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IEEE Standard for Inverse-Time Characteristics Equations for Overcurrent Relays

IEEE Power and Energy Society

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Power System Relaying Committee

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(Revision of IEEE Std C37.112-1996)

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Abstract: The inverse-time characteristics of overcurrent relays are defined in this standard. Operating equations and allowances are provided in the standard. The standard defines an integral equation for microprocessor relays that ensures coordination not only in the case of constant current input but for any current condition of varying magnitude. Electromechanical inverse-time overcurrent relay reset characteristics are defined in the event that designers of microprocessor based relays and computer relays want to match the reset characteristics of the electromechanical relays.

Keywords: IEEE C37.112™, inverse-time characteristics, overcurrent relays

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Introduction

This introduction is not part of IEEE Std C37.112–2018, IEEE Standard for Inverse-Time Characteristics Equations for Overcurrent Relays.

Induction overcurrent relay characteristics have been in continuous use for over 50 years and are a de facto standard in North America. When an overcurrent relay is installed in North America, it often must coordinate with existing induction relays and fuses. Induction characteristics appear in the form of stored data tables, polynomials, or spline curves in most relay coordination programs. There has been no previous defining standard and all the relay curve data was obtained from characteristics plotted from experimental data. Conversely, microprocessor relays execute algorithms that are mathematical procedures. They produce analytic characteristics that can be described accurately by an equation. This standard bridges the gap between the previous graphical practices and the present analytical practices. This is done by defining equations that ensure that microprocessor overcurrent relays will coordinate with induction overcurrent relays. The standard defines equations for the reset region as well as for the trip region of the time-current characteristic that are derived from the basic differential equation for input-dependent time delay as it applies to the induction relay.

Contents

IEEE Standard for Inverse-Time Characteristics Equations for Overcurrent Relays

1. Overview

1.1 Scope

The scope of this standard includes the review of various existing analytic techniques used to represent relay operating characteristic curve shapes and proposes analytical (formula) representation of typical operating characteristic curve shapes to foster some standardization of available inverse-time relay characteristics provided in microprocessor or computer relay applications.

1.2 Purpose

The purpose of this standard is to provide an analytic (formula) representation of typical relay operating characteristic curve shapes of various inverse-time relays to facilitate representation by microprocessor-type relays and promote a degree of standardization in the inverse shape of a selected curve.

2. Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.[1]

inverse-time overcurrent relay: A current sensing relay that produces an inverse time-current characteristic by integrating a function of current $F(I)$ with respect to time. The function $F(I)$ is positive above and negative below a predetermined input current called the pickup current. Pickup current is therefore the current at which integration starts positively and the relay produces an output when the integral reaches a predetermined positive set value.

For the induction relay, it is the disk velocity that is the function of current $F(I)$ that is integrated to produce the inverse time characteristic. The velocity is positive for current above and negative for current below a predetermined pickup current. The predetermined set value of the integral represents the disk travel, required to actuate the trip output.

reset characteristics: The time versus current curve that defines the time required for the integral of the function of current $F(I)$ to reach zero for values below current pickup.

[1] *IEEE Standards Dictionary Online* is available at: http://dictionary.ieee.org.

reset: The state of an inverse-time overcurrent relay when the integral of the function of current *F(I)* that produces a time-current characteristic is zero.

time dial: The time dial is the control that determines the value of the integral at which the trip output is actuated, and hence controls the time scale of the time-current characteristic produced by the relay. In the induction-type relay, the time dial sets the distance the disk must travel, which is the integral of the velocity with respect to time.

3. The time-current equation

3.1 Coordination of inverse time-current characteristics

Coordination practice in distribution systems is influenced by the type of grounding used. Notably, in Europe and Japan the practice is to operate three-wire primary distribution systems, either impedance grounded or ungrounded, over relatively short distances. Since there are no single-phase laterals protected by fuses, coordination can be achieved using definite-time characteristics. In North America the practice is to operate grounded four-wire distribution systems with loads served by single-phase laterals protected by fuses. As a result, coordination is obtained using inverse time-current characteristics suitable for fuse coordination. Figure 1 shows the close coordination of an extremely inverse induction characteristic with a high-voltage 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 emulate the maximum clearing time 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 best 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.

3.2 The analytic equation

Equation (1) and Equation (2) define the reset time and pickup time of an inverse-time overcurrent curve as shown in Annex A. By applying the constants to these equations, a characteristic curve can be accurately defined. Equation (2) is similar to the IEC equation (see IEC 60255-151:2009, Measuring relays and protection equipment—Part 151: Functional requirements for over/under current protection) except for the addition of constant B. The constant B defines the definite time component that is the result of core saturation of an induction type relay.

