A Novel Approach to Fast Eliminating the Characteristic Curves Crossing Problem of Relay Coordination in Radial Subtransmission Networks

YING LU
JARM-LONG CHUNG
WEN-SHIOW KAO

QUERY SHEET

Q1: Au: Please review your paper as a whole for correctness. Although you may have submitted your paper electronically, errors might have been introduced during the copy-editing and typesetting processes. It is very important that you check your paper for accuracy in all respects. Also, please check author names, affiliations, and contact information on the article opening page to be certain all is accurate and up-to-date. Thank you!

Q2: Au: Please check all artwork throughout article for correctness. Images may have been obtained from electronic files supplied. Please ensure that there were no software interpretation problems.

Q3: Au: Please confirm that all artwork is to appear in black and white on the web and in the print edition. If you are interested in any color artwork, please see the “Instructions for Authors” for a pricing breakdown, or contact me immediately for a quote: cheryl.hufnagle@taylorandfrancis.com
A Novel Approach to Fast Eliminating the Characteristic Curves Crossing Problem of Relay Coordination in Radial Subtransmission Networks

YING LU
Department of Computer and Communication Engineering
St. John’s University
Taiwan

JARM-LONG CHUNG
Department of Power Supply
Taiwan Power Company
Taiwan

WEN-SHIOW KAO
Department of Electrical Engineering
National Taipei University of Technology
Taiwan

Abstract A novel approach is presented to solve the coordination problem of overcurrent relays in radial subtransmission networks resulting from the intersection of characteristic curves. Based on the ANSI/IEEE standard characteristic curve equation of digital overcurrent relays, a slope adjustment equation for a selected point on the characteristic curve is derived and then used as the core of a dedicated software program developed to compute the corresponding relay setting with different tap value in order that, passed through the selected point, another curve with steeper slope is chosen and thus able to escape from the crossed position. Finally, with the assistance of the graphical capability of commercial package OneLiner in drawing the upstream and downstream relay coordination curves after adjustment, the curves intersection problem in protection coordination can be readily eliminated. In addition, an actual case of a radial subtransmission network with six buses in Taiwan Power Company is simulated to validate the feasibility of the approach.

Keywords characteristic curve, coordination time interval, overcurrent relay, protection coordination

Received 30 March 2006; accepted 25 July 2006.
Address correspondence to Prof. Ying Lu, Dept. of Computer and Communication Engineering, 49, Section 4, Tam King Rd., Tamsui, Taipei County, 251, Taiwan. E-mail: yinglu@mail.sju.edu.tw
1. Introduction

Overcurrent relays and directional overcurrent relays have been widely used as the important devices in power system protection for many years because of their reliable performance and low cost. In the power subtransmission networks, such as radial ones, overcurrent relays with various types and manufacturers have been adopted due to stations being constructed in different periods of time, or the protective relays are set at different tap values in accordance with the fault current pre-determined, thus, in general, resulting in the intersection of the time-current curves while setting protection coordination. As shown in Figure 1, if the curves intersect, relay A operates prior to relay B for fault currents before the crossing point, but relay B reacts before relay A for high fault currents. Therefore, coordination is lost [1].

The overcurrent relay coordination process is to decide the sequence of relay operations for each possible fault location and to provide sufficient coordination margins without excessive time delay, taking into account the desired protection qualities of selectivity, stability, sensitivity, and speed [1, 2]. In recent years, with the aid of computers, many research efforts have been made to automate the overcurrent relay coordination process and to achieve optimum protection coordination, using different techniques and methodologies [3]. Linear and non-linear programming techniques [4–6] as well as the evolutionary programming technique [7, 8] are employed to determine the optimal settings of the pickup current and/or the time dial and to minimize the operating time. In addition, the adaptive protection schemes are developed to set and coordinate the relays in response to changes in load levels, generation levels, and system topology [9–12].

