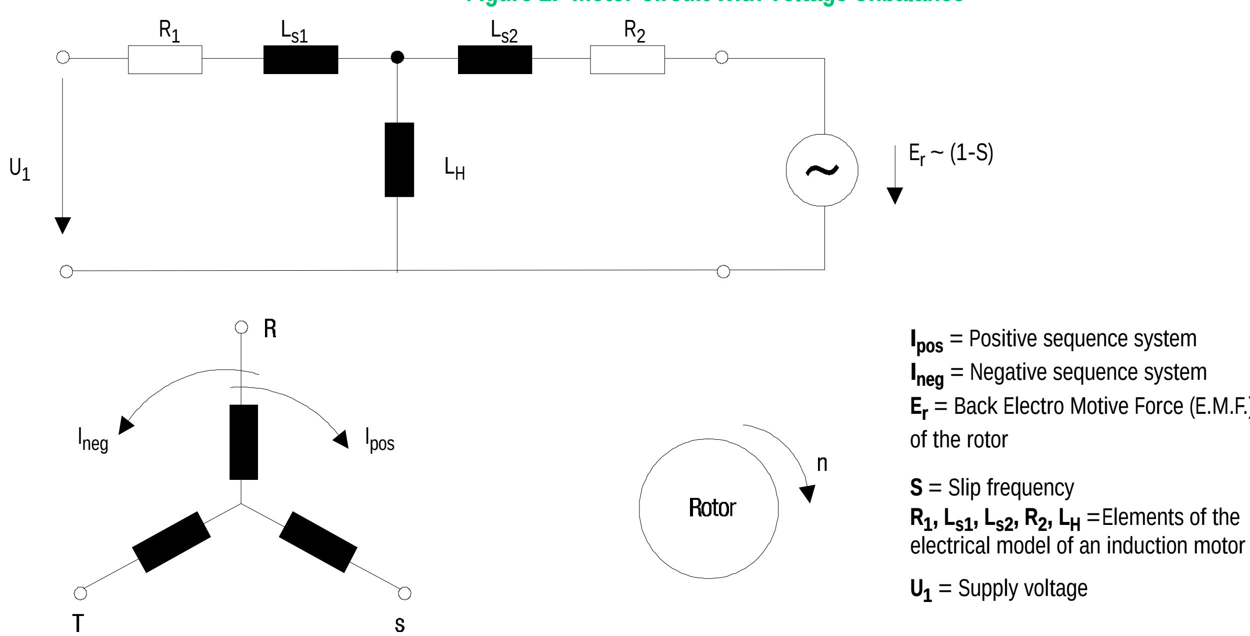
During normal running conditions, the current flowing through the stator windings produces stator copper losses proportional to the square of the current ($I^2$). However, the losses in the stator iron are due to magnetization and eddy currents, which are a function of voltage.

The main losses in the rotor are the rotor copper losses caused by the current induced in the cage. These losses are dependent on the loading on the motor. Frictional losses (air and bearings) and additional losses are relatively small and are of less importance. The heat generated in the rotor and stator lead to respective temperature rise.

The steady-state temperatures are a function of the size of the losses and for the most part a function of the load. The heat flows between those areas and to the ambient air. The thermal conductivity of the heat transfer paths partly depends on the speed of the motor, since an internal or an external fan's performance is speed dependent.

With an unbalanced supply and with harmonic distortions, extra losses are created, particularly in the rotor. The negative sequence currents caused by supply asymmetry and harmonic currents do not generate back EMF. For this reason, these negative sequence currents can reach relatively high values. Figure 2 shows the circuit of the motor. This is similar to the conditions with a symmetrical supply when staring a motor. The starting current of a *motor at rest* is limited only by the *resistance* and *inductance* in the stator and the rotor. The effective rotor resistance is increased due to the effect of current displacement or *skin effect* because the frequency of the current in the rotor equals line frequency.