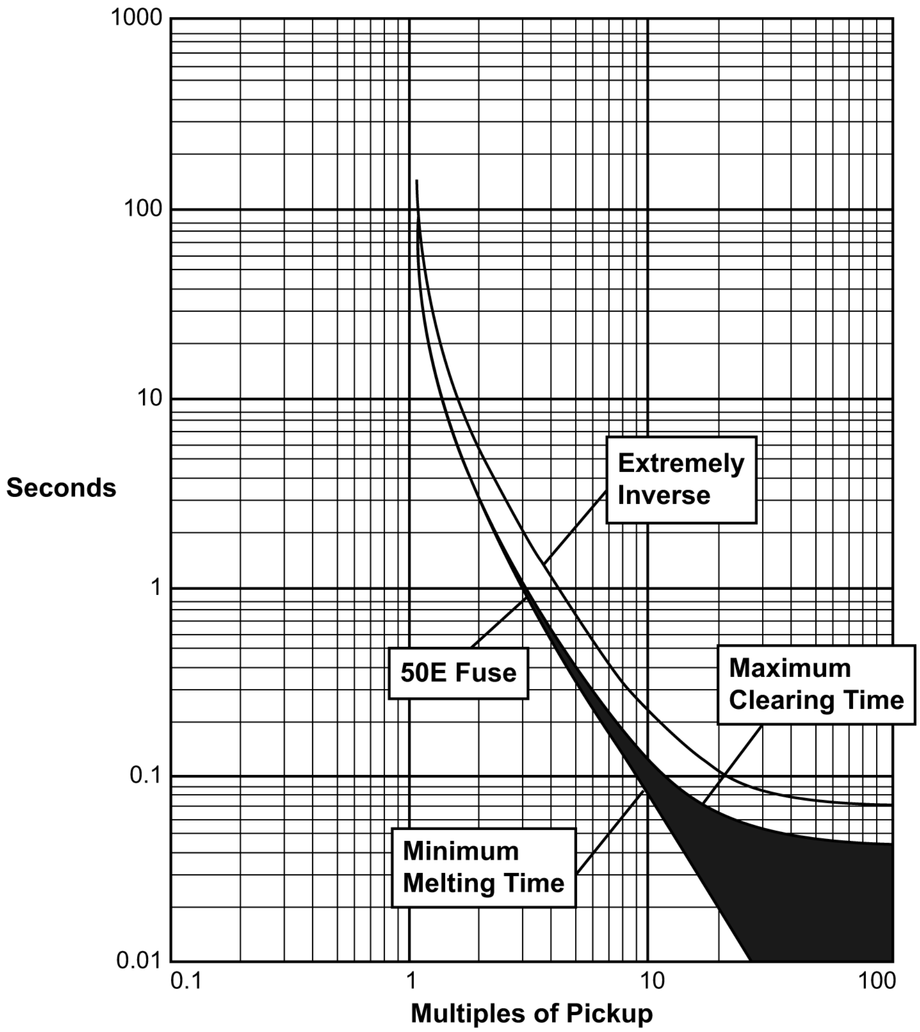

Figure 1—Extremely inverse characteristic compared with minimum melting and maximum clearing time of a 50E fuse

For $0 < M < 1$

$$t(I) = \left(\frac{t_{\mathrm{r}}}{M^2 - 1} \right) \tag{1}$$

For $M > 1$

$$t(I) = \left(\frac{A}{M^p - 1} + B \right) \tag{2}$$

where

$t(I)$ is the reset time in Equation (1) and the operate time in Equation (2) in seconds. The reset time is expressed as a negative number for values of current less than the pickup current. Refer to A.2 for further reset characteristic discussion

M is the current expressed in multiples of pickup current ($I_{\mathrm{input}}/I_{\mathrm{pickup}}$ where I_{pickup} is the relay current set point)

t_r is the reset time with no input current ($M = 0$)
A, B, p are constants chosen to provide the selected curve characteristics

Induction relays have a dynamic property that results in a higher rate of disk travel with higher current. Typically, faulted conditions may present the relay with a variable fault current prior to the relay tripping. Equation (3) emulates the dynamics of the induction disk inverse-time overcurrent relay and therefore coordination will be maintained even with varying current.

$$\int_0^{T_0} \frac{1}{t(I)} dt = 1 \tag{3}$$

where

T_0 is the operating time

3.3 Time dial

The time dial of an overcurrent relay is a control that permits the characteristic of the relay to be adjusted to a predetermined operate time at a specified current. The time dial generally allows a 15 to 1 or greater range of time adjustment. In the characteristic Equation (1) and Equation (2), the constants A, B, and t_r are varied proportionally with time dial. Whereas the ratio of A to B may vary to some extent with the time dial setting in induction relays, the ratio of A to B remains constant in microprocessor relays.

