IEEE STANDARD INVERSE-TIME CHARACTERISTIC EQUATIONS FOR OVERCURRENT RELAYS

Prepared by Working Group G-7
of the Relay Standards Committee
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Abstract: This paper introduces the new standard "IEEE Standard Inverse-Time Chracteristic Equations for Overcurrent Relays". It provides an analytic representation of typical electromechanical relays operating characteristic curve shapes in order to facilitate coordination when using microprocessor-type relays.

1. INTRODUCTION

Inverse-time induction overcurrent relay characteristics have been in continuous use for over fifty years and emulated in later solid state and microprocessor based relays. They constitute the mainstay of feeder protection in North America. The induction relay is still supplied and exists in such numbers that when a relay is installed in North America it most likely must coordinate with an existing induction relay. Yet there has never been a standard defining the requirements for an overcurrent relay to be compatible both under static and dynamic perspectives with induction relays, and therefore to fulfill requirements for coordination. The present IEC 255-3 standard [1] does not serve that purpose. For this reason, the new standard C37.112-1996 "IEEE Standard Inverse-Time Characteristic Equations for Overcurrent Relays" has been defined [2]. The present paper summarizes the basic principles of the new standard and its Annex.

2. THE PHYSICS OF THE INDUCTION RELAY

Since coordination with induction relays is a primary premise of the new standard, an Annex has been included to provide the following additional information:

- A description of elements of the physics of the induction relay.
- The characteristics of the two most popular series of overcurrent relays in North America, the CO and IAC series.

The purpose of the Annex is informative, and therefore the material it contains should not be considered as part of the main body of the standard.

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The Time-Current Equation

The following equation relates the various phenomena in an induction disk rotating towards the full travel position. The operating torque, which is proportional to the square of the current is equal to the sum of the moment of inertia of the disk times its acceleration, plus the damping torque (which is proportional to the angular velocity of the disk), plus the restraining torque provided by the spring [3]:

$$K_I I^2 = m \frac{d^2\theta}{dt^2} + K_d \frac{d\theta}{dt} + \frac{\tau_F - \tau_s}{\theta_{max}} \theta + \tau_s \tag{1}$$

where:

θ is the disk travel
θmax is the disk travel to contact closure
K_I is a constant relating torque to current
m is the moment of inertia of the disk
I is the input current
K_d is the drag magnet damping factor
τ_s is the initial spring torque
τ_F is the spring torque at maximum travel

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. Therefore Eq 1 can be represented as:

$$K_I I^2 - \tau_s = K_d \frac{d\theta}{dt} \tag{2}$$

Constant K_I can be eliminated by introducing the term M which is the ratio of the input current I to the current at which the disk just starts to move (the pick up current) i.e M=I/Ipu. Integration of Eq 2 provides:

$$\theta = \int_0^{To} \frac{\tau_s}{K_d} (M^2 - 1)\, dt \tag{3}$$

where To is the time required for the disk to travel to its full rotation. Dividing both sides of Eq 3 by θ gives the dynamic equation:

$$\int_0^{To} \frac{\tau_s}{K_d\theta} (M^2 - 1)\, dt = \int_0^{To} \frac{1}{t(I)}\, dt = 1 \tag{4}$$

t(I) is the time current characteristic and the constant A equals $K_d\, \theta / \tau_s$. Ultimately, the time current equation is provided as:

$$t(I) = \frac{\left(\frac{K_d\theta}{\tau_s}\right)}{M^2 - 1} = \frac{A}{M^2 - 1} \qquad (5)$$

The Reset Characteristic

Equation 5 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 5 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 5 gives the reset time t_r:

$$|t_r| = \frac{K_d\theta}{\tau_s} \qquad (6)$$

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

$$t = \frac{t_r}{M^2 - 1} \qquad (7)$$

Modification of the Time-Current Equation

The above derivation 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 curve is formed by deliberately saturating the electromagnet at a specific multiple of pickup current to introduce a definite time component. The effect of this saturation can be accounted for by introducing in Eq 5 a constant term B. It should be borne in mind that saturation occurs for values of current above the pick-up value, therefore the new equation applies in the range of M greater than one, the equation remaining the same in the reset region:

For $0 < M < 1$

$$t(I) = TD\left(\frac{A}{M^2 - 1}\right) \qquad (8)$$

For $M > 1$

$$t(I) = TD\left(\frac{A}{M^p - 1} + B\right) \qquad (9)$$

where:

t is the trip time in seconds

M is multiples of pickup current

TD is the Time Dial setting

p is a constant exponent of M replacing the square to emulate some specific curve shapes

The dynamic equation Eq 4 and the characteristic equation Eq 9 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.

