Voltage Restrained Time Overcurrent Relay Principles, Coordination, and Dynamic Testing Considerations

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INTRODUCTION

The coordination of voltage restrained time overcurrent relays is usually based on static characteristics in which the time-current plots assume constant current. This assumption greatly simplifies the coordination process but fails to account for the slow-down effect due to the decrement in generator fault currents. This paper addresses the dynamic response of 51/27R relays in which the overcurrent element conforms to the dynamic characteristic defined in the ANSI C37.112 standard. The purpose of this analysis is to compare the results obtained from a proposed approximation to the exact timing results derived from a relay model and actual test.

1 VOLTAGE ACTUATED OVERCURRENTS

Voltage restrained (51/27R) or controlled (51/27C) time overcurrent relays are applied in situations where simple time overcurrent relays cannot be properly set to provide adequate backup protection. The 51/27C is controlled by voltage, which allows the current pickup to be set below load. In the voltage restraint model (51/27R), the subject of this analysis, the current pickup is proportional to the applied voltage over a specified range. As a result, the current pickup must be set above load. The response time of the relay is easily determined from the characteristic when the current and voltage are steady. Variable current and voltage present a challenge and have, therefore, inspired users to rely on approximations when performing coordination studies.

1.1 Steady State Current Timing

The pickup characteristic of the 51/27R relay decreases proportionally to the applied voltage, from the set value, down to a minimum of 25% of this value. This is illustrated in the familiar graph shown in Figure 1. This means that for a given current, the multiple of tap increases (and, therefore, the operate time is lowered) as the voltage is lowered.

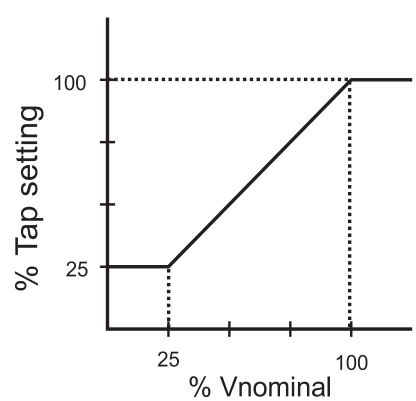

Figure 1: 51/27R Characteristic

This constant current and voltage are typical of distribution circuits where the 51/27R relay is occasionally applied to help the Protection Engineer segregate heavy loads from distant faults.

For the purpose of simplification, 51/27R will be synonymous with "51V" throughout the remainder of this discussion.

1.2 Variable Current Timing

In power systems, V & I do not vary independently. The multiple of tap may be predictably affected by the system parameters.

1.2.1 Generator Short Circuit Current

A three-phase fault near a generator is known to follow a decrement curve (decrease in current over time) as illustrated in Figure 2.

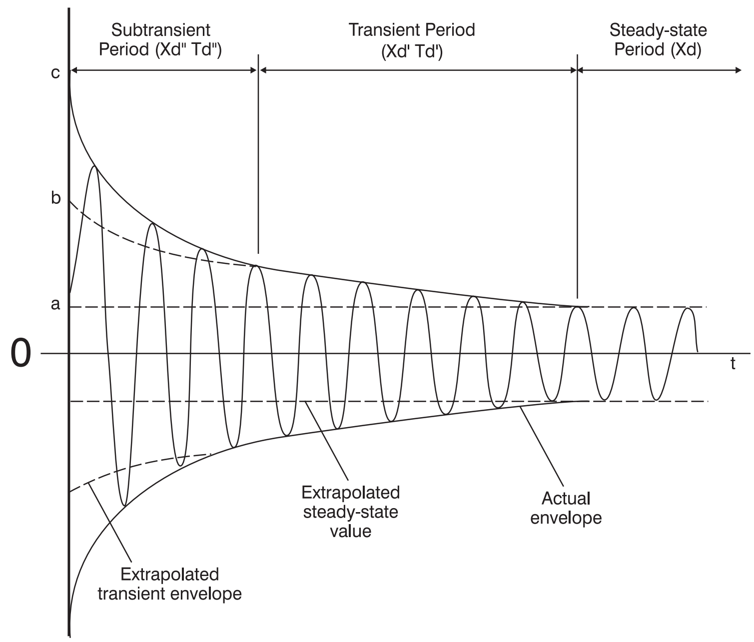

Figure 2: Generator Short Circuit Current

The decrement curve is determined by the generator impedances (Xd", Xd', Xd), time constants (Td", Td'), and the external impedance Xe (Figure 3).