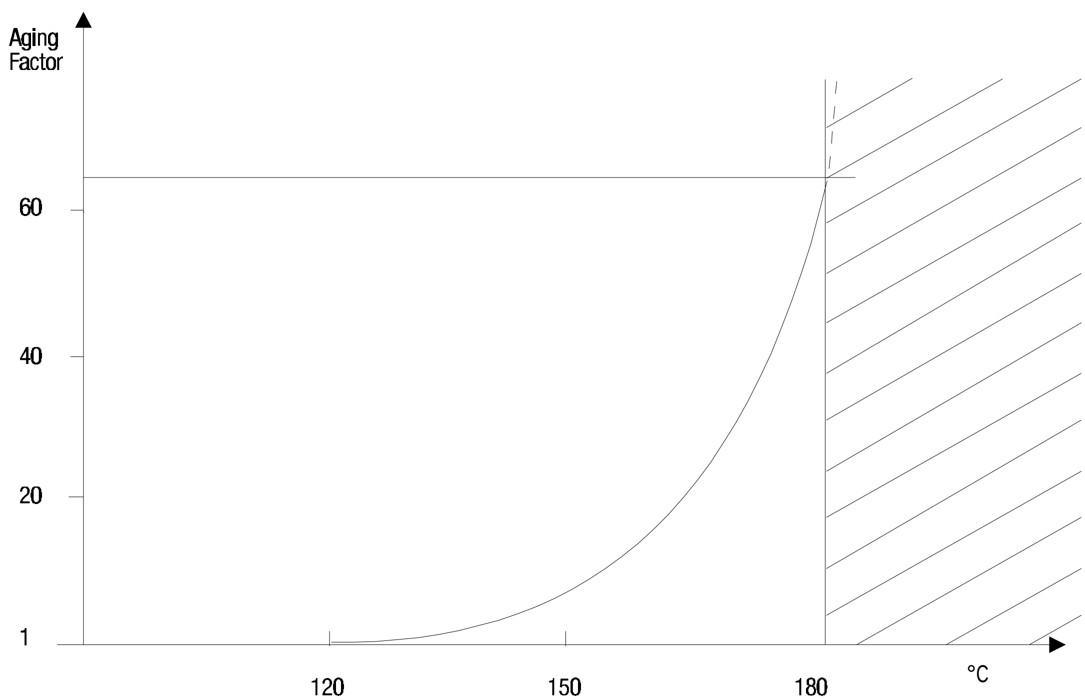
**Figure 2. Motor Circuit with Voltage Unbalance**



At the motor's rated speed, the rotor's electromagnetic field produces a back EMF in the stator, which in turn reduces the stator current to its rated value. The frequency of the rotor current itself is low and is equal to slip frequency. Therefore, there is no skin effect and the rotor resistance is low. In general, the load has to be reduced to avoid overheating should asymmetries or harmonics exist on the line.

The thermally critical parts of a motor are the stator windings and the rotor cage. The insulation materials used in the stator are subject to an aging process which is accelerated at higher temperatures as shown in Figure 3. As a point of reference, the normal life expectancy of insulation materials is 25,000 hours at rated temperature, (i.e., 120°C for class B and an ambient temperature of 40°C, rated load). Because actual motors only run continuously at that temperature level under exceptional circumstances, the typical motor insulation life would be considerably higher.

**Figure 3. Temperature Versus Thermal Aging**




Short-time over-temperatures do not reduce motor life considerably as long as certain limits are not exceeded. Motor manufacturers intentionally permit such short-time over temperatures during the start-up period. This can also be done for normal motor operation, i.e., a motor can be selected according to the desired time of service rather than to keep within the rated values of load.

For the rotor cage, the start is normally the most critical period when enormous losses are fed into the cage. Temperatures can reach levels in excess of 300°C and large thermal forces can stress the cage. For larger motors, the admissible start time is often limited by the rotor.