However, the effective treatment of the coordination curves crossing problem encountered in many practical applications for protecting subtransmission systems, which is the objective of this article, has not been reported as yet in the literature. Although [13–15] describe coordination of overcurrent protective devices such as relays and fuses, it is related to the characteristic curves of these devices being coordinated with comparable curves, applicable to the equipments such as transformers and motors. Therefore, their

![Figure 1. An example of curves crossing.](image-url)
Relay Coordination in Radial Networks 3

guidelines for curves crossover consideration are not suitable for that of the upstream and downstream relay coordination involved in protecting the entire subtransmission network, as this article concerns.

In practice, subtransmission systems are often installed with overcurrent relays having various types and producers, hence, leading to inconsistent characteristics among the time-current curves of these relays such that the relay settings planned even by the experienced protection engineers sometimes cannot prevent the characteristic curves of the coordinated protective relays from crossing to each other. In Taiwan, if this situation occurs, for the computer-aided protective relay coordination programs available do not support solving the crossing problem, the relay settings hence have to be readjusted by manual calculation with the trial-and-error process, which is tedious, time-consuming, and hard to get more optimal coordination, and will in general cause the change of the preferred coordination parameter values designed originally, such as coordination time intervals (CTIs). In this regard, to overcome the drawbacks of the existing method, a new practical method is proposed in this study and the program developed accordingly can then be utilized to fast and easily obtain the proper relay settings for eliminating the intersection of relay characteristic curves without altering the previously arranged CTIs, and, in turn, alleviating the impact on the quality of power system caused by such improper coordination.

Firstly, a slope adjustment equation for a selected point on the characteristic curve is derived from the ANSI/IEEE standard characteristic curve equation of digital overcurrent relays. Then, centered on the slope adjustment equation, a relay setting software program is developed to provide a technique, namely fixed-point slope adjustment (FPSA), to compute the corresponding values for relay settings with distinct tap values so as to select another characteristic curve with a steeper slope passed through the selected point for evading the curve intersection situation. Finally, using the proposed slope adjustment procedure, i.e., with the FPSA technique as well as the graphical capability of the commercial software package OneLiner provided by ASPEN, the undesired situations causing the shutoff in unnecessary areas, such as the upstream overcurrent relays being operated earlier than the downstream ones, induced by the coordination curve intersection problem, can be completely exterminated in short period of time. In addition, an actual case of a radial subtransmission network with six buses in Taiwan Power Company is simulated to validate the feasibility and practical value of the proposed method.

The rest of this article is organized as follows. Section 2 describes the proposed approach in detail, which explains the derivation of fixed-point slope adjustment equation from the ANSI/IEEE standard characteristic curve equation of digital overcurrent relays, introduces the structure of the relay setting program developed in this study, and delineates the procedure of fixed-point slope adjustment. Section 3 demonstrates and discusses the real case simulated, and then the conclusions are given in Section 4.

2. Description of the Proposed Approach

2.1. Formation of Fixed-Point Slope Adjustment Equation

To deal with the crossed condition of characteristic curves in protection coordination, this study utilizes the feature of the inverse time overcurrent relay that, with the trip time of the relay being fixed, as the multiple of pickup current decreases due to the increase of the tap value, the characteristic curve with a smaller lever setting, that is, a steeper slope, is applied by the relay. In addition, since relays are coordinated in pairs, with the
upstream relay being adjusted to coordinate properly with the downstream relay, the fault
current at the outgoing of downstream bus is selected as the critical reference current,
and the operating time of the upstream relay, which is the operating time of its paired
downstream relay plus the CTI used in between, is maintained unchanged in coordination
adjustment. Accordingly, on the relay characteristic curve, a point associated with the
above fault current in the horizontal axis and the above operating time in the vertical axis
can thus be located. Then, by increasing the tap value of the relay, another curve with
a steeper slope passing through that selected point, i.e., fixed point, is obtained, forcing
the curve to depart from the original position where the curve intersection appears.