Equations 8 and 9 have been used to emulate the moderately, very, and extremely inverse characteristics of the relays belonging to the two main series used in North-America. Eq 9 is the trip characteristic equation which emulates the saturation occurring for currents above pickup. However, the reset characteristic remains Eq 8 since no saturation occurs at currents below the pickup current.

The emulation has been done in the middle of the time dial range (using a value of 5) and the constants A, B, and p have been determined following the best fit with a value of M=5. The results are shown in Table I and II.

Table I. Model A Type CO Induction Relay

	Moderately Inverse	Very Inverse	Extremely Inverse
M	5.00	5.00	5.00
t	1.64	1.28	1.30
A	0.047	18.92	28.08
B	0.183	0.492	0.130
A/B	0.26	38.46	216.00
p	0.02	2.00	2.00
t_r	5.4	21.0	26.5

Table II. Model B Type IAC Induction Relay

	Moderately Inverse	Very Inverse	Extremely Inverse
M	5.00	5.00	5.00
t	1.83	1.35	0.92
A	0.056	20.29	20.33
B	0.045	0.489	0.081
A/B	1.24	41.49	250.99
p	0.02	2.00	2.00
t_r	4.3	22.3	22.7

The extremely and the very inverse induction time-current characteristics are emulated using an exponent p of 2. An accurate emulation of the moderately inverse characteristic is obtained by using an exponent of 0.02. The constants A and B and exponent p determine the curve shape of the trip characteristic

A comparison of the very inverse characteristics of Tables I and II are shown in the log-log plots of Figure 1. Similar comparisons are made in the standard for moderately and extremely inverse characteristics.

Test data for Model B shows 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 I and II.

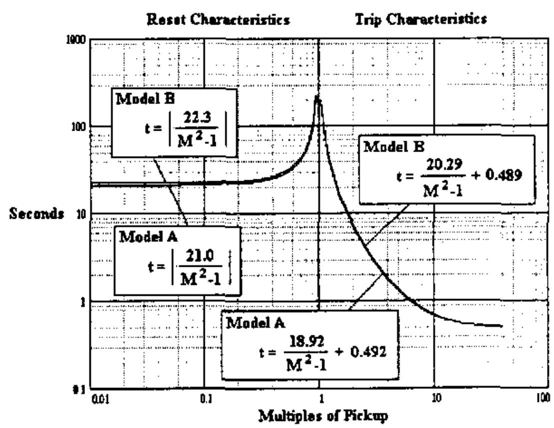

Fig. 1. Very Inverse time-current characteristics for two models of induction type relays.

3. THE MAIN BODY OF THE STANDARD

Based on the material developed in the informative Annex, the body of the standard consists mainly of the following material:

a) the scope and the purpose of the document

b) a series of four definitions

c) the mathematical definitions of the time-current equation together with the dynamics

d) the definition of time dial

e) the specific values of constants A, B, p, and tr for the three defined characteristics

Scope and purpose

The scope is to foster some standardization of available inverse-time relay characteristics provided in microprocessor relay applications.

The purpose is to provide an analytic representation of typical relay operating characteristics to facilitate representation by microprocessor-type relays.

Definitions

The above derivations define an inverse time overcurrent relay and its characteristics as follows:

An Inverse-time Overcurrent Relay is a current operated relay which produces an inverse time-current characteristic by integrating a function of current F(I) where F(I) is the reciprocal of the time-current characteristic t(I) . The function F(I) is positive above and negative below a predetermined input current called the pickup current. The relay actuates a contact when the integral reaches a predetermined positive value.

For the induction relay, it is the disk velocity that is the F(I) that is integrated to produce the inverse-time characteristic.

The time dial is the control which determines the value of the integral at which the trip contact is actuated and hence controls the time scale of the time-current characteristic produced by the relay.

Reset is the state of an inverse-time overcurrent relay when the integral of the function of current F(I) is zero. The reset characteristic is the time versus current curve representing the time required for the integral of the function of current F(I) used by the relay to produce the time-current characteristic to reach zero for values below current pickup when the integral is initially at the trip value.

The analytic equations

Two equations define the reset time and the pick-up time, and these two equations correspond to Eqs. 8 and 9.