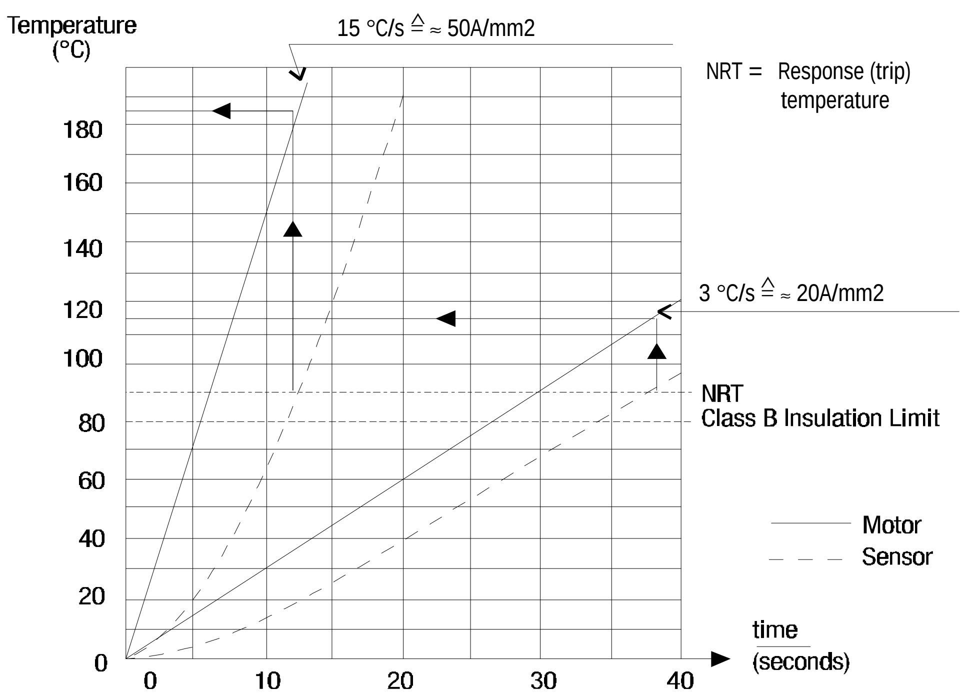
### Protection with Temperature Sensors

Temperature sensors are normally built into the windings and measure the actual winding temperatures. There are several advantages for using this type of protection. First, sensors detect changes in ambient temperature. Also, sensors can detect variations in cooling conditions such as blocked ventilation or a broken fan.

Rotor protection is only possible indirectly via the stator temperature, and is thus, at least, very questionable. Elaborate methods can be implemented for accurately measuring rotor temperature. For example, bringing out sensor leads via slip rings. However, this probably can be justified on only the most critical applications.

In order to follow temperature variations quickly, sensors must have a small mass and be in close contact with the motor's windings. Even then there is a delay between the actual temperature and the sensor temperature. Where these requirements are not followed actual winding temperatures can be above the desired maximum. Figure 4 illustrates the differences between actual and sensor temperature for two different sensors. This shows that not only is selection and mounting of sensors critical, but so is proper trip point calibration.

**Figure 4. Response Time of Sensors**




Sensor technology and the art of building them into the windings have reached a level of expertise such that sensors are becoming a standard requirement for large motors. Their limitation is that they can only protect against over temperatures and not against other fault conditions or hazards that can be detected by current evaluation. These other conditions are for example, single-phasing, ground (earth) faults, short-circuits, stalled rotor conditions, and others. This is the reason why temperature sensors are normally used in conjunction with current sensing relays.