3.4 Standard time-current characteristics

The constants and exponents in Table 1 when used in Equation (1) and Equation (2) define the shape of the standard moderately inverse, very inverse, and extremely inverse trip characteristics. The constant t_r, when used in Equation (1), defines the optional reset characteristic. These constants define the curve that represents the mean curve of the induction characteristics defined in Annex A.

Table 1—Constants and exponents for standard characteristics[a]

Characteristic	A	B	p	t_r
Moderately inverse	0.0515	0.1140	0.0200	4.85
Very inverse	19.61	0.4910	2.0000	21.6
Extremely inverse	28.2	0.1217	2.0000	29.1

[a]For the specified range of M, the number of digits represented for each constant is such that a unit change in the least significant digit will cause a change no greater than 0.5% in the subsequent computation of the relative time change $(\Delta t / t)$.

The characteristics of a microprocessor-based protective relay conform to this standard when they are implemented according to Equation (3), where $t(I)$ is given by Equation (2) and the operate time values corresponding to values in the range of 1.5 to 20 multiples of the pickup current are within the conformance bands shown in Figure 2, Figure 3, and Figure 4. Note that in each of these figures, the reset characteristic curve is shown on the left side of the plot, and the trip characteristic curve is shown on the right side of the plot. The upper and lower limits of the conformance bands are 1.15 and 0.85 times the characteristic defined in Table 1. The conformance band for the optional reset characteristic extends from 0.05 to 0.9 multiples of pickup current. The conformance bands are templates for classifying the shape of standard inverse time-current characteristics and are not tolerance bands for accuracy or repeatability.

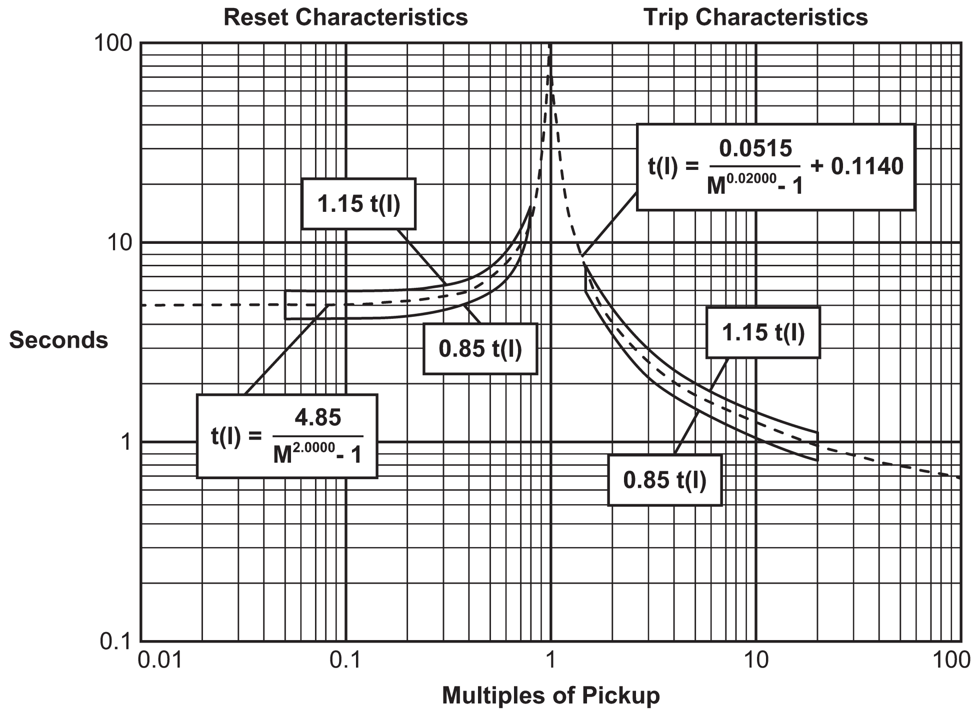

Figure 2—Standard moderately inverse time-current characteristic with standard conformance band