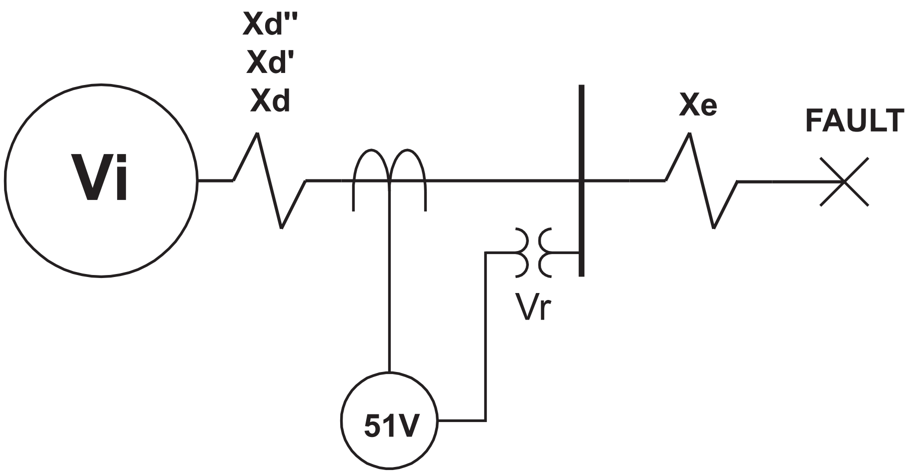

Figure 3: Typical 51V Application

The total admittance seen by the internal voltage Vi varies with time according the following equation.

$$y(t) = \left(\frac{1}{Xd''+Xe} - \frac{1}{Xd'+Xe}\right)\cdot e^{-\frac{t}{Td''}} + \left(\frac{1}{Xd'+Xe} - \frac{1}{Xd+Xe}\right)\cdot e^{-\frac{t}{Td'}} + \left(\frac{1}{Xd+Xe}\right) \quad \text{Equation 1}$$

Where
y(t) = admittance variations over time
t = time

The voltage Vr at the generator terminals is determined by the total current flowing into the fault impedance Xe. This voltage is also varying with time.

1.2.2 51V Pickup Analysis with Variable Current

Since the operate time of the 51V relay is determined by the effective multiple of tap, and the current and voltage are decaying simultaneously in the case of the generator 3-phase fault, it is interesting to analyze the effective multiple of tap resulting from the simultaneous and related variation of the current and voltage. The simulation also takes into account the effect of field forcing. The effect of the field forcing is negligible in the subtransient and transient phase of the fault, but is significant in the steady state phase.

Figure 4 shows the plot of I, V and the multiple of tap(t) over time, for the following parameter values:

Xd”=.18   Xd’=.25   Xd=1.5 Xe=.15   Td”=.05 Td’=1.5 Tdo’=4 Field Forcing Factor=1.3

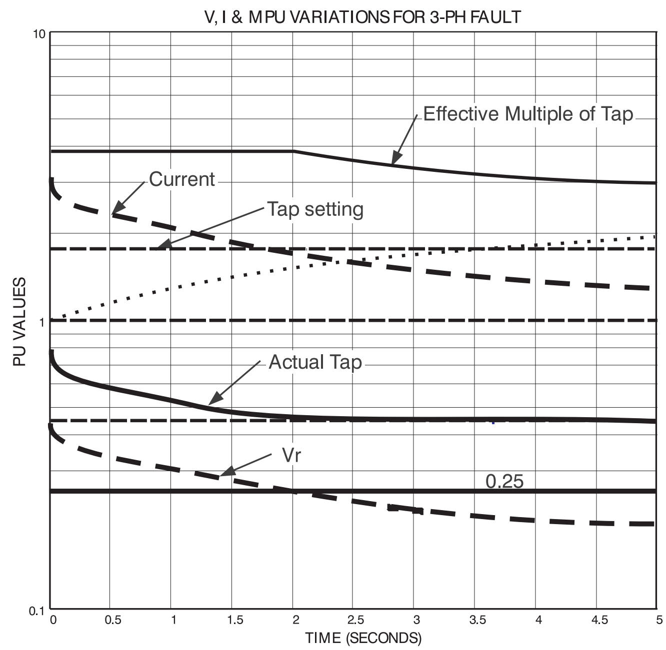

Figure 4: Actual Multiple of 51V Tap for 3-phase Fault with Field Forcing

It may be observed that while the voltage is greater than the lower limit of 0.25 pu, the effective multiple is constant. After the voltage falls below the 25% level, the tap remains constant (Tap/4), and the effective multiple decays with the current. During this period the relay “travel register“ increments fastest. This observation is valid only when the external impedance, Xe, is significant compared to the generator transient reactance.

