Induction Motor Protection

Protective Relaying
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Induction motors account for half of the electric power consumed across the United States; they are a very important part of a power system for an industrial company. Loss of the motor means you cannot produce the good which in turn does not allow you to make any money. Our project involves protecting the motor so that other parts of the system are not affected or that you stop the motor from causing more damage to itself. There are three considerations to keep in mind while protecting a motor: size, importance, and the load of the motor. All of these correlate to what type of protection system you should choose. For example, fuses can protect a small motor that is not driving something important, while much larger motors, which are more expensive, need to be protected by relays and circuit breakers.

There are many different types of failures that can occur with a motor. These types of failures include: motor-induced, load-induced, environment-induced, source-induced, and operation induced. Motor-induced failures can be caused by insulation failure, bearing failure, or mechanical failure. Each of these will cause an increase in temperature and/or increase in current. Load-induced faults range from simple overload of the motor and high inertia. High ambient temperature and cold-damp temperature will also cause a motor to break down. High ambient temperature will raise the temperature of the windings causing the insulation on the windings to breakdown. Just like a transformer the insulation will breakdown with overcurrent and high temperatures. Source induced failures can range from undervoltage, voltage unbalance, phase failure, or phase reversal. Since the kVA of the motor will not change, when you decrease the motors voltage the current will increase again causing damage to the motor. The removal of a phase and voltage unbalance can also cause a lot of damage to a motor. For example, voltage unbalance of 3.5% will cause a 25% increase in motor temperature [Blackburn]. This is due to the equation 1 that is proportional to temperature.

\[ I_1^2 t + \frac{R_{r2}}{R_{r1}} I_2^2 t \propto Temp \]  

\[ R_{r2} = \text{negativesequence} \]
\[ R_{r1} = \text{positivesequence} \]

Each of the values refers to motor rotor resistances in the respected sequence. Finally, operation-induced faults can be caused from stopping and starting the motors along with reclosing motors back into the system before the motor drops below 33% of motor voltage. Each
of these cases could cause problems; with the repetitive starts you will increase the temperature of the motor. Reclosing the motor back in will cause high transient torques. All of the above problems that can cause a failure of a motor have a few things in common. Most of them will cause overcurrent which in turn increases the temperature of the motor. High temperatures on motors will cause damage to the insulation and eventually cause motors to fail.

Before going into how to protect the motor it would be best to discuss how a motor is modeled in a power system. Below is a model of the equivalent circuit.

![Equivalent Circuit Diagram]

When looking at normal values:

Rs and Rr = .01 pu
jXm = j3.0 pu
jX = .15 pu

You can see that by figuring out the starting current that it could be up to 6.67 pu [Blackburn]. Other things you must consider when protecting the motor are the starting-current curve, thermal capability curve, and the K constant. The K constant is a ratio between the motor rotor resistance between the positive and negative sequences. The starting current curve will show the current as the motor approaches normal running speed. The thermal capability curve incorporates three different curves the time that the motor can stay at locked rotor current, accelerating thermal limit curve, and the running thermal limit curve. The running thermal limit curve represents what the capacity of the motor load can be during an emergency operation [Blackburn].
Motor Protection in Detail

The basic aim in protecting motors is to permit the motor to operate up to its thermal and mechanical limits while not exceeding them and providing maximum sensitivity for faults. This report only deal with motors with protection applied directly to them and will not cover motors for which the protection is built into them or motors using only fuses for protection.

Two Types of Motors and their Sequence Networks

(a) Synchronous Motor Positive Sequence Network

(b) Induction Motor Positive Sequence Network
As shown on page 3, induction motors have the same positive sequence network as synchronous motors, except that the positive-sequence voltage source $E_{m1}$ is removed. In the rotor circuits of induction motors, there is no dc source of magnetic flux, and therefore $E_{m1}$ is zero (short circuit).

The positive sequence network shown in Figure 1 is a simplified network for a rotating machine. They do not take into account factors such as saturation effects, machine saliency, and more complicated effects. However, these simplified networks are in many cases, accurate enough for power system protection studies.

