Aspects of Overcurrent Protection for Feeders and Motors

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ABSTRACT

This paper discusses the coordination of the characteristics and the backup and redundancy possible with microprocessor relays. The paper reviews the application of negative-sequence overcurrent characteristics for unbalanced protection in motors and also covers the rules for coordinating negative-sequence characteristics to provide sensitive phase-to-phase protection in feeders. The paper also covers reset characteristics and the requirements for stator and rotor thermal protection of induction motors.

Key Words: Inverse-time Overcurrent Relay, Negative-Sequence Overcurrent Relay, Motor Thermal Model, Motor Protection.

INTRODUCTION

A comprehensive list of non-directional overcurrent relays would include thermal overload, inverse-time, definite time, and instantaneous relays. The list could be further classified by operating quantities including individual phase, residual, and negative-sequence current. Taken collectively and depending on the characteristic shape, pickup and time range, and dynamics, these relays span the applications for motor, feeder, and breaker failure protection.

Because of the past necessity for using either discrete or specialized system relays, overcurrent characteristics for these applications may appear diverse and unrelated. However, microprocessor relay technology has advanced to where it is not only feasible, but it is of distinct economic advantage to consider all these characteristics collectively as attributes of a universal overcurrent relay. Furthermore, the issues of backup and redundancy are addressed since a single processor easily accommodates the computational burden of two complete and independent relays.

Figure 1 shows the block diagram for a dual universal overcurrent relay having one opto-isolated input, two output contacts, and a set of three-phase current inputs for each of the independent relays X and Y. In the relay setting procedure, the user is prompted for relay X or Y and then for the application. The relay then presents a group of elements to be set. Such an arrangement focuses attention, not only on the individual characteristics, but also on the elements that make up each application. This universal relay concept is used here to discuss the commonality, the differences, and the coordination of the elements required for feeder, motor, and breaker failure protection. The paper goes on to discuss the rules for the coordination of negative-sequence overcurrent characteristics for sensitive phase-to-phase fault protection in feeders, as well as for unbalanced current protection of induction motors.

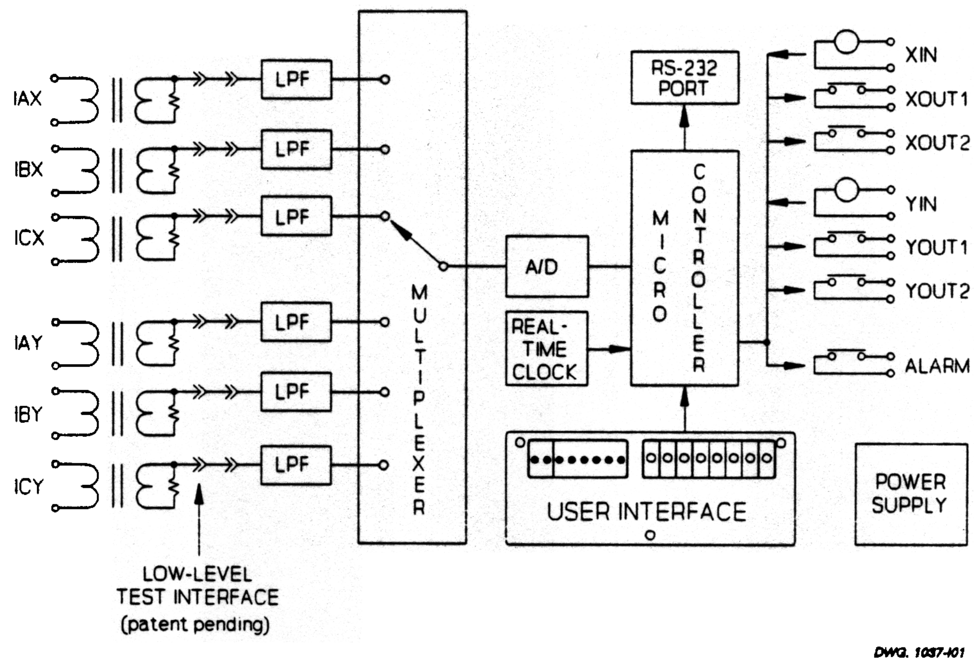

Figure 1: Relay Block Diagram

MEASURANDS AND THE DIGITAL FILTERING PROCESS

The input for a digital relay is obtained by sampling sine wave currents at discrete time intervals. A fixed number of instantaneous samples per cycle are converted to digital quantities by the A/D converter and stored in memory for processing. Digital Filtering is the simple process of combining successive samples to obtain the quantities which represent the phasor components of the input. For example, in Figure 1 six currents are sampled 16 times per cycle. Each successive sample is multiplied by the coefficients of a stored cosine wave and combined to obtain a phasor component. The cosine filter has the following properties ideal for protective relaying [1]:

1. Bandpass response about the system frequency.
2. DC and ramp rejection to guarantee decaying exponentials are filtered out.
3. Harmonic attenuation or rejection to limit effects of nonlinearities.
4. Reasonable bandwidth for fast response.
5. Good transient behavior.
6. Simple to design, build, and manufacture.

