Overcurrent Protection - Old Truths and New Applications

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Abstract— This paper reviews the reasons for selection of different types of time overcurrent relays with respect to their pickup setting, time current characteristics, dynamic and directional performance for a variety of applications. It will initially review previously documented information (old truths) and then go on to discuss new applications and technologies, and their impact on time overcurrent and directional overcurrent protection.

Overcurrent Protection - Old Truths and New Applications

1. Introduction

Overcurrent protection is the workhorse of electric equipment protection. Four major performance topics are important to the application of these devices. These topics are:

- pickup setting
- shape of the time current characteristics
- dynamic performance
- techniques for providing directional control

Many of the issues affecting performance criteria are traditional and previously documented but some new applications require understanding of the old truths and special consideration of the performance criteria. This paper reviews the old truths and discusses how the new applications affect these traditional criteria. The ages of references vary from more than 60 years (old truths), to the date of this paper publication (new applications).

In this paper, the conventional definitions of protective relaying reliability features are used:

- Dependability is the probability that the protection will operate when it is required to do so.
- Security is the probability that the protection will not operate when it is not required to do so.

2. Pickup setting

2.1. Old truths

2.1.1. Cold load pickup

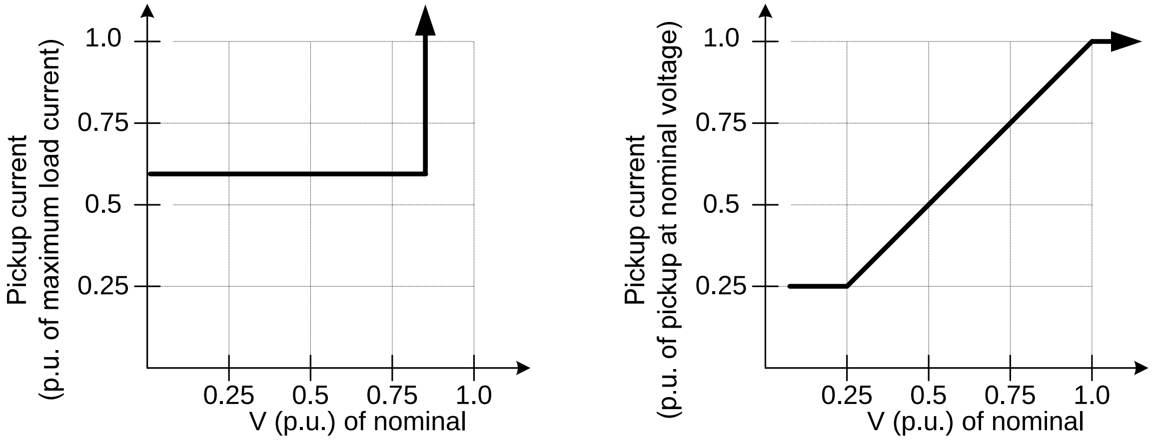
It is a fundamental criterion that the pickup setting of a time overcurrent device should be higher than maximum current of the load to be carried, and lower than the minimum fault current to be detected. It is also well known that the maximum load may include current higher than steady state for a short while after an extended outage. The temporary overload condition is known as “cold load pickup” and may take several minutes to decay to a steady state value. The phenomenon is documented in many publications, including [1 and 2]. Note that the solution to the cold load pickup problem provided in [1] is sectionalizing of the load while [2] describes more modern solutions such as the following:

- Timers to enable special logic after the breaker has been open for an extended period.
- Disabling or adjusting fast tripping curves during cold load pickup
- Alternate (less sensitive) pickup settings during cold load pickup

2.1.2. Steady state load/fault level conflicts

In addition to the temporary overload of cold load pickup, it has also been the case that there may be insufficient difference (for a secure and dependable overcurrent pickup setting) between maximum steady state load and minimum fault current levels. In this case, “load blinding” features may be added to prevent a time overcurrent function from starting during load conditions while enabling it to start during fault conditions. The load blinding functions are intended to discriminate between load and fault conditions by using additional information from voltage measurement which indicates the presence of a fault. The load blinding function will block starting of (or “torque control”) the overcurrent function unless a fault condition is declared. Load blinding from simple undervoltage sensors is commonly known as “voltage restrained” or “voltage controlled” overcurrent protection.