Equation (1) is the ANSI/IEEE standard normal inverse-time characteristic curve
expression of digital overcurrent relays [16] and is used to derive the fixed-point slope
adjustment equation for characteristic curves.

\[
t = \frac{0.14 \times L}{\left( \frac{i}{I_n} \right)^{0.02} - 1} = \frac{0.14 \times L}{M^{0.02} - 1}
\]  \hspace{1cm} (1)

where

- \( t \): time to trip, in seconds
- \( L \): time dial, or lever setting
- \( i \): the secondary fault current of the current transformer, in amperes
- \( I_n \): tap value
- \( M \): multiples of pickup current, where \( M = i/I_n \)

Due to the operating time of the upstream relay coordinated remains the same, that
is, \( t = T \), Eq. (1) can be rearranged as

\[
L = \frac{T}{0.14} \times (M^{0.02} - 1)
\]  \hspace{1cm} (2)

Differentiating (2) with \( M \) yields a derivative equation for the characteristic curve
as follows:

\[
\frac{dL}{dM} = \frac{T \times 0.02}{0.14} \times M^{-0.98}
\]  \hspace{1cm} (3)

A characteristic curve of the overcurrent relay, as expressed in (1), as well as a
tangent line, as expressed in (3), on a fixed point of the curve with the specified \( M \) and
\( T \) in the \( x \)-axis and \( y \)-axis, respectively, are illustrated in Figure 2, where the \( x \)-axis is
expressed in multiples of pickup current and the \( y \)-axis is the relay operation close time in seconds.

As the tap value increases while maintaining \( t = T \), the multiple of pickup current
decreases from \( M_1 \) to \( M_2 \), and hence another curve with different lever setting \( L_2 \) is
addressed, as shown in the left diagram of Figure 3, where the slope \((dL_2/dM_2)\) of the
fixed point, corresponding to \( M_2 \) and \( T \), on curve \( L_2 \) is steeper than that \((dL_1/dM_1)\)
of the fixed point, associated with \( M_1 \) and \( T \), of curve \( L_1 \). For better demonstration,
the diagram with \( x \)-axis representing the fault current instead of the multiples of pickup
current is illustrated in the right-hand side of Figure 3. Because the pre-determined fault
current \( i_f \) is fixed, with the increase of the tap value, which reduces the multiple of
pickup current, the original curve \( L_1 \) is substituted with another steeper-slope curve \( L_2 \),
which passes through the same fixed point corresponding to \( i_f \) and \( T \) in the \( x \)-axis and
Figure 2. Characteristic curve of overcurrent relay and its fixed-point tangent.

y-axis, respectively, so that this technique is able to adjust the characteristic curve on the fixed point determined by the selected fault current and specified trip time.

Substituting $t = T, L_1, M_1, L_2,$ and $M_2$ into (1) acquires

$$T = \frac{0.14 \times L_1}{M_1^{0.02} - 1} = \frac{0.14 \times L_2}{M_2^{0.02} - 1}$$

(4)

where $L_1$ and $L_2$ are time dial or lever settings.

Rearranging (4) yields the fixed-point slope adjustment equation expressed below.

$$L_2 = L_1 \times \frac{M_2^{0.02} - 1}{M_1^{0.02} - 1}$$

(5)

Figure 3. Illustration of fixed-point slope adjustment technique.
With (5), by changing the tap value, a new time dial setting $L_2$ can be calculated from $L_1$, $M_1$, and the new multiple of pickup current $M_2$ varied with the tap value. In addition, the proposed approach can be applied to digital overcurrent relays with characteristic curve equations other than the ANSI/IEEE standard one [17] to attain fixed-point slope adjustment equations similar to (5).

### 2.2. Structure of the Developed Relay Setting Program

Centered on the fixed-point slope adjustment equation of characteristic curve derived in the previous section, a dedicated software program for relay setting is developed to facilitate a better way to readily solve the time-current curve intersection of coordinated overcurrent relays, for the conventionally employed trial-and-error process is tedious, time-consuming, and even hard to get a suitable solution, particularly for complex systems.