2 OVERCURRENT RELAY TIME RESPONSE

2.1 Integration Basics

Numerical relays are expected to conform to the dynamic response defined in IEEE C37.112. This dynamic performance requirement consists of the integration of current to essentially replicate the behavior of electromechanical relays. It may be of interest, therefore, to consider the concept of integration in light of the familiar terms of disk-based relays.

2.1.1 Travel with steady current

Consider a simple overcurrent relay, shown in Figure 5, with a given Tap, time dial D setting and a curve such that the operating time is directly proportional to the applied current. The operating characteristic can be displayed in a time-distance diagram (Fig. 6).

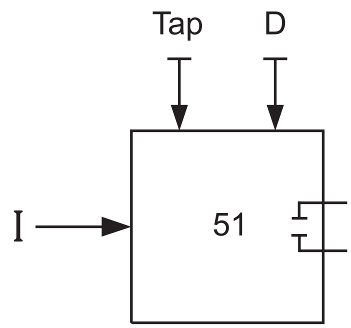

Figure 5: Simple Overcurrent Relay

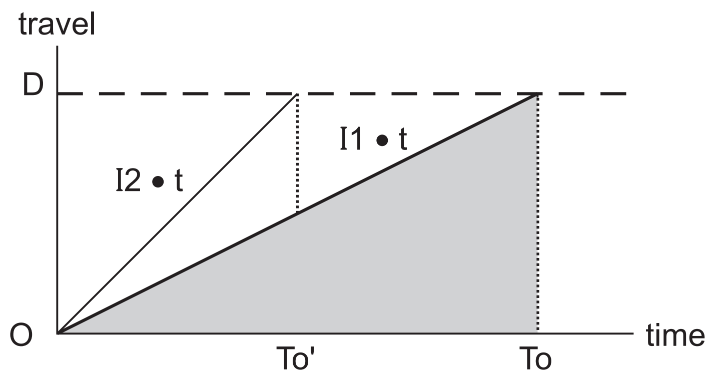

Figure 6: Time/Travel Characteristic of Simple Overcurrent

The following equations define the relay operation.
At t=0, the Trip Register (disk in an electromechanical relay) or distance is zero. When a current greater than the Tap setting is applied, the register increases with increasing time toward the time dial setting, which, by design, triggers the closure of a trip output contact. The trip condition is thus represented by the following equation, where To is the trip time:

$$\frac{I}{Tap} \bullet To = D \qquad \text{Equation 2}$$

This equation can be normalized , recognizing that I/Tap=M, multiple of tap:

$$\frac{To}{\frac{D}{M}} = 1 \qquad \text{Equation 3}$$

And by letting D/(I/Tap) = t(I)

$$\frac{To}{t(I)} = 1 \qquad \text{Equation 4}$$

In this case, t(I) is a simple function of the applied current and the time dial setting. Knowing the current and the time dial is sufficient to determine the trip time.

2.1.2 Travel with variable current

When the current is variable, the rate of travel changes with the current. In order to determine the accurate trip time, the relay must integrate the multiple current segments until the trip register reaches the trip value. This is illustrated in Figure 7. The trip equation now becomes:

$$\int_0^{T0} \frac{dt}{t(I)} = 1 \qquad \text{Equation 5}$$

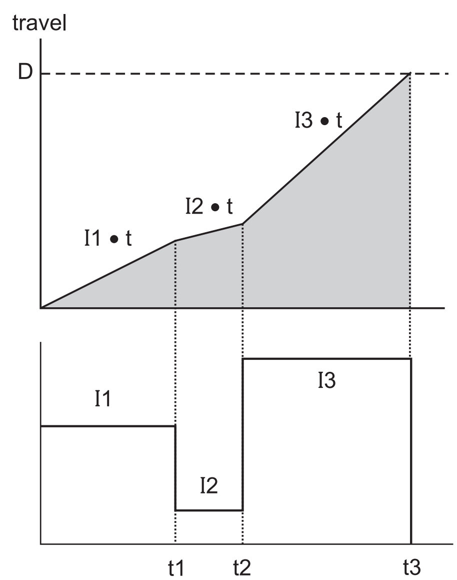

Figure 7: Effect of Varying the Fault Current on Travel Rate

2.2 51V Response to Variable Current

The previous examples showed the effect of varying the input current in discrete, constant current steps. A continuously variable current such as a generator decrement fault current is approximated by the integrating relay as a succession of small steps where the current is equal to the last calculated RMS value. This measurement process will be described in detail later in this paper.