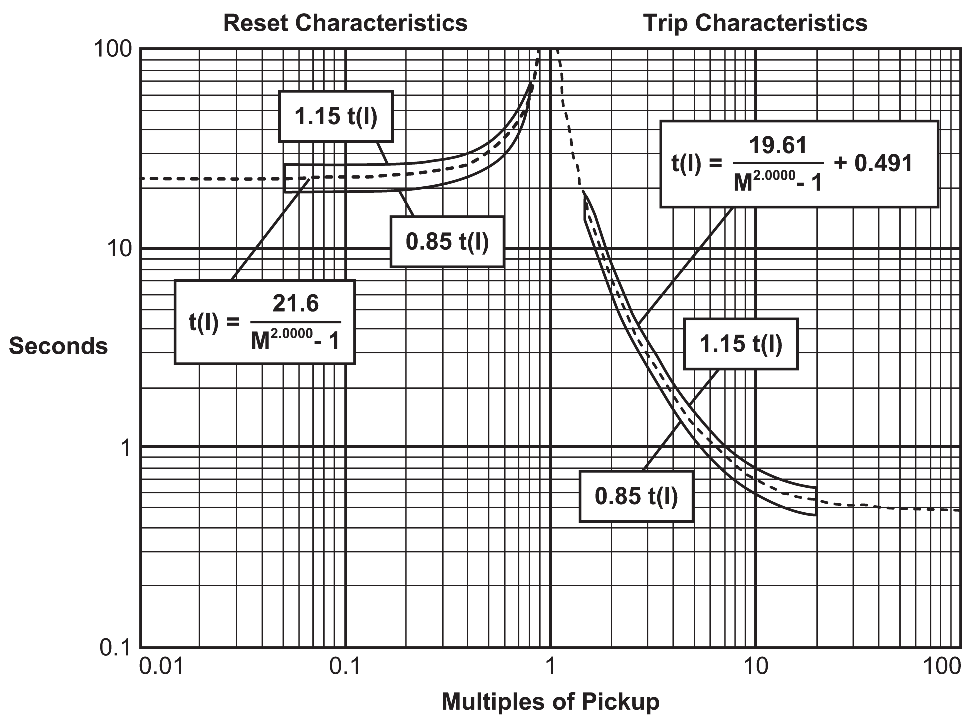

Figure 3—Standard very inverse time-current characteristic with standard conformance band

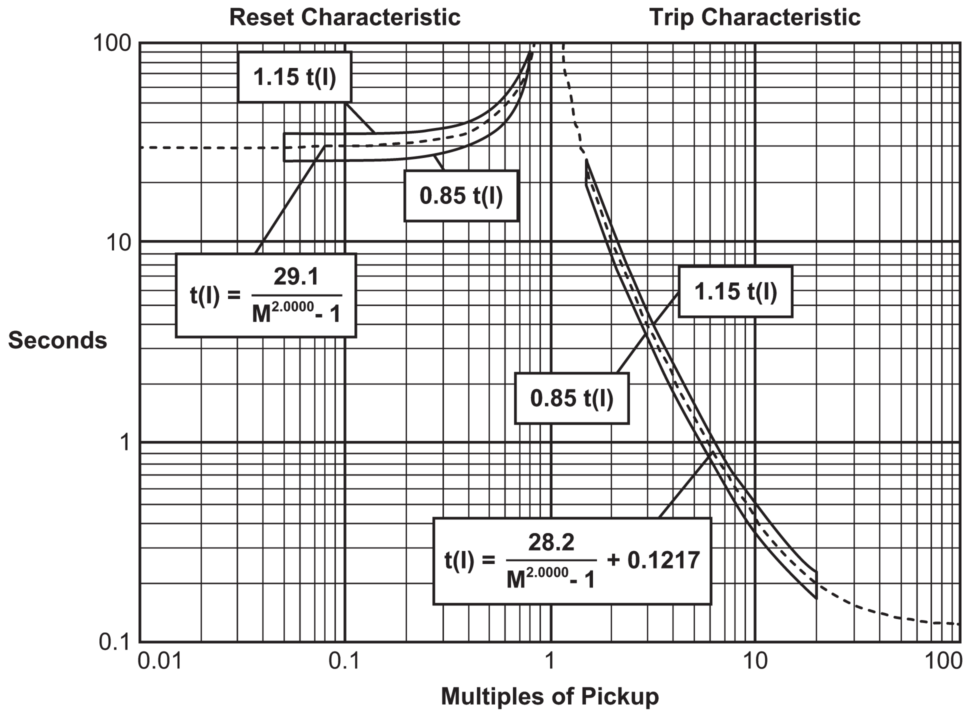

Figure 4—Standard extremely inverse time-current characteristic with standard conformance band