The voltage controlled overcurrent relay may have its pickup value set less than load current, but it will not start timing until the voltage drops to a level less than a set value (often in the range 70 to 85% of nominal). An example of the pickup versus voltage characteristic is shown in Figure 1a). The voltage restrained overcurrent relay will have its sensitivity decrease proportionally in a certain range, depending on the voltage at the relaying point. Figure 1b) shows an example of how the pickup setting may vary with voltage. It should be noted that since the pickup of this type of device is variable, it is more difficult than a fixed pickup voltage controlled overcurrent relay to coordinate with downstream simple overcurrent protection.



a) Voltage controlled pickup

b) Voltage restrained pickup

Figure 1 Example voltage controlled and restrained O/C relay pickup setting characteristics

The earliest type of load blinding was simple undervoltage detection as shown in Figure 1a) and Figure 1b). Later, additional load blinding functions were used. For instance, a distance protection function could be used to block starting of the time overcurrent unless an impedance within the characteristic was measured. This principle worked on the assumption that a fault would have a relatively low magnitude of impedance at an angle significantly greater than zero degrees as shown for the Fault region in Figure 2.

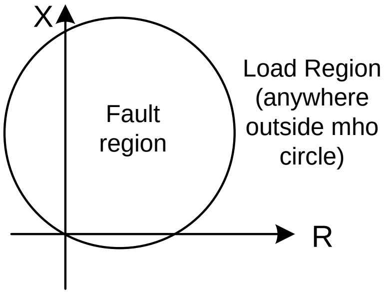


Figure 2 Mho Characteristic Fault Detector

As microprocessor relays provided more sophisticated functions, more advanced means of discriminating between load and fault conditions were developed. One popular characteristic was a “Bow Tie” characteristic as shown in Figure 3. In contrast to the Mho characteristic, the bow tie characteristic could be considered as a definition of a “load region” rather than as defining a fault region.

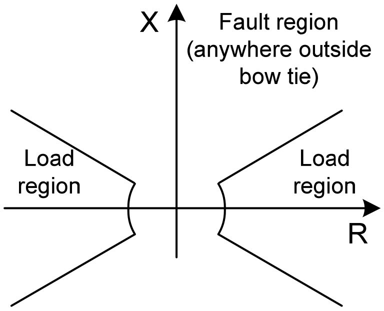


Figure 3 Bow Tie Characteristic Load Area Definition

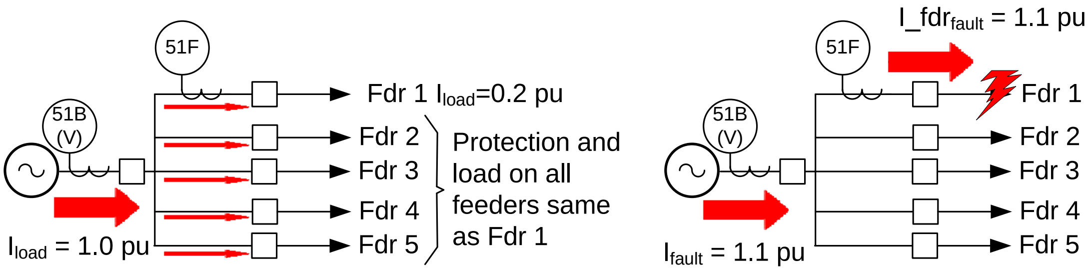
It can be seen by comparing Figure 3 with Figure 2 that the “fault region” is relatively much larger in the Bow Tie characteristic than in the Mho characteristic. The increase in the region classified as “fault region” means that in some applications the Bow Tie characteristic may be less secure that the Mho characteristic. This will be discussed further in Section 2.2.2 of this paper.

2.2. New Applications

2.2.1. More weak sources

Power electronic sources (also known as inverter interfaced sources) do not have the same fault current contributions as conventional rotating machine sources. These sources have controlled current outputs, and their fault current contributions are limited to little more than full load current. Typically power electronic sources are limited to a maximum of less than 1.5 per unit of rated load current, and often to as little as 1.1 per unit. For the main protection of a power electronic source, if overcurrent protection is required, it will need to include load blinding functionality as described in Section 2.1.2 of this paper. It should be noted however, that if the power electronic source feeds a distribution system with multiple feeders, conventional feeder overcurrent protection may still be applicable if the total load is divided into sufficiently small parts on each feeder.