The coordination problems are eliminated in the protection of the motor as it is the last device in the electrical system. As mentioned above, the induction motor backfeed into the faults on the grid is relatively small and decays in a few cycles (Figure 1) so in view of this, instantaneous non-directional overcurrent relays (50, 51) can be used for protecting the induction motors.

![Diagram](image)

**Figure 1: Guide illustrating the effects of induction motor decrements on symmetrical fault currents [Blackburn]**
As far as the relay settings are concerned, they are set above the asymmetrical locked rotor current but well below the minimum fault current. This is equated as

\[ I_{LR} = \frac{1}{X1s + Xd''} \]  \hspace{1cm} (2)

where \( I_{LR} \) is the locked rotor symmetrical and \( X1s \) is the total reactance of the power system. In many cases, the source \( X_{1s} \) is the reactance of the supply transformer for all practical practices.

A 3-Phase fault at the motor is given by

\[ I_{F,3\text{phase}} = \frac{1}{X1s} \]  \hspace{1cm} (3)

For a phase-to-phase fault with \( X1s = X2s \), \( I_{F,2\text{phase}} = 0.866 \) \( I_{F,3\text{phase}} = \frac{0.866}{X1s} \)

If \( P_R \) is the ratio of the relay pickup (\( I_{\text{pickup}} \)) to locked-rotor current and \( P_F \) is the ratio of the minimum fault current to the relay pickup (\( I_{\text{pickup}} \)), then

\[ P_R = \frac{I_{\text{pickup}}}{I_{LR}} \hspace{0.5cm} \& \hspace{0.5cm} P_F = \frac{I_{F,2\text{phase}}}{I_{pu}} \]  \hspace{1cm} (4)

For settings, \( P_R \) should be around 1.6 – 2.0 or greater & \( P_F \) should be 2 to 3 or greater.

Equating

\[ I_{F,2\text{phase}} = P_F \times I_{\text{pickup}} = P_F P_R I_{LR} \hspace{0.5cm} \text{and} \hspace{0.5cm} \frac{IF_{2\text{phase}}}{ILR} = P_F P_R \]  \hspace{1cm} (5)

\[ I_{F,3\text{phase}}/I_{LR} = 1.155 \ P_F P_R \]
Thus, 3-Phase solid motor fault should be 1.155 $P_F P_R$ or larger for decent instantaneous overcurrent protection.

If the minimum recommended values of $P_R = 1.6$ and $P_F = 2$, the 3-Phase fault should be 3.7 times $I_{LR}$.

If $P_R = 2$ and $P_F = 3$, the 3-Phase fault should be at least 6.9 times larger than $I_{LR}$. Thus,

$$I_{F,2phase} = 0.866/X1s = (P_F * P_R) / (X1s + X_d'')$$

(6)

$$X1s = 0.866 Xd'' / (P_F P_R - 0.866)$$

With $P_R = 1.6$ and $P_F = 2$, $X1s = 0.37 X_d''$

With typical values of $X_d'' = 0.15$ pu, $X1s = 0.056$ pu

With $P_R = 2$ and $P_F = 3$, $X1s = 0.169 X_d''$

With typical values of $X_d'' = 0.15$ pu, $X1s = 0.025$ pu

The source impedance can be defined this way, which should be as indicated or less for non-directional overcurrent protection. The per unit values are on the motor KVA, KV base where,

$$KVA \text{ rated} = \frac{(Horsepower)(0.746)}{(efficiency)(powerfactor)}$$

(7)

Differential protection is a preferred protection method for many motors but this is only possible if both ends of the windings are available on the motor. If these two ends of the windings are available, the best differential scheme relies on using a flux summation-type current transformer, with the three motor conductors passing through the CT opening. This is known as the flux-balancing differential scheme. The best settings for sensitivity, speed and security are derived from this, but the limitations are that the
maximum openings in these CTs are about 8 inches in diameter so conductors used in EHV systems cannot pass through them.