Annex A

(informative)

Derivation of the induction characteristic

A.1 The time-current equation

The analytical equation that defines the inverse time-current characteristic is derived from the basic differential equation for input dependent time delay as it applies to an induction relay as follows:

$$K_1 I^2 = m\frac{d^2\theta}{dt^2} + K_d\frac{d\theta}{dt} + \frac{\tau_F - \tau_S}{\theta_{\max}}\theta + \tau_S \qquad \text{(A.1)}$$

where

I	is the input current
θ	is the disk travel
$\theta_{\max}$	is the maximum disk travel
K_I	is a constant relating torque to current
m	is the moment of inertia of the disk
K_d	is the drag magnet damping factor
τ_F	is the spring torque at maximum travel
τ_S	is the initial spring torque

The gradient of the torsion spring used in the induction relay is small and results in only a small increase in torque from τ_S to τ_F with travel. The disk is also shaped to produce an increasing torque with travel to offset the increase in spring torque. The resulting net disk torque is as follows:

$$K_I I^2 - \tau_S \qquad \text{(A.2)}$$

Let the current I equal M multiples of the pickup current I_p so that the net torque may be written as follows:

$$K_I (MI_p)^2 - \tau_S \qquad \text{(A.3)}$$

At pickup $M = 1$ and the net torque on the disk is zero:

$$\begin{aligned} K_I I_p^2 - \tau_S &= 0 \\ K_I I_p^2 &= \tau_S \end{aligned} \qquad \text{(A.4)}$$

The net torque can then be expressed in terms of the spring torque by substituting Equation (A.4) into Equation (A.3) as follows:

$$(M^2 - 1)\tau_S \qquad \text{(A.5)}$$

By neglecting the small moment of inertia of the disk, Equation (A.1) is simplified as shown in Equation (A.6).

$$\tau_S (M^2 - 1) = K_d \frac{d\theta}{dt} \qquad \text{(A.6)}$$

The solution of this equation, which now lacks the second-order term, has the result that there is no acceleration or deceleration time. This means that, in this representation, final velocity is reached in a negligible period of time, and that there is negligible overtravel. This simplification is valid in most applications.

Integrating Equation (A.6) gives:

$$\theta = \int_0^{T_0} \frac{\tau_S}{K_\mathrm{d}}(M^2 - 1)dt \tag{A.7}$$

Dividing both sides of Equation (A.7) by θ gives the dynamic Equation (A.8) as follows:

$$\int_0^{T_0} \frac{\tau_S}{K_d\theta}(M^2 - 1)dt = \int_0^{T_0} \frac{1}{t(I)}dt = 1 \tag{A.8}$$

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

$$t(I) = \frac{\left(\dfrac{K_d\theta}{\tau_S}\right)}{\left(M^2 - 1\right)} = \frac{A}{(M^2 - 1)} \tag{A.9}$$

A.2 The reset characteristic

In some applications, it may be advantageous to reset the time integral in one cycle. However, optional reset characteristics should also be provided when required for reset coordination with existing induction relays.

Equation (A.9) defines the induction characteristic for currents both below and above the pickup current. If an induction disk has an initial displacement from its reset position when the applied current is reduced to zero, the disk will be driven in a negative direction toward the reset position. This is represented in Equation (A.9) by setting $M = 0$, which produces a negative number indicating the reset time and the rotation of the disk in the direction toward reset. With this substitution, Equation (A.9) gives the reset time t_r:

$$|t_r| = \frac{K_d\theta}{\tau_S} \tag{A.10}$$

And the reset characteristic for any value of *M* between zero and one is shown in Equation (A.11).

$$t = \frac{t_r}{M^2 - 1} \tag{A.11}$$

The dynamic Equation (A.8) and the characteristic Equation (A.9) are important since they specify how an inverse time-current characteristic must be implemented in order to assure coordination with existing inverse time overcurrent relays under all conditions of varying current such as decreasing fault resistance and remote terminal clearing.

A.3 Curves shaped by saturation

The torque due to current is proportional to the square of the flux caused by the current, and the previous derivation assumes a linear relation between the flux and the current. It does not take into account the saturation of the electromagnet that is used to shape the time-current characteristics produced by the induction principle.