The relay setting program is roughly structured into four parts, as indicated by the rectangles with round angles in Figure 4, which illustrates the block diagram for

![Figure 4](image-url)
the process of relay setting program. In part 1, the system data table is established by entering initial data, including system's title and voltage rank, bus's title and voltage rank, positive-sequence and zero-sequence impedances of transmission lines, CT ratios, manufacturers and types of protective relays, etc. After these essential data are provided, both the data entered and information for unconnected buses and lines are printed out for checking manually. If everything is fine, then go to part 2.

In part 2, three-phase short-circuit and single-phase ground fault currents for buses and transmission lines are computed according to the power transmission network structure and relevant system parameters obtained in part 1. With the calculated fault currents, the coordination relay pairs in the system can then be determined.

In part 3, based on the distribution of three-phase short-circuit and single-phase ground fault currents in the power transmission network, the schedule for setting the upstream and downstream relay pairs involved in the coordination is resolved. Then, in accordance with the sequence indicated in the schedule, every coordinated relay pair, located in the outgoings of upstream and downstream buses, respectively, is adjusted with proper tap values, which are utilized to compute the corresponding time dial settings with the derived fixed-point slope adjustment equation. And the calculated settings of phase and ground directional overcurrent relays located in every bus outgoing are printed out in part 4.

2.3. Procedure of Fixed-Point Slope Adjustment (FPSA)

The fixed-point slope adjustment procedure consists of two programs; one is the relay setting program developed in this article, used for computing the corresponding time dial setting as the tap value of relay varies, and the other is the commercial software package OneLiner released by ASPEN, with its graphical capability, assisted for plotting the characteristic curves of overcurrent relays coordinated in the system. Figure 5 is the flowchart of the fixed-point slope adjustment procedure. The following steps describe the procedure in detail.

Step 1: OneLiner is executed to draw the time-current curves of overcurrent relays participating in the protection coordination for the power transmission network, based on the relevant system and relay parameters. Then, the characteristic curves diagram is inspected to see if any intersection among those curves exists. If none, the procedure is over; otherwise, proceed to the next step.

Step 2: The valid incremented tap value is given to the relay setting program. Via the fixed-point slope adjustment equation, a new time dial or lever setting is obtained from the program. Then go back to step 1 to examine whether the new relay setting cures the curve intersection problem.

3. Case Study

A case simulation of a radial subtransmission network with six buses in Taiwan Power Company is conducted to confirm the feasibility of the method proposed in this study. Figure 6 shows the radial subtransmission system, in which the six buses, named in the simulation as A BUS, B BUS, C BUS, D BUS, E BUS, and F BUS, respectively, have the same voltage rank of 69 kV. Source impedances of A BUS are \( Z_1 = 0.000 + j1.849 \Omega \) and \( Z_0 = 0.001 + j47.552 \Omega \). Other circuit parameters and relevant data regarding the protective relays employed are depicted in Table 1. Overcurrent relays adopted in the protection...
Figure 5. Flow chart of the fixed-point slope adjustment procedure.

Figure 6. A radial subtransmission network with six buses in Taiwan Power Company.
### Table 1