Consider for example the system shown in Figure 4a). It can be seen that each feeder load is a maximum of 1/5th of the total rating of the source. If the controls of the source are set to limit the fault current to 1.1 per unit of rated source current, then as can be seen in Figure 4b), the current available to a fault on any feeder is 5.5 times the rated feeder load current. This is ample current to allow a secure and dependable pickup setting of a simple overcurrent relay of (say) 1.5 per unit of rated feeder load current.



a) Prefault conditions b) Fault conditions

Figure 4 Prefault and Fault Currents from Power Electronics Source

Note that in Figure 4, the bus overcurrent device needs to have some sort of load blinding function applied (shown as voltage controlled, (V)) since this device is subject to the full load current of the source. However, the feeder overcurrent device need not have any load blinding function applied since the fault current is more than five times the rated feeder load. Any overcurrent protection (or fuse) downstream of the feeder breaker would also have more than enough fault current available for dependable operation.

2.2.2. Modified Bow Tie Characteristic

The characteristic shown in Figure 3 has allowed undesirable tripping of a distribution bus phase overcurrent device under a certain case of a large capacitive power factor. This operation brought to light the difference in operating area between the load discrimination characteristics shown in Figure 2 and Figure 3. It was realized that the main concern for dependability in the case of a radially fed distribution bus was to allow operation of the overcurrent function when the apparent impedance presented to the protection was within a fault region in the first quadrant. Therefore to increase the security of the bus overcurrent protection, the bow tie characteristic was modified to increase the area in which blocking would occur to make it more secure. The characteristic of the modified load area definition is shown in Figure 5. This modified characteristic resembles a keyhole more than a bow tie, and provides a similar level of security as the fault detector characteristic of Figure 2.

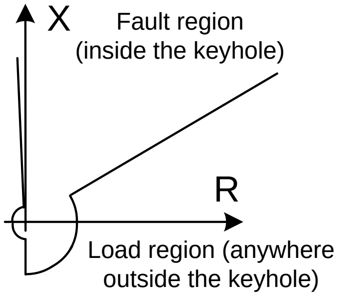


Figure 5 Modified Bow Tie Characteristic

3. Shape of the Time Current Characteristics

3.1. Old truths

3.1.1. Difference Between ANSI/IEEE and IEC Time Current Characteristics

The time current characteristics (TCC) of various overcurrent relays are defined in the IEEE standard C37.112 for time overcurrent relays [3]. This standard provides the general formula for the operating time where the multiple of pickup current is greater than 1.

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

Where *t(I)* is the time to operate and is a function of the current,

A, *B* and *p* are constants that define the shape of the TCC

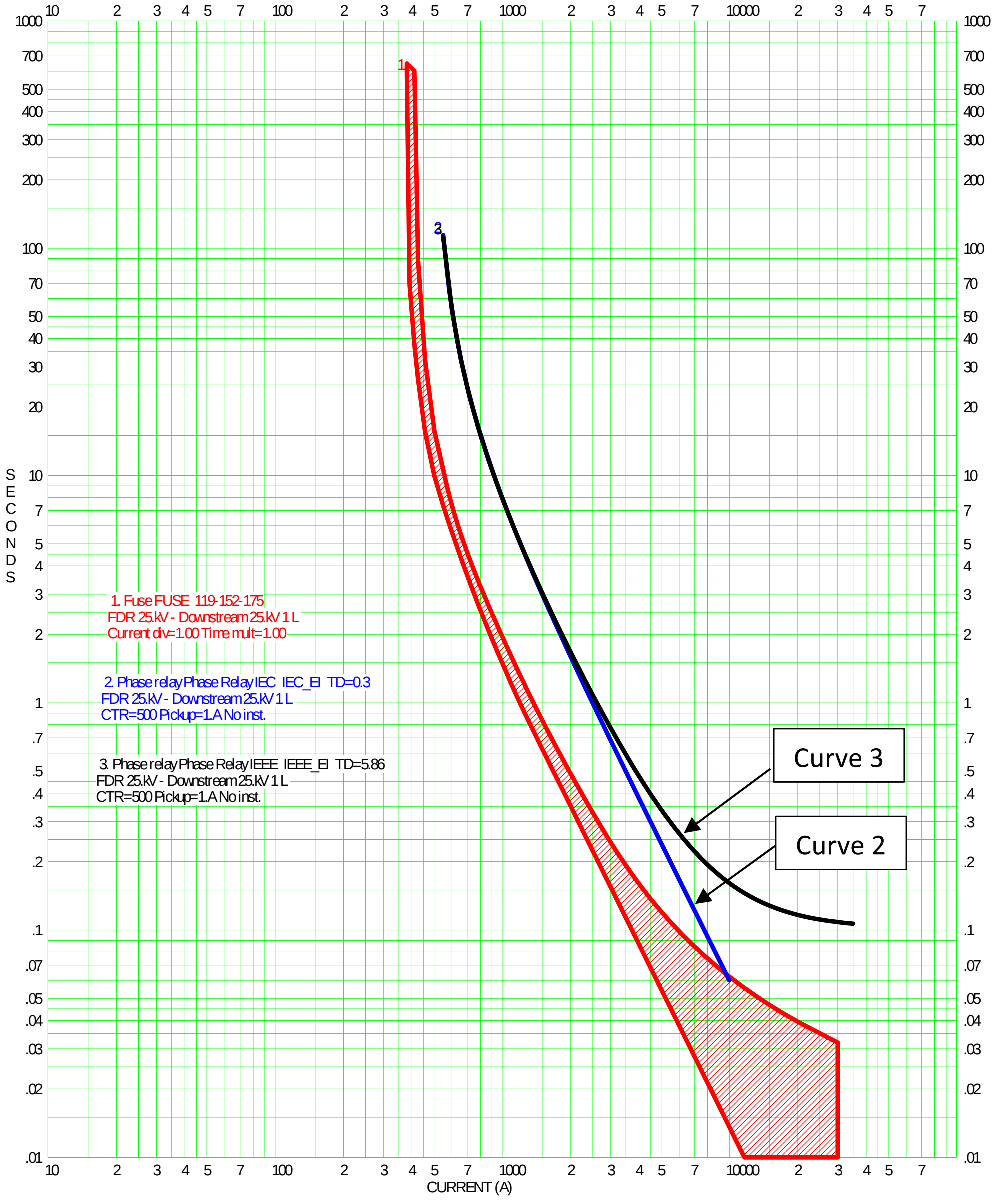
M is multiples of pickup current.