In the case where the flux summation type CTs cannot be used, conventional methods are used where conventional-type CTs and differential relays are employed for protection work. Two-restraint differential relays would be applicable in this case having two sets of CTs of same type and ratio.

With equal CT ratios, for all external faults and loads, the secondary currents through the relay restraint windings would be the same and the operating current would be close to zero. When a fault occurs between the two sets of CTs, all fault current flows through the operate winding thus triggering the relay and providing high sensitivity protection for both phase and ground faults.

Instantaneous overcurrent relays (50G,50N,51N) are applied for ground-fault protection. The preferred method is to use a flux summation-type CT, with the 3 motor conductors passing through the CT openings. The magnetic summation of 3-phase currents are obtained, which produces a zero-sequence current \(3I_o\) to the relay secondary output. The advantage of this is that the CT ratio is commonly 50:5 and is independent of the motor size. This was also mentioned for the phase protection.

For larger motors and conductors, ground relays (50 N) in neutral must be used. Ground relay must be set above any false residual current that can result from unequal performance of the 3 CTs on high, unequal-offset, starting currents. Though difficult to determine, the chances of this happening are low if the phase burdens are balanced and the CT voltage developed by maximum-starting current is not more than 75% of the CT accuracy class voltage.

Thermal and locked-rotor protection is very important. The importance of this concept is that the settings of the relays have to match closely with the thermal and locked-rotor curves shown in Figure 2. To meet this requirement relays 49-51 are chosen. These are thermal relays that reach thermal limit curves and inverse-time-overcurrent relays for locked rotor protection. This method provides very good protection for most motors.
Figure 2: Starting curve of motor [Blackburn]

Thermal relays are available in several forms.

1. A "replica" type where a bimetallic element is used to approximate the motor-heating characteristics. This operates on current.

2. A type that operates from resistance temperature detectors (RTDs), which are embedded in motor windings and operate on winding temperature. These detectors are places at the most probable hot spot or danger area at the time of manufacturing. This is common in motors from about 250 hp and higher.

3. Types that operate the RTDs as well as the "replica" type.

The comparison of motor-starting and inverse-time-overcurrent relay curves on the same plot can sometimes provide false information. This usually occurs in large
motors, where the space between the starting current and locked-rotor limit is extremely narrow.

The protection for this can be a zero-speed switch built into the motor. Should the motor not accelerate on energization to open or operate the switch in a prescribed manner, the supply circuit is open. This also introduces difficulties as the motor could start and lock up at less than full-load speed.

The alternative protection can be obtained by applying a distance relay which is set looking into the motor. The impedance, which is the ratio of system voltage and starting current, is determined and plotted as a vector on the R-X diagram. The distance relay (21) is set, with a timer, so that its MHO operating circle encloses the locked-rotor impedance vector.

If the start is successful, the impedance vector moves out of the 21 relay operating circle before the timer expires. If the start is unsuccessful, the impedance stays in the circle, allowing the timer to operate which initiates the trip.

The most common cause of unbalances in 3 phase motors is the loss of phase resulting from an open fuse, connector, or conductor. Detecting these problems you can look at a few different results such as negative sequence current, negative sequence voltage or a simple magnitude difference between phase currents. A (46) will respond to a difference in magnitudes while the (47) will respond to a negative sequence voltage. The negative sequence current can be detected many different ways using a ground relay or using a special (46).

Low voltage on a motor results in a high current and one of the following failures can occur: failure to start, failure to reach rated speed and failure to lose speed resulting in the motor pulling out for instance. Thus, an inverse time undervoltage relay (27) is recommended to trip when prolonged undervoltage exists and as back up for a protection that is included sometimes as part of the motor starter.

When motors are reenergized before they have stopped rotating, high transient torques can result with possible damage. This may occur when a rapid transfer of motors is made from a bus that has lost voltage to a live auxiliary bus. The safe limits for reconnection of motors are complex and the best policy is to delay a reclosure, ensure that the motors are promptly disconnected from the system, or reenergize the motors.
For induction motors, reenergizing should not occur until motor voltage has dropped to 33% or less of normal. For synchronous motors, reclosing or reenergizing must not happen until proper resynchronization can take effect.