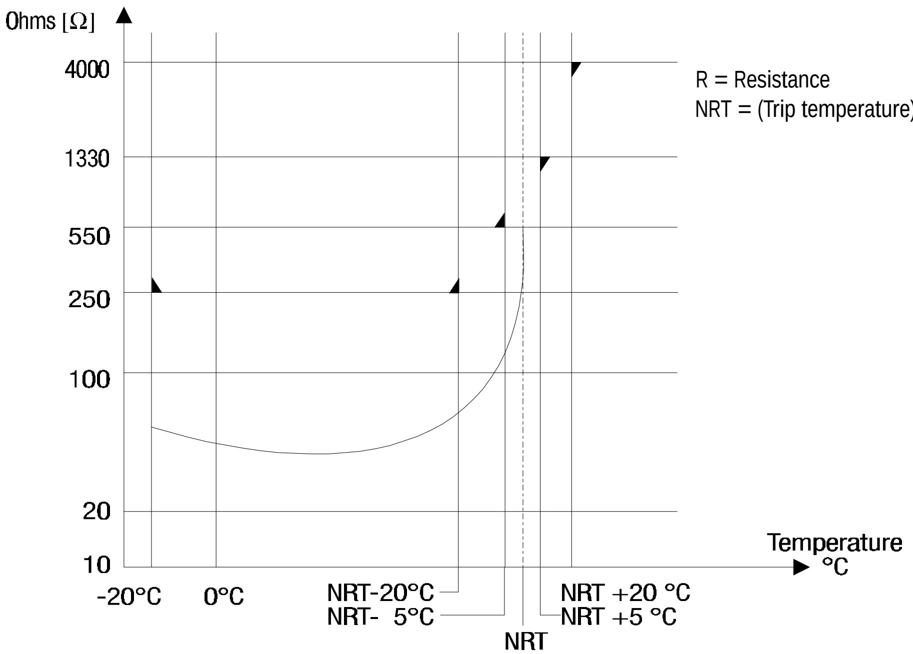
## Sensors with Linear Characteristic

One type of sensor has linear characteristics. As the temperature changes the characteristic of the sensor changes in a linear manner. For reasons of cost, PT 100 sensors have emerged as the most popular type of the linear characteristic sensor group. In general, they are only used for large motors, particularly medium voltage motors. A linear characteristic permits multiple sensing point. A trip setting of one or more detection levels such as a warning annunciation prior to actual trip, and reset levels according to the specific requirements given of the application.

## Sensors with Threshold Characteristic

Another type of sensor is one that has a "knee" or threshold in its characteristic resistance verses temperature curve. The resistance remains fairly constant until the temperature reaches the threshold point. As this point a small increase in temperature causes a relatively large change in resistance. There are two types of sensors in this category. The Negative Temperature Coefficient or NTC sensor and the Positive Temperature Coefficient or PTC sensor. PTC sensors are most widely used as an economic and reliable approach for motor protection. Figure 5 shows a typical Resistance verses Temperature curve for the PTC sensor.

Figure 5. PTC Resistance Versus Temperature




The trip or release temperature is determined by the sensor that is selected. So, the protective device cannot change the trip point. The motor manufacturer selects the sensor set to the correct detection temperature to match the insulation class of the motor windings. These sensors are embedded into the windings when the motor is built. If a warning function is required, a separate set of sensors having a lower response temperature is required.

## Thermal Protection with Current Sensing Relays

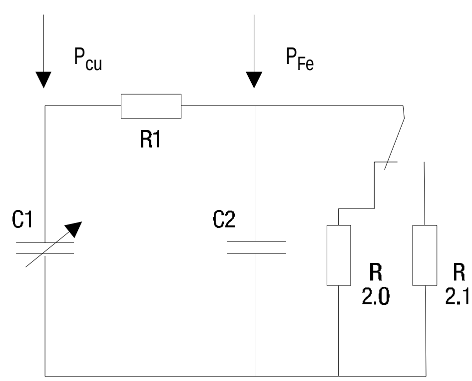
Motor protection is also accomplished using current sensing relays. This group is divided into electromechanical and electronic relays. The electromechanical devices can be either eutectic alloy or bi-metal overload relays. In the eutectic alloy overload the current flows through a heater element which is calibrated to the motor current. In bi-metal overload relays the motor current flows through a bi-metal strip, which is part of the relay. Both of these overloads have proven reliability and good protection capabilities for most standard applications.

Electronic overload relays are a relatively new technology. They permit more flexibility with regard to the quality of the thermal simulation and trip characteristic. Electronic overloads can perform additional functions for little extra investment.

## Temperature Simulation and Trip Characteristics

As described in the *Functions and Operational Principles* section, a motor is a complex device with regard to its thermal behavior. The thermal equivalent circuit of Figure 6 has proved to be a high quality and practical thermal model of the motor, offering accurate protection even under varying load conditions and intermittent duty cycles. Current and time setting capabilities match the motor protection relay characteristics to the individual motor and application. It is not practical to manufacture simulation models of greater complexity and with more parameter settings, since those motor parameters are not known.