The present samples and the samples occurring a quarter-cycle earlier form the real and imaginary components of the current phasors. The measurands calculated from the phasor components each cycle are:

Phase Current	I_a, I_b, I_c
Residual Current	I_0
Negative-Sequence Current	I_2
Positive-Sequence Current	I_1

APPLICATION GROUPS AND ELEMENTS

All the elements of the universal relay are organized under the applications of feeder, motor, or breaker. The feeder application group provides three separate sets of Instantaneous, Definite-Time, and Inverse-Time elements. The first set responds to I_a, I_b, and I_c and provides conventional phase fault protection. The second set responds to $3I_2$ and provides for sensitive phase-to-phase fault, and ground backup protection. The third set responds to residual current $3I_0$, and provides conventional ground fault protection.

The motor application group shares the phase, negative-sequence, and ground instantaneous and definite-time elements to protect the motor for winding faults or faults in the connecting leads. However, an added element, responsive to both positive-sequence and negative-sequence current, provides thermal protection for overload, locked rotor, or unbalanced current conditions.

COORDINATION OF INVERSE TIME-CURRENT CHARACTERISTICS

Coordination practice is ultimately determined by the type of grounding used in distribution systems. Notably, in Europe the practice is to operate high impedance grounded or ungrounded 3-wire distribution systems. Since there are no single-phase laterals protected by fuses, coordination is obtained using definite-time characteristics. Conversely, in North America the practice is to operate grounded 4-wire distribution systems with loads served by single-phase laterals protected by fuses. Consequently, coordination is obtained using inverse time-current characteristics suitable for fuse coordination. Figure 2 shows the close coordination of an extremely inverse induction characteristic with that of a high-voltage fuse.

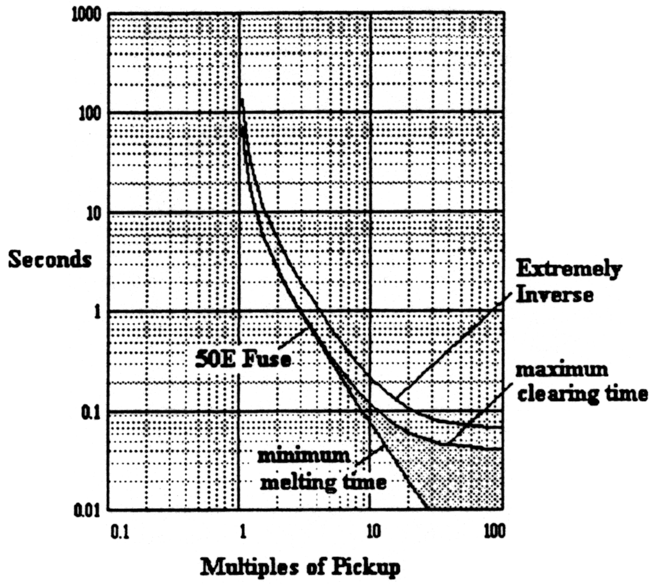

Figure 2: Extremely Inverse Characteristic Compared with Min. Melting and Maximum Clearing Time of a 50E Fuse

The straight line I^2t log-log plot of a fuse minimum melting time is often visualized as the basic time-current characteristic. However, a definite time must be added to form the maximum clearing time characteristic of the fuse. This illustrates the fundamental concept that whenever fixed clearing time is added to a straight line log-log plot the result is a curve. For this reason, the most viable shape for a time-current characteristic for coordination purposes is the curve formed when a definite time is added to the straight line of a log-log plot.