The standard identifies the constants for operate times of various TCC (near the middle time dial setting) as follows:

Table 1 Standard Characteristic Curve Constants

Characteristic	A	B	P
Moderately inverse	0.0515	0.1140	0.0200
Very Inverse	19.61	0.491	2.000
Extremely inverse	28.2	0.1217	2.000

The standard also notes that the equation for the TCC is similar to the equation for TCC defined by the relevant International Electrotechnical Commission (IEC) standard for time overcurrent relays, except that the IEC equation does not use the constant B. The constant "B" adds a small definite time to the total operating time, and represents saturation of the magnetic path in an electromechanical overcurrent relay. As noted in reference [5], the additional definite time provides significant advantage with respect to the ability of the extremely inverse relay TCC to coordinate above a fuse TCC. It can be seen from Figure 6 that the IEEE extremely inverse TCC (curve 3) matches the fuse TCC (curve 1) more closely than the IEC TCC (curve 2), especially at high currents.



EI Coordination with Fuse TCC @Voltage 25kV	By CFH
For IEEE EI TCC comparison with IEC EI TCC	No. 1
Comment	Date 12 June 2018

Figure 6 Comparison of IEEE and IEC and Fuse TCC

3.1.1. Use of Varying Degree of Inverse TCC

The intention of an inverse time current characteristic is that for larger, more damaging fault currents, the relay should operate more quickly to limit the fault damage to the protected equipment. A variety of degrees of inversness may be used to optimize protection for any specific application. The two limits of degree of inverseness of a TCC are extremely inverse and definite time, as shown in Figure 7. As can be seen from Figure 7, the definite time TCC provides faster clearing at lower currents, and may still coordinate with a fuse if the fuse is significantly more sensitive than the definite time element. Note that the term "definite time" used in Figure 7 is the strict definition of "definite time".

In some other uses of the term “definite time”, the TCC may have a degree of curvature at the transition between pickup and operating time. The more inverse the TCC, the faster it can operate for higher fault currents.