**Figure 6. Motor Thermal Circuit**




$P_{cu}$ = Copper losses
$P_{Fe}$ = Iron losses
C1 = Thermal capacity of the windings (adjustable)
C2 = Thermal capacity of the iron masses
R1 = Thermal resistance between copper and iron
R2.0 = Cooling resistance at standstill
R2.1 = Cooling resistance at run

The quality of a protection relay cannot be measured on the basis of the trip characteristics, but only in knowing the simulation circuit and the loss feeds used. The trip characteristic (even if a so called break-point curve is used which is matched to the motor) only indicates within what time the relay trips when starting from the ambient temperature at a constant load. The load from a cold start is never constant because of the over current during starting. Also, during operation, the motor heats up and reaches specific copper temperatures dependent on the load and its variations. After one single start, the windings would cool down rapidly, since the stator iron is still cold. However, after long periods of operation, the cooling time is be considerably longer, since the stator iron is hot.

A good thermal simulation should also permit the restart of a motor at the shortest possible intervals. This would be done by automatically taking into consideration whether the actual start time was long or short, and whether the motor was warm from previous operation. Simple start interval timers would normally lock out the motor for too long of a period of time, since their use is based on “worst case” conditions

## Analog verses Digital Relays

Which technology to use is mainly a question of cost verses performance trade-offs. Because of the decreasing cost of digital components, high-level digital relays are becoming more popular. In addition to the various protective features they also offer easy data links (currents, temperatures, signals, etc.) to other microprocessor based control equipment.

Analog technology has satisfactory time constants (time constant of the motor iron masses) for practical applications. But digital relays have no limitations with regard to long time constants.

On the other hand, some progress is still called for with microprocessors to make functions fast enough, for example, earth fault detection.

Microprocessor based protective relays require more parameters for proper setup during commissioning. Additional data not normally supplied by motor vendors is also required. The benefit of this extra effort is protection that is tailored to the motor and application.

## Single-phasing and Line Unbalance (Asymmetry) Protection

It is standard for modern electronic relays to have at least single phase protection in addition to normal overload protection. It is best to disconnect a motor quickly with the loss of a phase, since in the majority of cases the motor would stall due to the reduced torque. This would unnecessarily heat the motor if only a thermal function was available. By early detection and trip, the waiting time until a restart can be kept to a minimum.

Another function is line unbalance or asymmetry protection. Formulas exist to calculate the extra losses fed into the rotor, which may be a good approximation of actual conditions. Currents at normal operating conditions can be in the order of 6 to 10 times the voltage unbalance. With an unbalance of as little as 3% the motor must be de-rated by approximately 10%. Motor manufacturers state that operation of the motor when the unbalance is greater than 5% is not recommended.

In addition, asymmetries do not normally just affect one motor, but the whole plant. If an unbalanced supply is a possible condition, then a central supervising relay should alert the attention of personnel to the fact that certain limit are exceeded and permitting them to take corrective measures before motor overheating becomes critical.

### Ground/Earth Fault Protection

A large percentage of motor insulation failures result in ground/earth fault currents. Early detection keeps damage to a minimum, thereby shortening repair times and minimizing repair costs. In isolated supply systems, a first ground/earth fault could even be reason for only an alarm. The plant could continue to operate until a convenient time to shut down such as the end of the shift, day, or week. During the scheduled shutdown, maintenance personnel could then correct the fault without affecting production time.

Ground/earth fault trips normally work with a short delay in order to overcome the problem of current transformer saturation at the start of the fault. This delay is also important for discrimination against short-circuits. This allows the fuses or circuit breaker to clear the fault instead of attempting to have the relay interrupt the fault.

Ground/earth fault protection can be applied as individual protective devices. But this protection is also standard with high level digital protection.