Appendix I shows that, were it not for the use of saturation, the induction characteristic would be the straight line log-log characteristic of a fuse. However, the viable curve is formed by deliberately saturating the electromagnet at a specific multiple of pickup current to introduce a definite-time component as discussed in [2]. Therefore, adding a constant definite time term to Eq. 12 of Appendix I forms the induction characteristic equation. Consequently, all the characteristics can be accommodated in the dual overcurrent relay using the following equations:

For $0 < M < 1$

$$t = TD\left[\frac{A}{M^2 - 1}\right] \qquad (1)$$

For $M > 1$

$$t = TD\left[\frac{A}{M^p - 1} + B\right] \qquad (2)$$

where: t is the trip time in seconds
M is multiples of pickup current
TD is the time-dial setting (1 through 15)

where the constants A, B, and the exponent p determine the shape of the characteristic. The constants A and B can be chosen to accurately emulate the extremely and the very inverse induction time-current characteristics with the exponent p of 2. An accurate emulation of the moderately inverse characteristic is obtained by using an exponent of 0.02 with specific values for A and B. The shapes of the induction characteristics are defined by the ratios of A to B and the exponents listed below:

Curve	A/B	p
Moderately Inverse	0.46	0.02
Inverse	33.05	2.0
Very Inverse	40.29	2.0
Extremely Inverse	161	2.0

COORDINATING NEGATIVE-SEQUENCE OVERCURRENT ELEMENTS

It is well understood that ground overcurrent elements, operated by the residual current $3I_0$, do not respond to balanced load and can be set to operate faster and more sensitively for the most frequent fault type, the phase-to-ground fault. Similarly, negative-sequence overcurrent elements, responding to $3I_2$, do not respond to balanced load and can be set to operate faster and more sensitively for the second most frequent fault type, the phase-to-phase fault.

Negative-sequence elements are useful in clearing faults on the secondary of a delta-wye. Also, the settings realized for a bus negative-sequence element may be as sensitive as the feeder phase-overcurrent elements for effective backup for feeder phase-to-phase faults. The feeder relay sensitivity for phase-to-phase faults may also be improved.

Table 1: Faults on a Radial line

Fault	$\lvert 3I_2/I_p \rvert$
AG	1
BC	$\sqrt{3}$
BCG	$\leq\sqrt{3}$

Table II: Sec. Faults on Delta-Wye Transformer

Fault	$\lvert 3I_2/I_p \rvert$
AG	$\sqrt{3}$
BC	1.5

The negative-sequence elements differ only in their operating quantity and are easily coordinated with phase and ground relays. Elneweihi et al. [3], have devised a simple method for setting negative-sequence elements. The method is based on the observation that the greatest ratio between the negative-sequence current $3I_2$ and the phase current I_p is $\sqrt{3}$ as illustrated in Tables I and II. The simple method of setting negative-sequence overcurrent elements is as follows:

1. Start with the most downstream negative-sequence element (e.g., feeder relay).

2. Identify the phase-overcurrent device (relay, fuse, etc.) downstream from the negative-sequence element that is of the greatest concern for coordination. This is usually the phase-overcurrent device with the longest clearing time.

3. Consider the negative-sequence element as an "equivalent" phase-overcurrent element. Derive the setting for this element as any phase element would be done. The setting only differs in that it is only governed by coordination time and not by load.

4. Retain the time-dial or time-delay settings but multiply the "equivalent" phase-overcurrent pickup setting by $\sqrt{3}$. The result is the negative-sequence overcurrent element pickup in terms of $3I_2$ current.

5. Set the next upstream negative-sequence element to coordinate with the first downstream negative-sequence element (and the third with the second and so on).

MOTOR PROTECTION

The characteristics of the motor application are shown in Figure 3 with the starting current of an induction motor. In the motor application, definite-time and instantaneous elements provide protection for faults in the motor leads and internal faults in the motor itself. A definite-time setting of about 6 cycles allows the pickup to be set to 1.2 to 1.5 times locked rotor current to avoid tripping on the initial X_d" inrush current (shown magnified). The instantaneous can then be set at twice the locked rotor current for fast clearing of high fault currents.