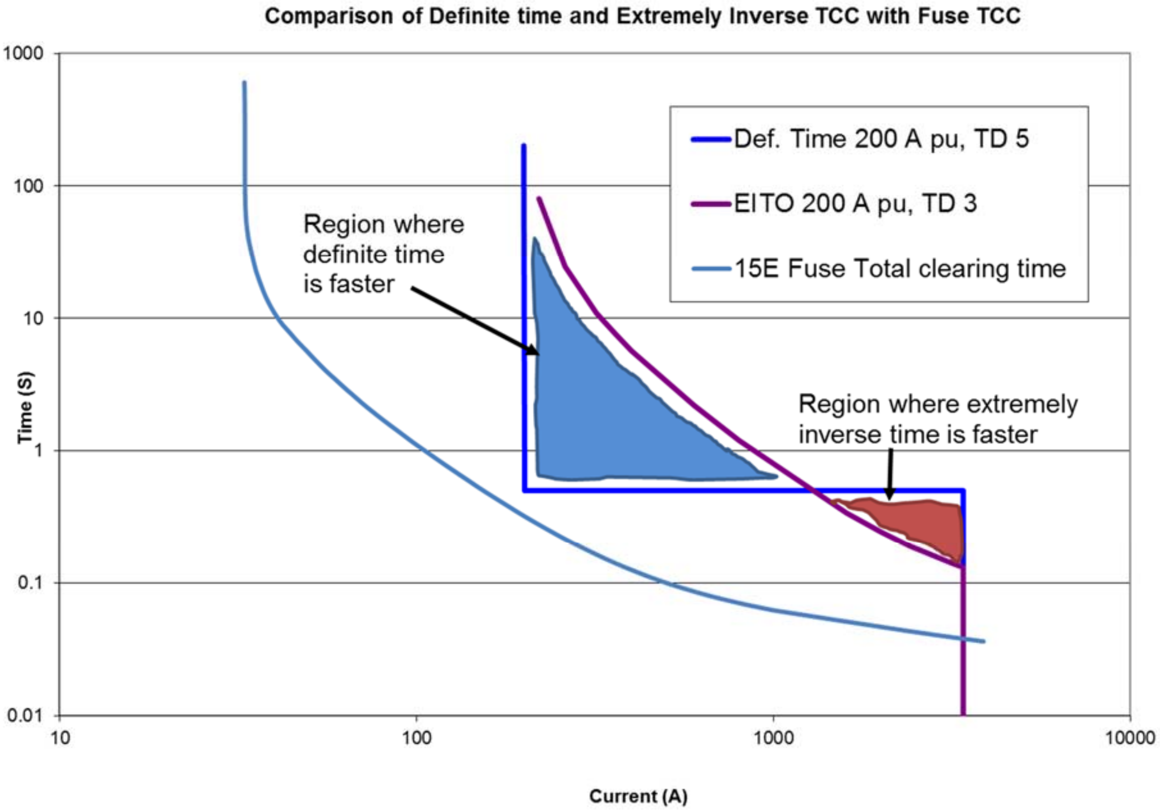


Figure 7 Comparison of Extremely Inverse and Definite Time TCC with Fuse TCC

As was pointed out in [1], the less inverse curve may provide optimum performance if the range of magnitudes of currents for faults in the protected zone is relatively small. For instance, the lesser inverse TCC may be preferred on short lines, where the difference between the magnitude of a close-in fault and a remote fault is small.

In cases where the ground fault current is limited by a neutral grounding impedance, the magnitude of the ground fault current will be limited to a fairly constant value determined by the neutral grounding impedance even if the line is not short. Therefore, definite time ground overcurrent TCC may offer the advantage of faster clearing of most ground faults than more inverse TCC. Of course attention will also need to be paid to the possible requirement to coordinate with downstream inverse time TCC devices such as fuses.

3.2. New Applications

3.2.1. Power Electronic Sources

As noted in Section 2.2.1, power electronic sources will only deliver a maximum amount of short circuit current up to little more than load current. While Section 2.2.1 focused on the pickup setting of the overcurrent protection, the shape of the TCC should also be considered. The current limiting nature of power electronic sources means that the magnitude of short circuit current delivered by it will be more or less independent of the distance of the fault from the source. Therefore, all lines connected to such sources may be considered “short”, regardless of their physical length. As long as the possible need for coordination with downstream devices is kept in mind, less inverse, or definite time TCC may be preferred for lines supplied by power electronic sources.

The application of less inverse TCC to equipment supplied from power electronic sources applies in many cases, whether or not load blinding features as described in Section 2.1.2 are required.

3.2.2.Hybrid TCC

Although not a particularly new application, the benefits of hybrid TCC have been pointed out in reference [6]. It was shown that in cases where coordination had to be maintained in looped systems, that the use of combined definite time and inverse time characteristics could result in improved performance of time overcurrent protection. For instance, in the looped 60 kV transmission system shown in Figure 8 multiple ground overcurrent TCCs needed to be stacked one upon the other, and this stacking resulted in high time dial settings.