The good choice of relay to use in this case would be an underfrequency relay (81), which would have settings at 97-98% rated with time to override the momentary voltage dip effects but before reenergization takes place.

High motor temperatures can result from repetitive starts with insufficient time between or operating them with extreme load variations. It is very possible that this high temperature will not exceed the motor thermal limits and continue to exist in a normal operation. Protection is provided by adopting a (49) relay which can operate on both over current and temperature. Both high current and high temperature must exist for the relay to operate and a presence of only one may not cause an operation of a relay. Microprocessors relays can monitor both of these characteristics effectively.

**Commercial Brand Relays**

As stated previously it is important to protect motors and as the motors get more expensive it is even more important to have the right equipment that will protect them from damage. Finding the right relay for your application is crucial so no damage is done to the motor and production can continue. It may be worth it to spend the extra dollar to get quality equipment to ensure complete protection and in the long run it will most likely save money too. Today on the market most motor protection relays all come with the standard features but there may be some specialty features one would want for their certain scenario. In order to find out what exactly these relays provide we took a look at three different relays at three different companies. We looked at the Multilin 269 Plus at General Electric, the SEL 701 at Schweitzer Engineering Laboratories, and the MM30 at Cooper Power. All the relays provide excellent protection and the main features can be seen in Table 1 below.
Table 1: Comparison of Relays [GE website, SEL 701 Datasheet, MM30 Datasheet]

<table>
<thead>
<tr>
<th>Relay’s Standard Features</th>
<th>Multilin 269 Plus</th>
<th>SEL 701</th>
<th>MM30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>General Electric</td>
<td>Schweitzer Eng. Lab</td>
<td>Cooper Power</td>
</tr>
<tr>
<td>Multiple Start Protection (66)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Locked Rotor Protection (50S)</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Variable lock-out timer</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal pre-alarm element (49)</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Thermal Protection (49)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Overload Protection (49)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Phase Reversed Protection (47)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Current Unbalance Protection (46)</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Undercurrent Loss of Load (37)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Short Circuit Protection (50)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Ground Fault Protection (50G or 67G)</td>
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<td>✓</td>
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<tr>
<td>Neutral and Ground Overcurrent (50N)</td>
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<td>Negative Sequence Overcurrent (50Q)</td>
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<tr>
<td>Pre-trip alarm warnings</td>
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<td>✓</td>
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</tr>
</tbody>
</table>

As one can see these relays provide the basic protection, which includes protection in starting, thermal limits, current unbalanced, undercurrent, short circuit, and ground fault situations. The relays come with a few other protection features as shown. The SEL 701 also has a voltage option but it is not standard. This provides protection against undervoltage, underpower, power factor, reactive power, overvoltage, and under/over frequency. The three relays researched can be seen below in Figure 3.

![Figure 3: GE 269 Plus Motor Management, SEL 701 Motor Protection, and Cooper Power MM30 relays](image-url)
Conclusion

When we choose to research motor protection we were not really sure what we were getting into. We had looked into protection of lines, buses, and transformers in protective relaying class but had not yet learned about motor protection. We also did not deal with this topic in senior design so we decided it would be something different to learn about and it wound up being a very interesting topic.

Motor protection is essential to the United States in that one-half of the power generated is consumed by induction motors. It is important to keep these motors running and damage free; the best way to do this is to have protective relays that can ensure this. As one can see from our research motor protection involves many different issues ranging from overcurrents to having the motor start to many times in a given time. All these issues are important and the relays are designed to handle any one of the issues.

Over the past month we have learned all the basic issues that can occur to a motor and how these issues are monitored. This may help us in our future industrial jobs by knowing the basics and understanding how these motors can be protected.
References


Cooper Power Systems website visited during April 2003

GE website visited during April 2003
http://www.geindustrial.com/cwc/products?pnlid=6&id=269p&catid=218&from=
menu


IEEE Standards. “IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems” Chapter 9 and Intro.

SEL Data Sheet on 701 visited during April 2003.