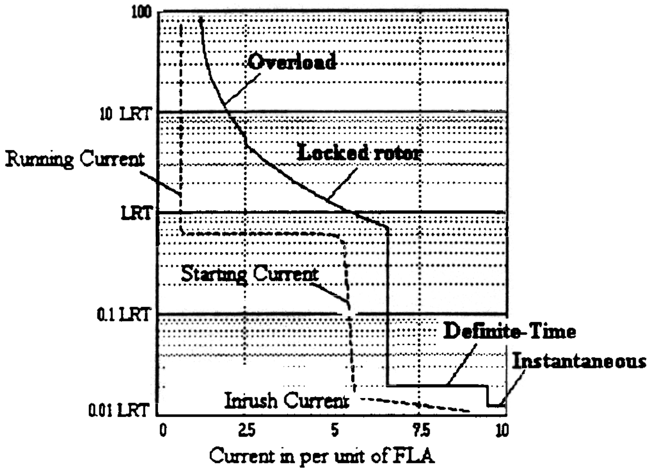

Figure 3: Motor Characteristics Plotted with Motor Starting Current

An inverse-time phase overcurrent element and a separate negative-sequence overcurrent element could be applied to prevent the overheating caused by a locked rotor or an unbalance current condition. However, neither of these elements can account for thermal history or track the excursions of temperature. Instead, an element is used which accounts for the I^2r heating effect of both positive- and negative-sequence current. The element is a thermal model, defined by motor nameplate and thermal limit data, that estimates motor temperature. The temperature is then compared to thermal limit trip and alarm thresholds to prevent overheating for the abnormal conditions of overload, locked rotor, too frequent or prolonged starts, and unbalanced current.

DEFINING THE THERMAL MODEL

The I^2r heat source and two trip thresholds can be discerned from a motor characteristic of torque, current, and rotor resistance versus slip shown in Figure 4. The plot shows the characteristic of the induction motor to draw excessively high current until the peak torque develops near full speed. Also, the skin effect of the slip frequency causes the rotor resistance to exhibit a high locked rotor value labeled R_1 which decreases to a low running value at rated slip labeled R_0.

Using a typical starting current of six times the rated current and a locked rotor resistance R_1 of three times value of R_0, the I^2r heating is estimated at 6^2 x 3 or 108 times normal. Consequently, an extreme temperature must be tolerated for a limited time to start the motor. Where an emergency I^2t threshold is specified by the locked rotor limit during a start, a threshold for the normal running condition is specified by the service factor. Therefore, the thermal model requires a trip threshold when starting, indicated by the locked rotor thermal limit, and a trip threshold when running, indicated by the service factor.

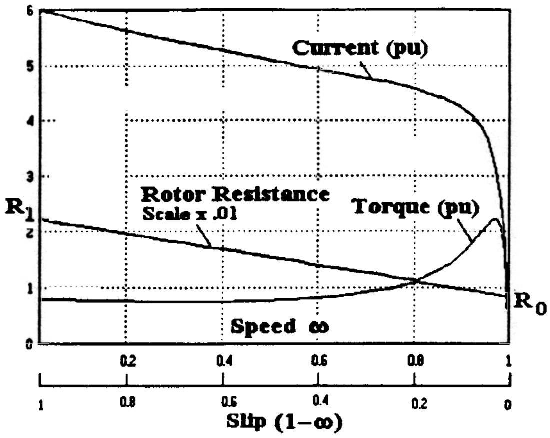

Figure 4: Current, Torque, and Rotor Resistance of an Induction Motor Versus Speed

The slip dependent heating effect of positive- and negative-sequence currents is derived as follows. The positive-sequence rotor resistance plotted in Figure 4 is calculated using current, torque, and slip in the following equation:

$$R_r = \frac{Q_M}{I^2} S \tag{3}$$

and can be represented as a linear function of slip. The positive-sequence resistance R_{r+} is a function of the slip S:

$$R_{r+} = (R_1 - R_0)S + R_0 \tag{4}$$

The negative-sequence resistance R_{r-} is obtained when S is replaced with the negative-sequence slip (2-S):

$$R_{r-} = (R_1 - R_0)(2 - S) + R_0 \tag{5}$$

Factors expressing the relative heating effect of positive- and negative-sequence current are obtained by dividing Eqs. 4 and 5 by the running resistance, R_0. Consequently, for the locked rotor case, and where R_1 is typically three times R_0, the heating effect for both positive- and negative-sequence current is three times that caused by the normal running current.

$$\frac{R_{r+}}{R_0}\bigg|_{s=1} = \frac{R_{r-}}{R_0}\bigg|_{s=1} = \frac{R_l}{R_0} = 3 \qquad (6)$$

For the running case, the positive-sequence heating factor returns to one and the negative-sequence heating factor increases to 5:

$$\frac{R_{r+}}{R_0}\bigg|_{s=0} = 1 \qquad \frac{R_{r-}}{R_0}\bigg|_{s=0} = 2\left[\frac{R_l}{R_0}\right] - 1 = 5 \qquad (7)$$

These factors are the coefficients of the positive and negative currents of the heat source in the thermal model.