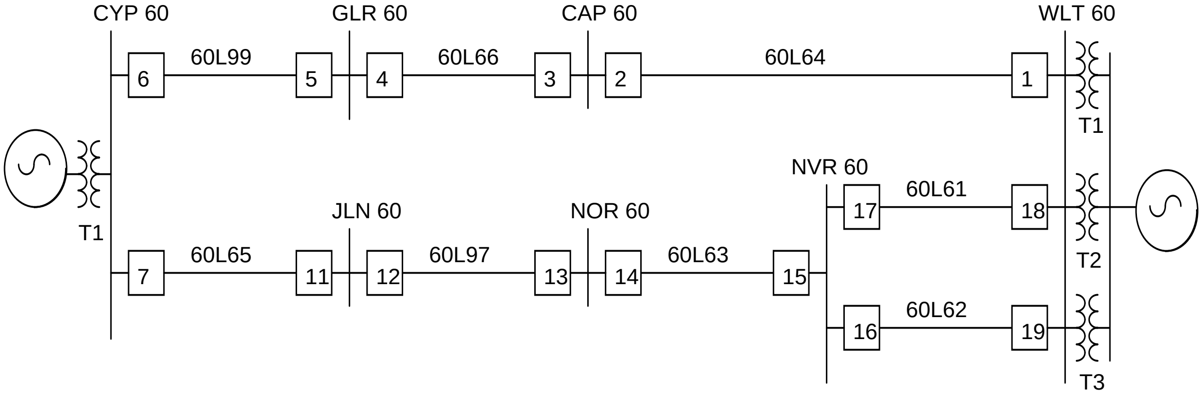


Figure 8 - Looped 60 kV transmission network (from [6])

Reference [6] showed how the use of hybrid definite and inverse time TCCs could provide improved speed and sensitivity for the protection on Breaker 18 as an example. Figure 9 shows a comparison of the hybrid and conventional TCCs that could be achieved. This figure illustrates the performance improvement. Reference [6] also discussed the importance of dynamic performance of TCCs and identified a concern with the use of independent definite and inverse time TCCs to achieve performance improvement. Dynamic performance issues will be discussed in Section 4 of this paper.

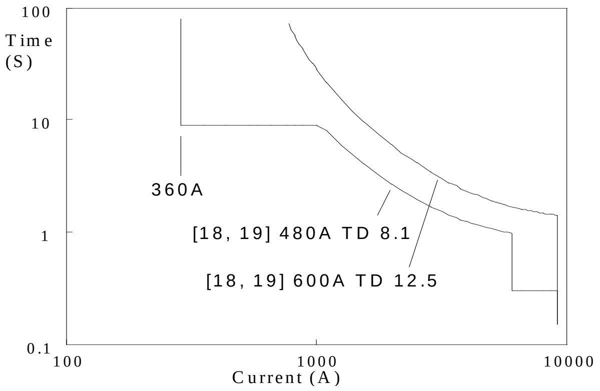


Figure 9 Comparison of Hybrid and Conventional TCC (from [6])

4. Dynamic performance of the time overcurrent function.

4.1. Old truths

Time overcurrent relays may be required to fault currents that do not remain constant while the relay is responding to the fault. This is easily understood by noting that during a short circuit on a transmission line supplied from sources at both terminals, typically, one terminal will open before the other. If the remote terminal opens first, it is quite possible that the current through the local (still closed) terminal will increase. In an electromechanical implementation, if the current increases while the disk is turning, the speed of rotation of the disk will increase. However, the increase in speed during the fault will result in an operating time that is a combination of two rotation speeds during the fault. In a digital implementation of an overcurrent relay, a simple lookup table will not emulate the dynamic performance of an electromechanical relay with a rotating disk.

Reference [7] was an early documentation of the need for integration of a series of operating times with small steps of time for digital implementation of a time overcurrent relay to emulate the dynamic performance of a rotating disk. Figure 10 Shows one type of injected alternating current signal (amplitude modulated ac) that was described in reference [7] to test the dynamic performance of a digital implementation.