3 TOC SIMULATION

In order to obtain the trip time of an integrating overcurrent relay to a continuously varying input current, the surest way is to apply the current to the relay and record the actual operate time. While this technology is widely available in most computer aided test sets, access or the time to prepare the test files may not be. In this section we examine simulation techniques that will yield approximate results close enough to the tested values in most applications.

3.1 Simplified method

In applications where the 51V is the upstream device needing to coordinate with a 67 device, the coordination method must assure that the 51V always operates slower than the 67 relay. A simple way to achieve this result is to assume that the current remains constant and equal to the larger initial value. If the 51V coordinates with the 67 under this assumption, the decaying fault current can only improve the coordination, since the effective multiple of tap is decreasing over time. It has been found that good practical results are obtained by using the transient current value and by further assuming that the voltage will be less than 25% of nominal at this value. These combined assumptions provide the maximum and worst case multiple of tap. In other words, the 51V will actually operate slower than the times obtained from this method. This paper explores whether the trip times are slowed excessively by using this method.

An example, shown in Figure 8, illustrates a 67 and 51V relay with settings shown on the plot. This coordination plot suggests that a miscoordination occurs at low fault currents. This appears to be the case, but test results reveal otherwise. Remember that the 51V coordination, based on the fixed transient current, will appear faster than the actual. This cross-over further begs to question if the 51V relay will operate at all for low fault currents.

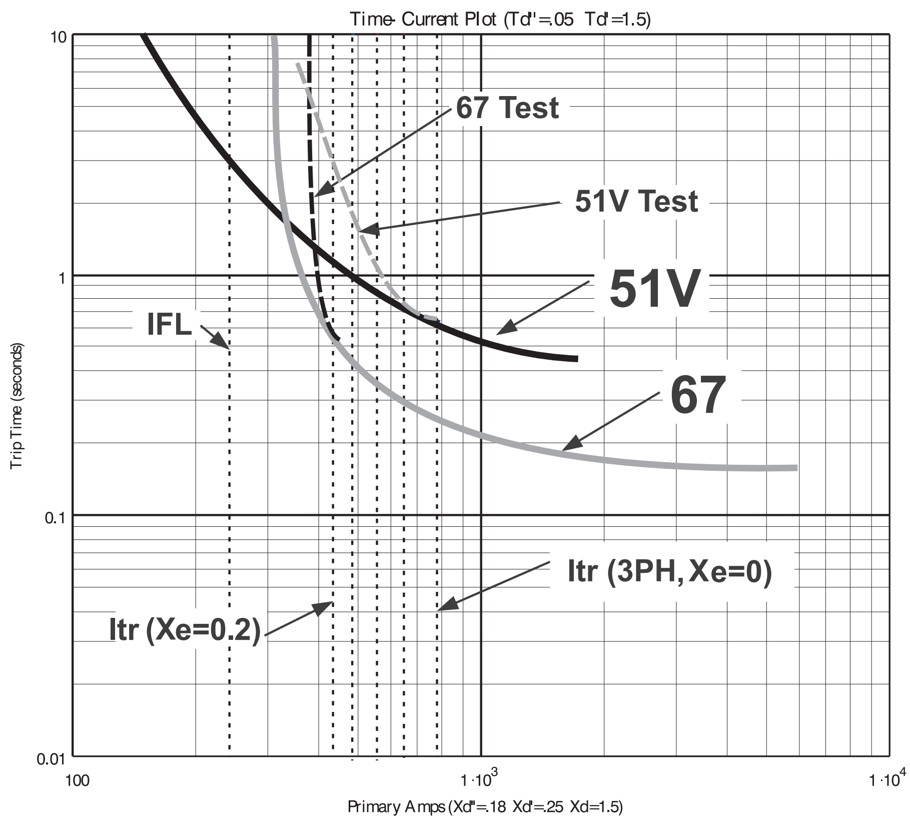

Figure 8: A Typical 51V Coordination Plot Using the Simplified Method

3.2 Integration time calculation

In a numeric relay, integration of the current is performed by sampling the applied signal and periodically updating the travel register. Referring to the flow chart in Figure 9, we can examine a typical integration method.