Equation 4 emulates the dynamics of the induction disk overcurrent relay and provides the principle of how to implement digitally any characteristic [4-6].

Standard Time-Current characteristics

The constants A, B, p, and tr are defined in the standard by taking the arithmetic average of the values found when emulating the two main series of induction overcurrent relays found in North-America for the time-dial number 5 and presented in Tables I and II. The standard constants are presented in Table III.

Table III Standard Constants

Characteristic	A	B	p	t_r
Moderately Inv.	0.0515	0.1140	0.02000	4.85
Very Inverse	19.61	0.491	2.0000	21.6
Extremely Inv.	28.2	0.1217	2.0000	29.1

The characteristics of a microprocessor relay conform to the standard when they are implemented according to equation that defines the dynamics of the relay. In this equation, t(I) is provided by equations 10 and 11, and the constants A, B, tr, and p are provided by Table III. For a range of currents between 1.5 and 20 times the pick-up current, the trip time values for a particular relay must fall within a conformance band. The upper and lower limits are 1.15 and 0.85 times the characteristic defined in table III.

Fig. 2 shows the conformance band for the very inverse characteristic. This conformance band has been defined in order to insure that practically all numerical relays, existing at the time the standard was completed, were falling within its limits.

The conformance band is a template used for classifying the shape of the standard inverse-time current characteristic and is not a tolerance band for accuracy and repeatability.

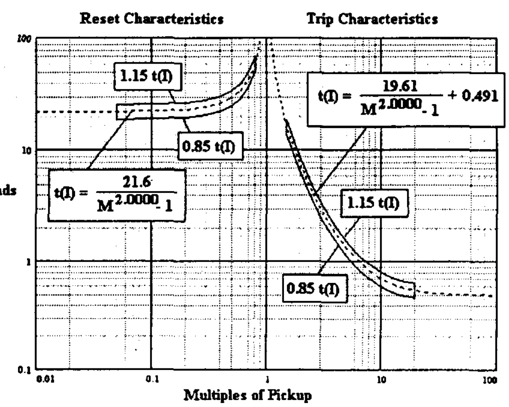

Fig. 2. Standard very-inverse time-current characteristic with standard conformance band near the middle of the time dial range

The time dial

In the standard the time dial is defined as the proportional variation of constants A, B, and tr in the characteristic equations 10 and 11. This variation allows the characteristic of the relay to be adjusted to a predetermined trip time at a specified current.

The time dial in conventional relays allows a 15 to 1 range of time adjustment. A numerical relay complying with the standard is expected to offer about the same adjustment.

When in a microprocessor relay, the ratio A to B will remain constant, but the same ratio will vary to some extent as the time dial is varied in an induction relay. A consequence of this is that the characteristic equation cannot be used for curve fitting purposes for time dials too far from 5. This, however, does not impair the coordination between relays of different technologies for time dials other than 5. As an example, Fig. 3 shows how a CO-9 relay with a time dial of 2 could be coordinated with the standard very inverse characteristic using two possible time dials above and below the induction curve.

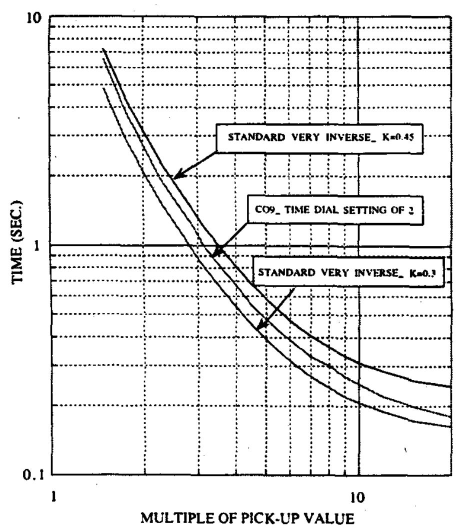

Fig. 3. Example of coordination with a CO-9 relay

Coordination of Inverse Time-Current Characteristics

Coordination practice is ultimately determined by the type of grounding used in distribution systems. 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 4 shows the close coordination of an extremely inverse induction characteristic with that of a high voltage expulsion type fuse.