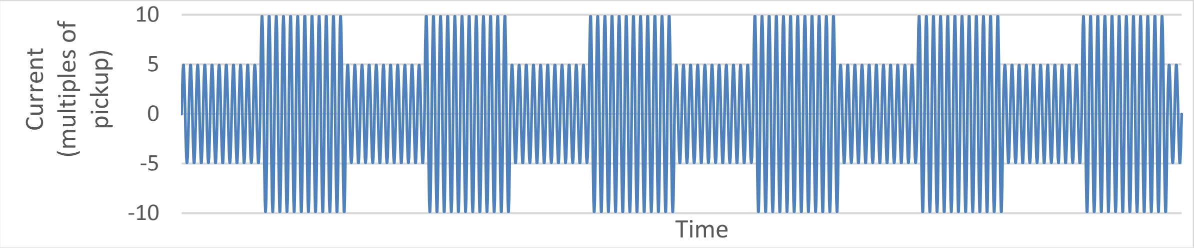


Figure 10 Example Test Signal for Dynamic Response

At first glance it might not be clear as to why such an unrealistic time varying signal would be used to test an overcurrent relay. However, when it is realized that the intent is to compare the dynamic response between two different implementations of a time overcurrent function, it is apparent that only the time varying nature of the amplitude of the test signal is important. Reference [7] shows that the total operating time *T0* for an overcurrent relay with a test signal as shown in shown in Figure 10 is given by:

$$T0 = \frac{2*T1*T2}{T1+T2} \qquad (2)$$

Where *T1* is the operating time of the relay for a steady state current of larger magnitude

And *T2* is the operating time for a steady state current of smaller magnitude.

Realistically, the amplitude of the measured current might change only once or twice during a fault, but if the response to the multiple variations of test signal amplitude is the same in digital implementation as in electromechanical implementation, the validity of the digital implementation will be proven.

4.2. New Applications

A relatively new application of the principle of dynamic response is the development of hybrid definite time and inverse time characteristics as discussed in Section 3.2.2 and reference [6] of this paper. The dynamic response of an induction disk time overcurrent relay is defined by continuously integrating the distance traveled by the disk until a threshold value is reached that indicates the relay disk has traveled to its fully rotated position. The dynamic performance of an induction disk moving towards the trip condition is defined by Equation (3) of Reference [3] as follows:

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

Where *T0* is the total operating time and *t(I)* is the fraction of the total operating time of a disk at a specified current over a small sample of time. Note that the definition of *t(I)* is not necessarily a standard inverse TCC as shown in Equation (1) of this paper, but may be any curve shape that the designer of the characteristic wishes to use, even a hybrid characteristic such as the lower curve of

Figure 9.

To date, a dynamic implementation of the hybrid TCC is not widely available. However, some relay manufacturers do offer user configurable curves (references [8] and [9]) that may provide the opportunity for hybrid characteristics with acceptable dynamic performance.

5. Directional Overcurrent Functions

5.1. Old truths

Most directional overcurrent relays are based on traditional power systems that include resistive and reactive components with behaviour following physical laws. Figure 11 shows the three sequence networks (positive negative and zero) commonly used for short circuit analysis. Consider for example, a directional relay that may be placed somewhere in a network looking towards the terminals of the sequence network measuring V and I. The relay may be placed in a location where it measures the voltage at locations shown in Figure 11 where Zns (n=1, 2, or 0) is considered to be the source impedance and Znf (n=1, 2, or 0) is the impedance between the relay location and the fault location. Note that if rotating machine impedances are not a significant part of Zns, then Z1s is usually very close to, or equal to Z2s.

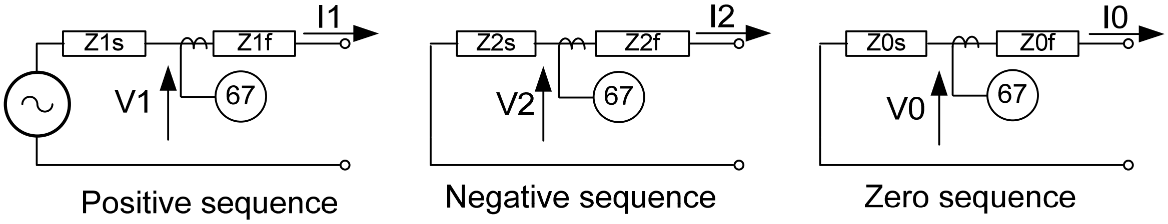


Figure 11 Conventional Sequence Impedance Networks

Phase directional relays will measure relationships of phase currents (I) and voltages (V) that are the sum of the three sequence components. Positive, negative and zero sequence relays also may be used, and measure only the relationship of the currents and voltages of the sequence component quantities.