Initially, the travel register is set at zero. The current waveform is sampled periodically to monitor the applied current. Each time a ¼ cycle's worth of new data is accumulated, a one cycle Discrete Fourier Transform, or DFT, is performed using the new data and the previous ¾ cycle's data. From the DFT, the magnitude of the applied current is determined.

The current magnitude is compared to the pickup setting for the 51V function. If the current is over the pickup setting, a multiple of pickup, or MOP, is determined. The MOP is applied to the timing equation along with the curve constants and the update time interval to determine an incremental change. Larger MOPs result in greater incremental changes and, therefore, faster trips.

The incremental change is normalized to 1 or 100% and represents the percentage of travel occurred in one time interval. Since the time interval is a ¼ cycle in our example, the rate of travel is updated each ¼ cycle. Each ¼ cycle, the incremental change is added to the previous travel register value to obtain a new value of travel.

This process is continued until the travel value reaches one. This indicates the timing has reached a trip value and a trip output is issued. If the MOP drops back below the pickup prior to trip, the travel register is decreased according to the reset characteristic selected by the user.

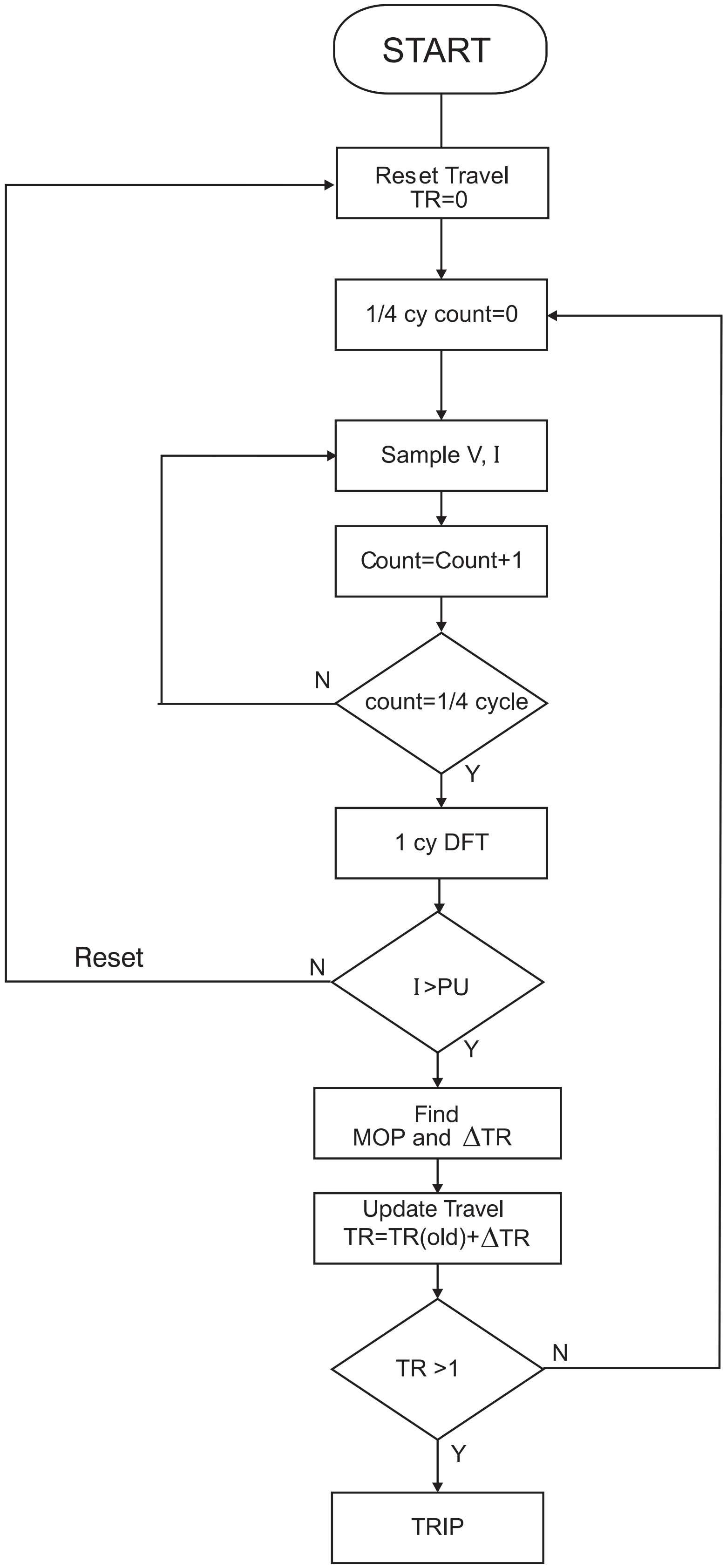

Figure 9: Flow Chart of an Integrating O/C Relay Algorithm

This integrating algorithm is approximated in the following simulation equation which yields the trip time for an input current with a time varying multiple of pickup M(t).

$$ANS := \begin{array}{|l} m \leftarrow 0 \\ \text{while } \left[a \leftarrow \int_0^{T_m} \left[\frac{A \cdot D}{(|M(t)|)^N - C} + B \cdot D + K \right]^{-1} dt \right] < 1 \\ \quad \begin{array}{|l} m \leftarrow m + 10 \text{ if } a < 0.9 \\ m \leftarrow m + 1 \end{array} \\ m \\ T_m \end{array} \qquad \text{Equation 6}$$

Where
m: time interval in mS
M(t): A function of Multiple of Pickup, determined by the generator's load characteristics.
Tm : Time to Trip
A, B, C, D, N, and K: Time Characteristic Curve Constants
a: temporary results for comparison