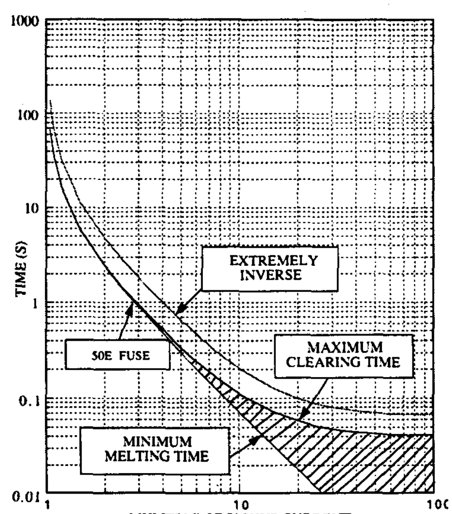

Fig. 4. Extremely inverse characteristic compared with min. melting and max. clearing time of a 50E fuse.

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. This principle justifies the curve shape obtained in an induction overcurrent relay by manipulation of the saturation point in the magnetic material.

5. CONCLUSION

The new standard has introduced a number of concepts that facilitate coordination of new numerical relays with electromechanical relays.

It should be borne in mind that, without an existing official standard at the time of their conception, practically all digital overcurrent relays fall within the prescribed conformance band of +/-15% of the standard characteristic. This is an indication that manufacturers have made an effort to coordinate with electromechanical relays. The rationale behind this endeavor has simply been embedded in this standard.

6. REFERENCES

1. IEC Publication 255-3 (1989-05), Single input energizing quantity measuring relays with dependant or independant time, Second Edition.

2. IEEE Std C37.112-1996, IEEE Standard Inverse-Time Characteristic Equations for Overcurrent Relays.

3. W. K. Sonneman and W. E. Glassburn, " Principles of Induction Type Relay Design", AIEE Winter General Meeting, New York, N. Y., January 19-23, 1953.

4. S. E. Zocholl and G. Benmouyal, "Dynamic Performance of Protective Relays", 18th Annual Western Protective Relay Conference, Spokane, WA, October 22-24, 1991.

5. G. Benmouyal, "Design of a Digital Multi-Curve Time-Overcurrent Relay," IEEE Trans. on PD, Vol. 6, pp. 656-665, April 1991.

6. H.K. Verma and T.M.S. Rao, "Inverse Time Overcurrent Relays using Linear Components," IEEE Trans. PAS-95, No. 5, September/October 1976.

Discussion

T. E. McDermott (Electrotek Concepts, Clairton, PA): The paper presents a general model of time overcurrent relays that may be used to design digital relays that will coordinate with electromechanical relays. The standard constants in Table III average the characteristics of the CO and IAC series, but the paper presents both sets of constants. We are developing software to predict power quality impacts of the overcurrent protection system, including interruptions and voltage sag magnitudes and durations. We are not concerned with setting or coordinating relays in this software, since we assume that task has been done correctly. Does the working group feel that the constants in Tables I and II are suitable for this kind of modeling? If yes, over what range of time dials?

On a distribution feeder, digital relays would also have to coordinate with older line reclosers. Does the standard address this?

In the second column on page 3, the text refers to equations 10 and 11, which do not appear in the paper. Should these be equations 8 and 9?

Gabriel Benmouyal (Schweitzer Engineering Laboratories, Boucherville, PQ, Canada):

The discusser has very correctly defined in his introduction, the main purpose of the standard which is to present "a general model of time overcurrent relays to be used to design digital relays that will coordinate with electromechanical relays." In this perspective, three main issues are being addressed in the standard: the shapes of the time-overcurrent characteristics, the relays dynamics (or how they respond to time-varying currents) and the relays reset (which could be included in a broader definition of their dynamics). These three features are defined only for the relays operation at fundamental frequency.

It is very important to note that the standard does not include any current magnitude frequency response (or how the relays would respond to any frequency component other than the fundamental frequency). Furthermore, the standard does not try to characterize the electromechanical relays performance when frequency components other than the fundamental are present in the waveforms. In that perspective, we feel that if "power quality impact" includes studies encompassing waveforms with a broader frequency spectrum, the model in the standard would not be adequate. It could be helpful, however, if these studies are limited to current variations at fundamental frequency.

It should be borne in mind that Table I and II provided in the paper are not part of the standard and are only provided in the annex A which is purely informative. Table III belongs however to the main body of the standard.

The standard does not address the issue of old reclosers if they have not been designed to be compatible with electromechanical relays characteristics (time-overcurrent shapes, dynamics and reset).

Finally, we thank the discusser for having pointed to an error in the text, equations 8 and 9 should be read instead of equations 10 and 11.