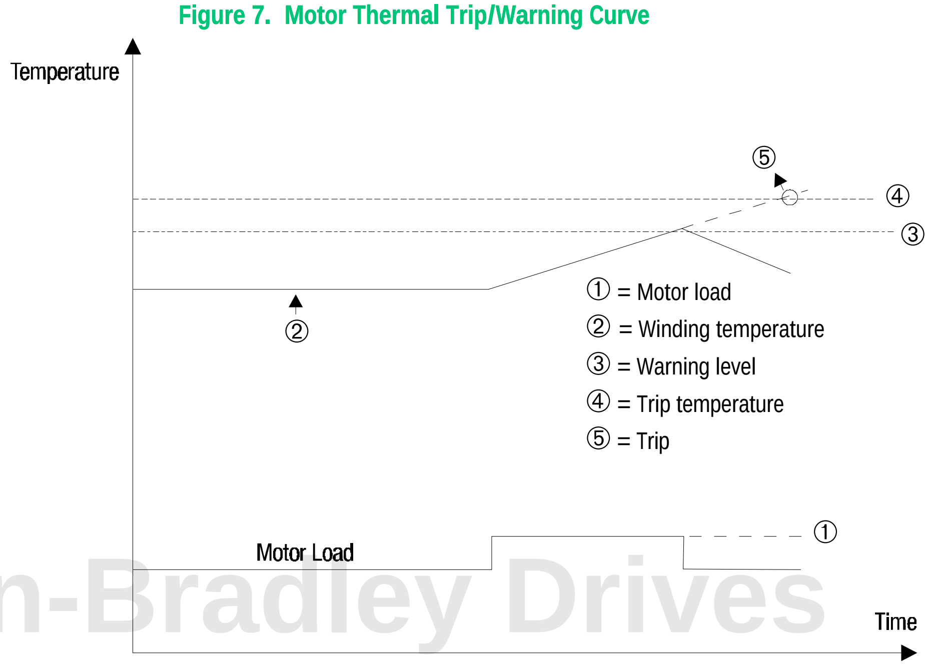
## Modern Protection Features Increase Productivity

Protection relays generally contribute to increased productivity because they reduce unscheduled downtime and help prevent irreparable motor failure. With electronic circuitry, additional functions mainly aim at supporting uninterrupted operation or maximum motor output, at a low cost. These protective relays can provide indications in addition and prior to the basic protective functions.

### Pre-warning and Load Control

It is evident that in many cases, a warning signal indicating that thermal trip is pending, alerts attention to the overload condition and gives time to clear it without shutting down the motor. With microprocessor relays, and assuming a constant load, even the time left before trip can be indicated as shown in Figure 7.

Figure 7. Motor Thermal Trip/Warning Curve

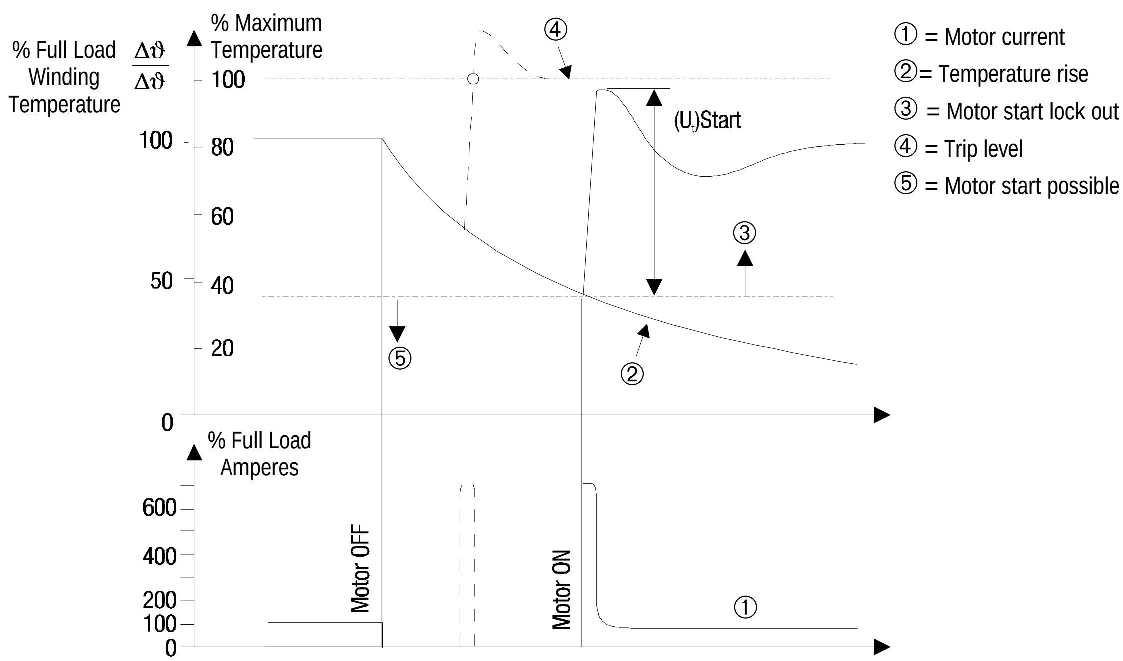


In certain production processes where the load can be varied, as with stone crushers or saw mills, a temperature output has proven to be very useful. By controlling the load, the motor temperature rise can be optimized and production from existing installations has been increased in excess of 20%.