To determine the trip time, we need to solve for Tm for a given function of M(t). Due to the complex nature of the function M(t), solving the integral directly is not practical. Instead, actual values are substituted for Tm, making the equation a closed integral over a known time period. This allows standard approximation methods to be applied for solving the integral.

Using the MathCAD model, values are systematically substituted for Tm starting with zero. The value is incremented and the integral solved. The solution is compared to one. If the solution is less than one, Tm is incremented again and a new solution computed. The WHILE loop continues this process until the solution is equal to one, indicating a trip time out has occurred. This final value for Tm is the expected trip time of the numerical relay. To reduce computing time, Tm is initially incremented in steps of ten until the solution reaches 90% of value. Then the step size is reduced to one to provide a more accurate result. Further optimizations are possible using larger step sizes or different initial values for Tm depending on the application.

3.3 Calculated trip times

The results from the simulation for both a 51V and a 67 relay are shown in Table 1. The external impedance Xe is varied as shown.

RELAY	Xe =0.00	0.05	0.1	0.15	0.2	0.25	0.3
51V Calculated	0.644	0.765	0.969	1.749	2.967	4.789	7.506
51V Calc w/o field forcing	0.707	0.886	1.213	2.235	NOP	NOP	NOP
51V Simplified method	0.618	0.715	0.831	0.969	1.128	1.310	1.516
51V Test	0.661	0.772	1.006	1.746	2.950	4.769	7.459
67 Calculated	0.233	0.275	0.333	0.425	0.586	1.051	NOP
67 Calc w/o field forcing	0.240	0.289	0.365	0.519	NOP	NOP	NOP
67 Simplified method	0.240	0.279	0.333	0.410	0.528	0.727	1.128
67 Test	0.236	0.285	0.350	0.446	0.625	1.230	NOP
I transient	776	647	554	485	431	388	353

Table 1: Calculated and Measured Times are with Field Forcing = 1.3, except where indicated

3.4 Test Results and Comparison

For the actual relay test, the current and voltage signals were generated in Mathcad, converted to Comtrade files, and played back into the relay under test.

Trip times from the simplified method, simulation calculation (Equation 6), and actual relay test are compared in the above table and are plotted in Figures 10 and 10a. Figure 10 shows the results with field forcing (FF=1.3), whereas Figure 10a is without field forcing. The times shown in Figure 10a were obtained from simulation. No test data was acquired.