The degree of saturation used to produce a particular curve can be determined by substituting the normalized flux for M in Equation (A.11):

$$t = \frac{t_r}{\left(\dfrac{\phi}{\phi_{pu}}\right)^2 - 1} \tag{A.12}$$

where

ϕ / ϕ_{pu}	is the normalized flux
t_r	is the reset time for $I = 0$
t	is the time to operate

From Equation (A.12) normalized flux in terms of the operating and reset time is shown in Equation (A.13).

$$\left(\frac{\phi}{\phi_{pu}}\right) = \sqrt{\frac{t_r}{t} + 1} \tag{A.13}$$

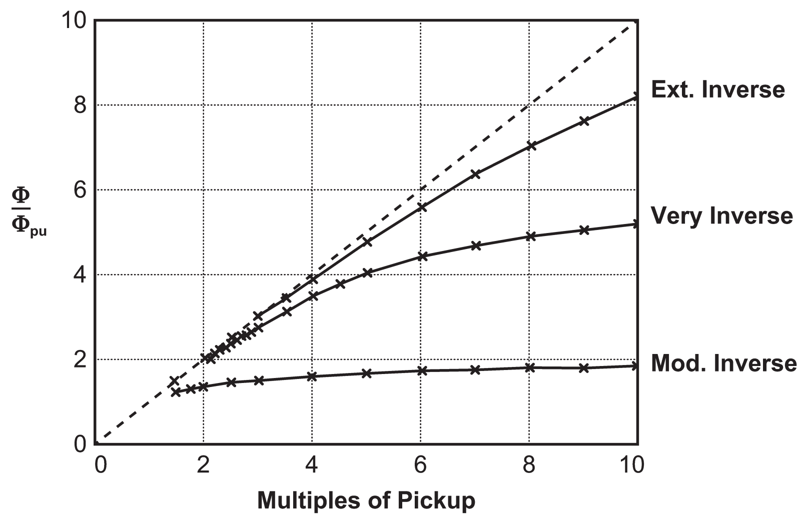

Figure A.1—Normalized flux in extremely inverse, very inverse, and moderately inverse relays

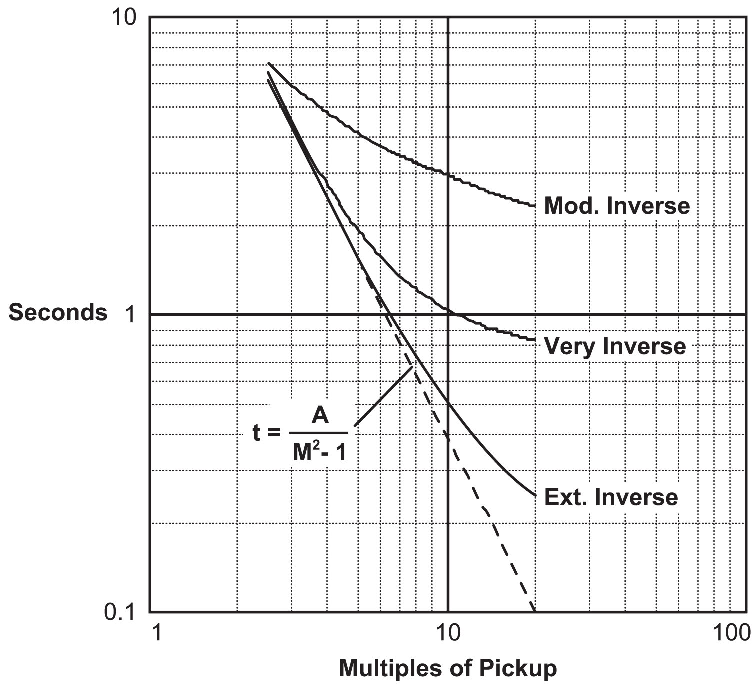

Figure A.2—Comparison of extremely, very, and moderately inverse characteristics

The normalized flux versus M multiples of pickup can be determined by setting t_r equal to the total reset time with zero current and then substituting values of operating time corresponding to various multiples of pickup current. Plots of normalized flux for an extremely inverse, a very inverse, and a moderately inverse induction-type overcurrent relay are shown in Figure A.1 and the resulting characteristics are compared in Figure A.2. The plot shows the electromechanical technique uses specific degrees of saturation to produce the familiar time-current characteristic and shows the following order. The extremely inverse relay saturates at four multiples of pickup, the very inverse at two multiples (half the previous value), and the moderately inverse at pickup (again, half the previous value).