Various techniques are employed to determine the direction of the fault, but they all depend on measurement of the appropriate currents and voltages. In a traditional power system, all impedances are a combination of resistive and reactive impedances. Except for neutral grounding resistances the angles of all impedances are mostly inductive and approximately similar (i.e., the network is fairly homogenous). The required angular relationships of the currents and voltages for relay operation are well defined by the power system networks and are explained in the instruction manuals of the various directional relays. For instance, a directional overcurrent may simply measure the angle between the measured voltage and current to make a decision about the direction of the fault. The validity of this principle can be seen in the negative and zero sequence networks as shown in Figure 11. These sequence networks have no voltage sources; so if Zns is known, the angular relationship between current and voltage for a forward fault is defined. For a reverse fault, the impedance to the remote source will determine the angular relationship between current and voltage. In cases where Zns or the impedance to the remote source is indeterminate, it is usually the case that the angles of forward and remote impedances will be nearly the same as each other and the angular relationship between current and voltage can be approximated.

Directional overcurrent relays have been used successfully on traditional power systems for many decades.

5.2. New Applications

The widespread application of power electronic sources in in recent years has revealed some problems with the performance of directional overcurrent relays that are designed to be applied in traditional power systems. The problem is caused by the fact that the source impedances are no longer necessarily conventional impedances made up of resistive and reactive components.

The positive and negative sequence source impedances may be particularly problematic because they are not actually impedances. The sources are current sources with controlled magnitude and phase angle. In the zero sequence the power electronic source is usually isolated from the directional relay by an interface transformer that is open in the zero sequence. Recent references [11], [12] and [13] discuss concerns with the application of negative sequence directional protection. The performance of power electronic sources with respect to negative sequence currents in the presence of unbalanced short circuits may be uncertain in many cases. Until the performance of power electronic sources in the negative sequence is well defined, it may be preferable (where possible) to avoid the use of that type of directional element in applications where the fault current contribution from these sources is significant.

In the positive sequence, fault current contribution from power electronic sources is generally better defined than in the case of negative sequence. The contribution is also controlled by power electronics, but is better defined by grid codes. The positive sequence current contribution to a fault is generally a constant current source that lags the voltage such that it tends to support the voltage at the terminals of the source. This means that the angle of the positive sequence current supplied from an electronic power converter source is similar to that supplied from a conventional generator.

In the zero sequence, the power electronic sources are often open circuited. The uncertain output in the zero sequence does not matter as it is isolated from the power system. If (as is often the case) the source interconnected to the power system by a transformer which includes a path for zero sequence currents on the power system side, the use of zero sequence directional overcurrent relays may offer superior performance compared to negative sequence directional overcurrent.

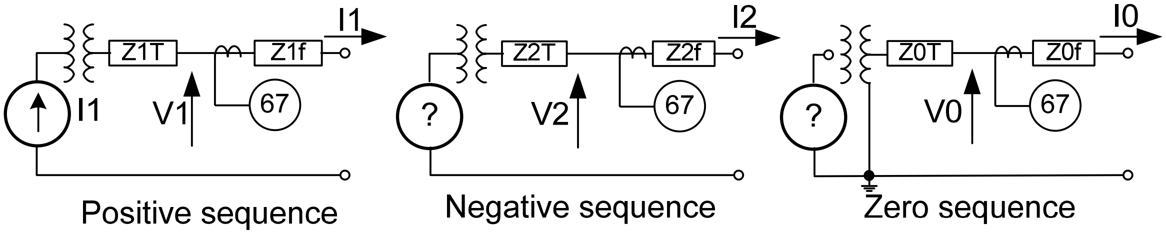


Figure 12 Sequence Networks for Power Electronic Sources and Interconnecting Transformers

Figure 12 shows the three sequence networks for a power electronic source connected to a power system through an interconnecting transformer with an impedance of ZnT (n=1, 2, or 0). It can be seen that the zero sequence network includes only traditional impedances as far as the external power system is concerned.

6. Conclusion

The old truths are not invalidated by new applications. However, an understanding of their strengths and limitations in new applications may result in improved security and dependability. The main issues discussed (with respect to new applications) in this paper are:

a) Impact of advanced load blinding characteristics and power electronic converter sources on pickup settings of time overcurrent devices.

b) Application of less inverse phase TCC on systems supplied by power electronic converter sources and less inverse ground TCC on systems supplied by sources with neutral grounding impedances.
c) Use of modern overcurrent relays with user configurable TCC to provide correct dynamic performance of hybrid inverse time and definite time characteristics. These hybrid characteristics can provide improved performance in some challenging applications.
d) The uncertainty of negative sequence current contributed to faults from power electronic sources may favor use of zero sequence directional overcurrent protection (over negative sequence directional protection) in applications where transformers with zero sequence paths are available for use by ground overcurrent protection.

7. Acknowlegements

The author is grateful to Gabriel Benmouyal and Mukesh Nagpal for their careful review and thoughtful comments on the draft of this paper.

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