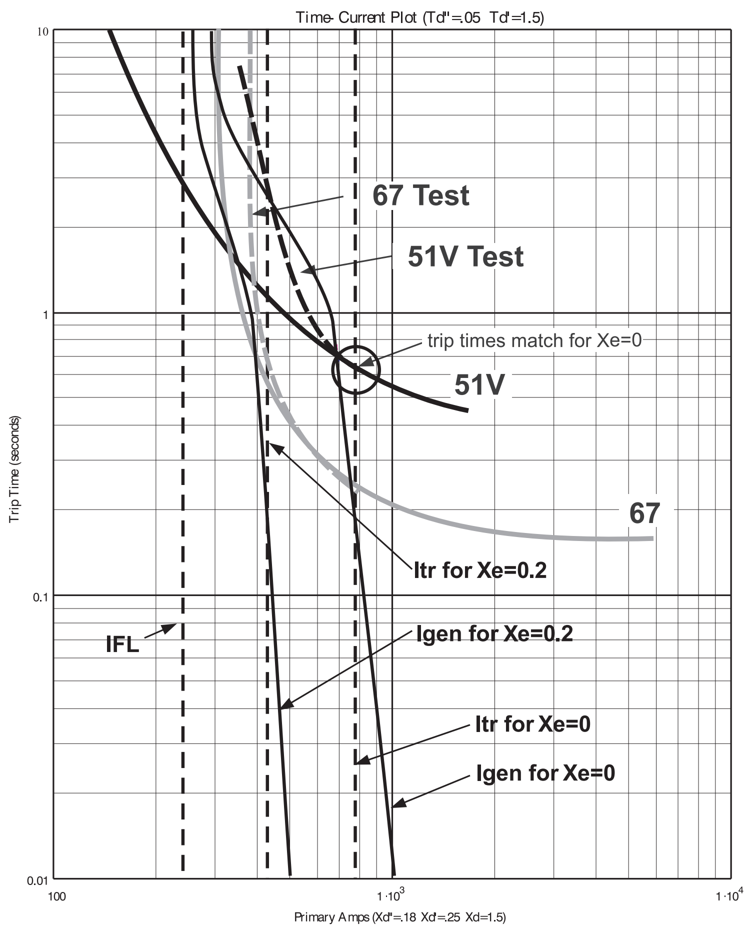

Figure 10: 51V and 67 Trip Times Compared (WITH Field Forcing Factor = 1.3)

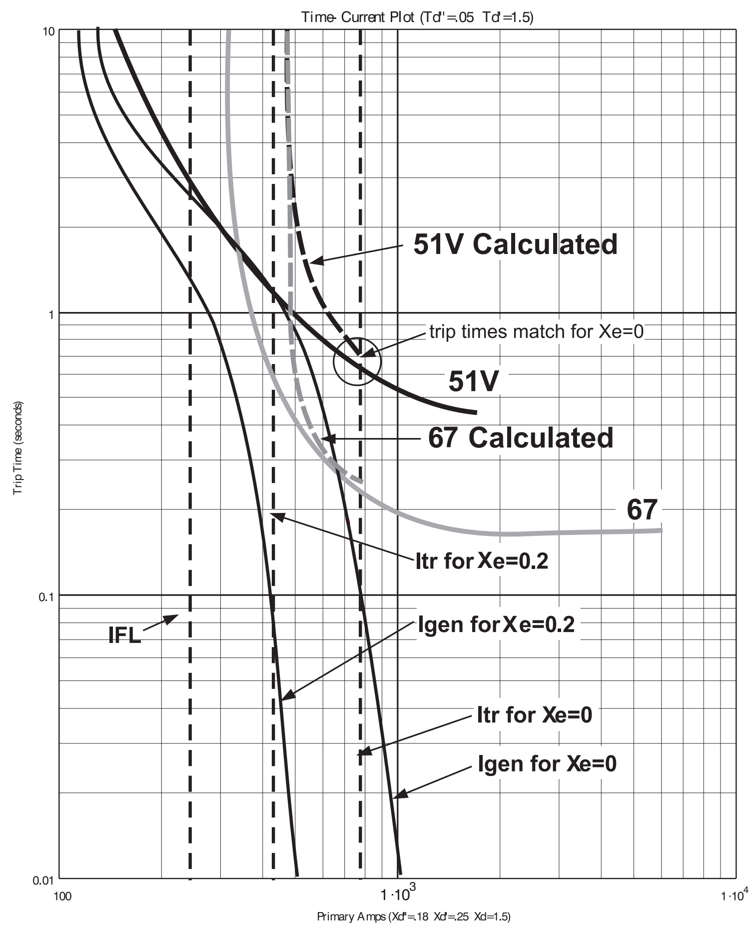

Figure 10a: 51V and 67 Trip Times Compared WITHOUT Field Forcing

4 51V AND 67 COORDINATION

A practical application of the coordination problem is considered in the typical industrial configuration shown in Figure 11. The 51V relay on generator G1 must coordinate with the 67 relay for the worst case F2 fault when T2 and G2 are out of service.