STATES OF THE THERMAL MODEL

Because of its torque characteristic, the motor must operate in either a high-current starting state or be driven to a low-current running state by the peak torque occurring at about 2.5 per unit current. The thermal model protects the motor in either state by using the trip threshold and heating factors indicated by the current magnitude. The two states of the thermal model are shown in Figure 5. The thermal model is actually a difference equation executed by the microprocessor. However, it can be represented by the electrical analog circuit shown in Figure 5. In this analogy, the heat source is represented by a current generator, the temperature is represented by voltage, and thermal resistance and capacitance are represented by electrical resistance and capacitance. The parameters of the thermal model are defined as follows:

R_l = Locked rotor electrical resistance (per unit ohms)
R_0 = Running rotor electrical resistance also rated slip (per unit ohms)
I_L = Locked rotor current in per unit of full load current
T_a = Locked rotor time with motor initially at ambient
T_o = Locked rotor time with motor initially at operating temperature

The starting state is shown in Figure 5a and is declared whenever the current exceeds 2.5 per unit of the rated full load current and uses the threshold and heating factors derived for the locked rotor case. Thermal resistance is not shown because the start calculation assumes adiabatic heating. The running state, shown in Figure 5b, is declared when the current falls below 2.5 per unit current and uses the heating factors derived for the running condition. In this state the trip threshold "cools" exponentially from a locked rotor threshold to the appropriate threshold for the running condition using the motor thermal time constant. This emulates the motor temperature which cools to the steady-state running condition.

In the model, the thermal limit $I_L^2T_a$ represents the locked rotor hot spot limit temperature and $I_L^2(T_a - T_o)$ represents the operating temperature with full load current. The locked rotor time, T_a, is not usually specified, but may be calculated by using a hot spot temperature of six times the operating temperature in the following relation:

$$\frac{I_L^2T_a}{I_L^2(T_a - T_o)} = 6 \quad \therefore \quad \frac{T_a}{T_o} = 1.2 \qquad (8)$$

There are two reasons for using the rotor model in the running state. The first is that, despite a difference in thresholds, it is an industry practice to publish the overload and locked rotor thermal limits as one continuous curve as illustrated in Figure 3. The second is that the rotor model accounts for the heating of both the positive-sequence and the negative-sequence current. As a final refinement, assigning standard values of 3 and 1.2 to the ratios R_l/R_0 and T_a/T_o respectively, allows the model parameters to be determined from five fundamental settings:

FLA Rated full-load motor current in secondary amps
LRA Rated locked rotor current in secondary amps
LRT Thermal-limit time at rated locked rotor current
TD Time dial to trip temperature in per unit of LRT
SF Motor rated service factor

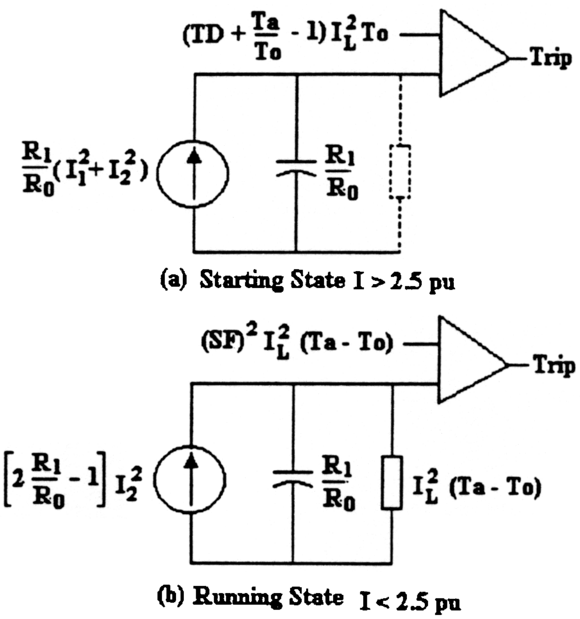

Figure 5: States of the Thermal Model

DUAL APPLICATIONS

Out of the many possible applications, two shown in Figure 6a and 6b illustrate the versatility of the dual universal overcurrent relay. In Figure 6a, both the relays X and Y are set for feeder application to protect a delta-wye transformer bank. Relay X provides phase and negative-sequence overcurrent protection on the high side (delta) that also see through the bank to the low side. The ground overcurrent elements provide sensitive protection for the high side but cannot see through the delta. However, relay Y provides the ground protection for the low side. In Figure 6b, relay X is set as a feeder where the phase and negative-sequence overcurrent elements provide protection for high phase-to-phase faults using a higher ratio ct. Relay Y is set for motor application using a low ratio ct to protect the small motor.