The derivation shows that the induction characteristic, were it not for the deliberate saturation, is the straight line log-log characteristic of a fuse. However, the curve is formed by saturating the electromagnet at a specific multiple of pickup current. It has also been shown that saturation is the means that, in effect, incorporates the definite time component to form a practical curve for coordination. Therefore, adding a constant definite time term to Equation (A.9) forms the induction characteristic equation.

$$t = \frac{A}{M^2 - 1} + B \tag{A.14}$$

The constants A and B can be chosen to emulate accurately the extremely and very inverse induction time-current characteristics. An accurate emulation of the moderately inverse characteristic can be made by changing the exponent from 2 to 0.02 with specific values for A and B. Equation (A.14) is the trip characteristic equation that emulates the saturation occurring for currents above pickup. However, the reset characteristic remains Equation (A.11) since saturation does not occur at currents below the pickup current. The constants A and B and exponent p determine the curve shape of the trip characteristics. The constants for the middle curve time dial of models of induction relay characteristics are listed in Table A.1 and Table A.2. A comparison of the moderately inverse, very inverse, and extremely inverse characteristics of Table A.1 and Table A.2 are shown in the log-log plots of Figure A.3, Figure A.4, and Figure A.5. A factor of 1.4 has been used with Model B in Figure A.5 in order to give equal times at 5.0 per unit. According to the above derivation, the constant A

is equal to the reset time. However, test data for Model A and Model B show there can be a difference between the constant A in the trip characteristic and the zero current reset time t_r, as shown in Table A.1 and Table A.2.

Table A.1—Induction relay Model A

Curve type	*M*	*t* (seconds)	*A*	*B*	p[a]	t_r (seconds)
Moderately inverse	5.00	1.64	0.047	0.183	0.02	5.4
Very inverse	5.00	1.28	18.92	0.492	2.00	21
Extremely inverse	5.00	1.30	28.08	0.130	2.00	26.5

[a]Exponent $p = 2.00$ for reset.

Table A.2—Induction relay Model B

Curve type	*M*	*t* (seconds)	*A*	*B*	p[a]	t_r (seconds)
Moderately inverse	5.00	1.83	0.056	0.045	0.02	4.3
Very inverse	5.00	1.35	20.29	0.489	2.00	22.3
Extremely inverse	5.00	0.92	20.33	0.081	2.00	22.7

[a]Exponent $p = 2.00$ for reset.

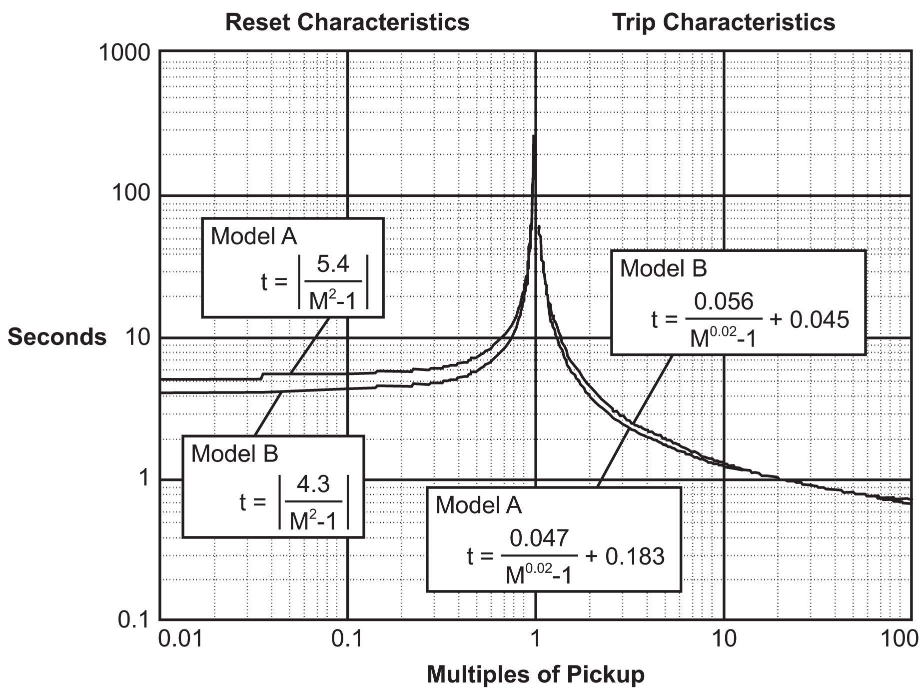

Figure A.3—Moderately inverse time-current characteristic for two models of induction type overcurrent relays