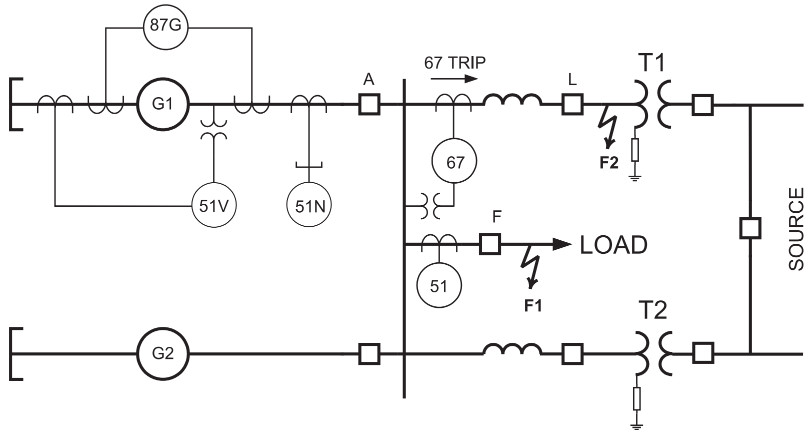

Figure 11: Typical Industrial Configuration

4.1 Steady State Current

Manual, and even computer aided, coordination studies do not consider the effects of the decaying current and voltage on the time-current characteristics of the relays. The simplified method assumes steady current is used. The specific assumptions are as follows:

- the current remains steady and equal to the transient level while the relays are timing to trip
- the 51V voltage is below 25% of nominal, forcing the 51V tap to ¼ of the normal setting

The coordination plot in Figure 10 reflects these assumptions. By applying traditional reasoning in the analysis of this coordination plot, one might conclude that mis-coordination occurs at low fault currents. This is only apparent, as the simulation and test results show. The cross-over, however, begs to question if the 51V relay will operate at all for low fault currents.

In the next section we observe that this static coordination plot does not faithfully represent the relay performance.

4.2 Variable Current

The actual relay trip time under a decrementing generator current condition is nearly identical to the value obtained under the simplified assumption stated earlier, at the *maximum fault current* , i.e. for fault near the generator terminals. For remote faults (F2 in Figure 11), the external impedance causes the resulting voltage drop and effective tap on the 51V relay to increase. The trip time becomes longer than the value obtained by assuming that the voltage was below ¼ of the nominal voltage. This effect is attenuated in the 67 relay. Consequently, the cross-over that appears on the simplified coordination plots actually does not occur.

A significant observation must be made: the rapid trip time increase with increasing external impedance limits the reach of the 51V relay to a shorter distance than the limit obtained by considering the constant transient current. This fact must be taken into account when determining the zones of protection. In other words, the 51V may not provide the backup protection in the entire assumed zone of protection. Also, it was shown that field forcing extends the reach of the 51V relay. This is one of the benefits of static excitation.

5 CONCLUSION

The foregoing analysis has shown that voltage restrained overcurrent can be practically coordinated with normal overcurrent relays under certain simplifying assumptions. The resulting coordination plots are valid for close-in faults. Distant faults, for which the 51V is applied to provide backup protection, have significantly longer trip times than suggested by the simplified coordination method. A simulation technique has been shown to assist the Relay Engineer in predicting the approximate reach of the 51V relay for the limiting case of three-phase faults. Field forcing, when in use, tends to increase the reach of the 51V relay.

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BIOGRAPHICAL INFORMATION

Jerry Johnson is a Product Manager for Basler Electric Company, based in Richmond, Virginia. Prior to joining Basler in 1999, Jerry spent 29 years in the System Protection organization of Virginia Power, including 12 years as Director of the System Protection Engineering Department. Jerry is a graduate of Virginia Commonwealth University and is a registered professional engineer in the State of Virginia. He has been a member of IEEE for 8 years and a working member of the Power System Relaying Committee since 1993. Mr. Johnson is a member of the Georgia Tech Planning Committee.

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