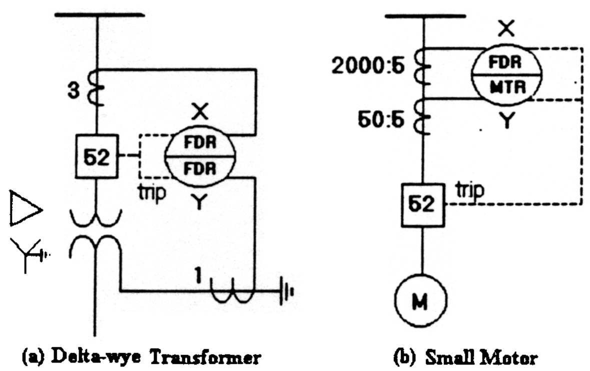

Figure 6: Applications of a Dual Universal Overcurrent Relay

CONCLUSION

1. An analytic equation for induction-type inverse time-current characteristics has been derived. The integral equation also defines reset characteristic and the dynamics which guarantee close coordination with induction relays under all conditions of varying current.

2. The equations of a motor thermal element have been derived. The element exists as two-state thermal which accounts for the slip-dependent heating of positive- and negative-sequence current. The model is defined by motor nameplate and thermal-limit data and provides protection during the abnormal conditions of overload, locked rotor, and unbalanced current.

3. The overcurrent elements applied for feeder, motor, and breaker protection consist of sets of thermal, inverse-time, definite-time, and instantaneous elements. These elements, grouped by application, are collectively accommodated as attributes of a universal overcurrent relay.

4. The issues of backup and redundancy have been addressed by a dual-relay implementation.

5. Negative-sequence elements, as well as traditional phase and ground elements, are obtained from three phase-current measurands. Negative-sequence elements with induction-type characteristics coordinate directly with phase and ground elements and can be set independent of balanced load to provide sensitive phase-to-phase fault coverage.

APPENDIX I

The Time-Current Equation

An equation for the inverse time-current characteristic can be derived from the following basic differential equation for input dependent time delay as it applies to an induction relay:

$$\tau_s(M^2 - 1) = K_d \frac{d\theta}{dt} \qquad (9)$$

Where:

M	is the ratio I/I_p
I	is the input current in amperes
I_p	is the pickup current in amperes
τ_s	is the spring torque
K_d	is the damping factor due to the drag magnet
θ	is the angular displacement and $d\theta/dt$ is the angular velocity

The small moment of inertia of the disc is neglected and the spring torque is represented by a constant because the effect of its gradient is compensated by an increase in torque caused by the shape of the disc. Integrating Eq. 9 gives:

$$\theta = \int_0^{T_0} \frac{\tau_s}{K_d}(M^2-1)dt \qquad (10)$$

Dividing both sides of Eq. 10 by θ gives the dynamic equation:

$$\int_0^{T_0} \frac{\tau_s}{K_d\theta}(M^2-1)dt = \int_0^{T_0} \frac{1}{t(I)}dt = 1 \qquad (11)$$

where t(I) is the time-current characteristic and the constant A equals $K_d\theta/\tau_s$:

$$t(I) = \frac{\left[\frac{K_d\,\theta}{\tau_s}\right]}{(M^2-1)} = \frac{A}{(M^2-1)} \qquad (12)$$

Reset Characteristic

Where the time integral of any element can be reset in one cycle, an optional reset characteristic is available when required for close coordination with existing induction relays.

Eq. 12 defines the induction characteristic for currents below, as well as for currents above, the pickup current.

If an induction disc has an initial displacement from its reset position when the applied current is reduced to zero, the disc will be driven in a negative direction toward the reset position. This is represented in Eq. 12 by setting M = 0, which produces a negative number indicating the reset time and the rotation of the disc in the direction toward reset. With this substitution, Eq. 12 gives the reset time t_r:

$$|t_r| = \frac{K_d \theta}{\tau_s} \tag{13}$$

and the reset characteristic for any value of M between zero and one is:

$$t = \frac{t_r}{M^2 - 1} \tag{14}$$

The dynamic equation, Eq. 11, and the characteristic equation, Eq. 12, are important since they specify how an inverse time-current characteristic must be implemented in order to guarantee coordination with existing inverse-time overcurrent relays under all conditions of varying current such as decreasing fault resistance and remote terminal clearing.

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