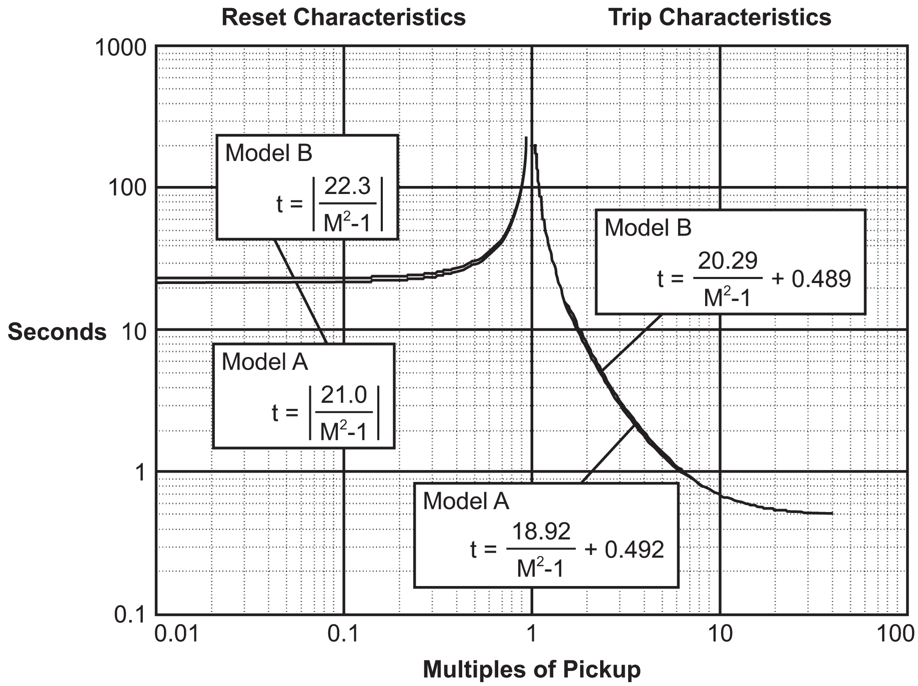

Figure A.4—Very inverse time-current characteristic for two models of induction type overcurrent relays

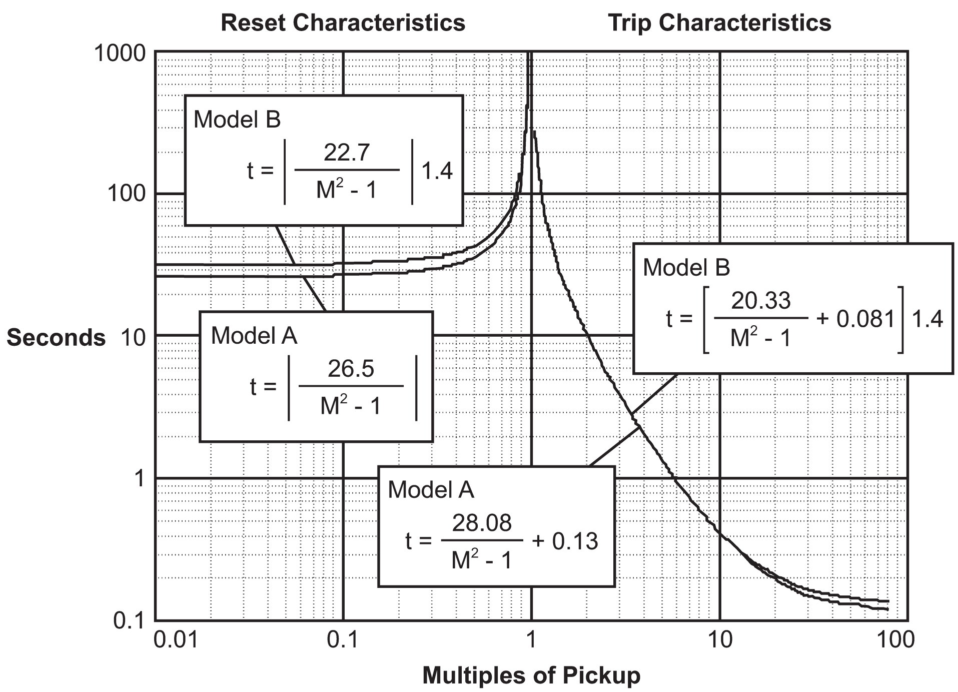

Figure A.5—Extreme inverse time-current characteristic for two models of induction type overcurrent relays

Annex B

(informative)

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