## Start Prevention

The same temperature output can be used for inhibiting a start if the thermal reserve of the motor is not sufficient for the restart. With a good thermal simulation model, the shortest waiting times can be achieved. And with microprocessor based relays, even an indication of the remaining waiting time, as shown in Figure 8 could be provided to operators.

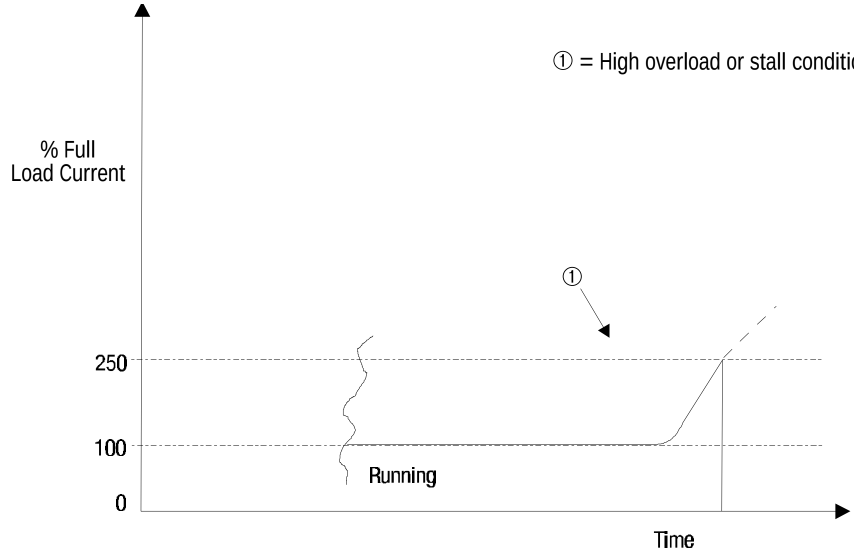
**Figure 8. Inhibiting Motor Starting**




## Stalling Protection

When a stalled rotor condition or a high level overload (which would inevitably lead to a thermal trip) occurs while running, it is advantageous to disconnect the motor immediately and not to wait until the motor becomes hot. This reduces motor stress and can even protect machinery. This feature which is also known as “jam” protection can be realized when a motor current signal is available in the relay (Figure 9).

Figure 9. Motor Jam Protection




### Under Load Protection

It may seem surprising to talk about *under load* protection when motor protection is normally required when overloads occur. In cases where the motor is cooled by the medium it drives, such as fans and submersible pump motors, a lack of this medium (due to an obstruction of air or liquid flow) would result simultaneously in a reduced motor load and excessive motor heating. For this reason a warning signal or a trip before damage occurs is useful.

### Detection of Damage in the Motor

By analysis of the motor currents, failures such as broken bars in the cage, a rubbing of the rotor against the stator, other similar periodic loading originating from failures on the load side, or even bearing failures can be detected. For the bearing failures, however, an analysis of the noise produced is the more common method. This even permits a prediction of the end of operational life. Generally, the detection of these failures is limited to a small percentage of applications.

## Signals, Indicators, and Test Functions Ease Diagnosis

With electronic relays, it is easy to supply electrical, displays, visual indicators or even acoustical signals to give information regarding operational conditions and failures. These displays and visual indicators also help in making settings and functional tests. Through electric signals (e.g., communications bus connections) remote indications and connection to other automation equipment is also possible. Needless to say, these features again help in reducing commissioning and maintenance costs, as well as down times by providing more detailed information about the failure which has occurred.

## Summary

There are many options available to provide motor protection. Everything from basic overloads to networked microprocessor devices. The objective is to provide the optimum protection in order to maximize production capabilities. Costs are always important factors when evaluating a motor protection solution. However, higher initial hardware costs may result in overall lower production costs by providing new levels of protection not available in the past.

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