Related system and relay parameters of the radial transmission system

<table>
<thead>
<tr>
<th>Line section</th>
<th>Rated current (A)</th>
<th>Protective devices</th>
<th>Positive sequence impedance (ohm, p.u.)</th>
<th>Zero sequence impedance (ohm, p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A BUS–B BUS</td>
<td>800</td>
<td>CB no.</td>
<td>CT ratio relay type</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>610</td>
<td>800/5</td>
<td>0.248 + j1.203</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>51:Sepam2000 : 5/0.97</td>
<td>0.00521 + j0.02527</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>51N:Sepam2000 : 1/1.03</td>
<td></td>
</tr>
<tr>
<td>B BUS–C BUS</td>
<td>800</td>
<td>630</td>
<td>800/5</td>
<td>0.616 + j2.974</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>51:SPAJ140C : 5/0.23</td>
<td>0.01294 + j0.06249</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>51N:SPAJ140C : 1/0.23</td>
<td></td>
</tr>
<tr>
<td>C BUS–D BUS</td>
<td>800</td>
<td>610</td>
<td>800/5</td>
<td>0.191 + j0.630</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>51:CO-8 : 5/1.75</td>
<td>0.00401 + j0.01323</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>51N:CO-8 : 1/1.75</td>
<td></td>
</tr>
<tr>
<td>C BUS–E BUS</td>
<td>800</td>
<td>660</td>
<td>800/5</td>
<td>0.807 + j4.181</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>51:CO-8 : 5/2.0</td>
<td>0.01695 + j0.08783</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>51N:CO-8 : 1/2.0</td>
<td></td>
</tr>
<tr>
<td>D BUS–F BUS</td>
<td>800</td>
<td>750</td>
<td>400/5</td>
<td>0.000 + j33.327</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>51:Sepam2000 : 4.5/0.3</td>
<td>0.0000 + j0.70000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>51N:Sepam2000 : 0.75/0.1</td>
<td></td>
</tr>
</tbody>
</table>

51:CO-8—ABB Co. E/M phase inverse directional overcurrent relay.
51N:CO-8—ABB Co. E/M ground inverse directional overcurrent relay.
51:SPAJ140C—ABB Co. digital normal phase inverse directional overcurrent relay.
51N:SPAJ140C—ABB Co. digital normal ground inverse directional overcurrent relay.
coordination comprise electromagnetic overcurrent relays CO-8 and digital overcurrent relays SPAJ140C, manufactured by ABB Company, as well as digital overcurrent relays Sepam 2000 made by M/G Company [17–19].

The three-phase short-circuit and single-phase ground faults are considered, and phase and ground directional overcurrent relay settings for protection coordination are adjusted for these two fault cases, respectively.

3.1. FPSA for Phase Overcurrent Relays

The isolation of the phase-to-phase or three-phase short-circuit faults of transmission lines is facilitated by phase overcurrent relays, which provide faster tripping for the heavy short circuit faults. In general, due to the three-phase short-circuit fault generating maximum fault current, it is the major fault that requires to be targeted while setting the protective relays for coordination.

At first, the existence of crossed characteristic curves of the 51 relays involved in the coordination of the radial network is checked with the characteristic curve coordinating diagram plotted by OneLiner, as shown in Figure 7, where curve no. 5 is the characteristic curve of the relay corresponding to A BUS#610, curve no. 4 is the characteristic curve of the relay corresponding to B BUS#630, and so on. In the figure, it is noticed that, with all the tap values being set as 5A except the relay associated with D BUS#750, that is 4.5 A, curves no. 5 (A BUS) and no. 4 (B BUS) intersect curve no. 3 (C BUS#610) at the points with respect to fault currents of 1600A and 2300A, respectively, due to the fact that inconsistent time-current characteristics exist among the employed relays with various types and manufacturers. And these intersections may cause the following potential impacts:

1. If a three-phase short-circuit fault is occurred in the outgoing of C BUS#610, while the fault current is smaller than 1600A, the upstream A BUS#610:51 relay would pick up before the C BUS#610:51 relay does, thus, resulting in the undesired blackout in both B BUS and C BUS.

2. If a three-phase short-circuit fault happens in the outgoing of C BUS#610, while the fault current is below 2300A, the B BUS#630:51 relay, rather than the C BUS#610:51 relay, would be activated, leading to the blackout of C BUS.

Therefore, the proposed FPSA procedure is applied to solve the preceding curve intersection problems.

In Figure 7, although curves no. 2 (C BUS#660) and no. 3 (C BUS#610) are intersected, no adjustment is required because they are responsible for protecting different transmission lines connected to the same bus, i.e., C BUS, and both of them are coordinated with the upstream B BUS#630:51 relay, so the unwanted operation mentioned above would never happen.

To adjust the aforementioned incorrect coordination, the FPSA starts with the B BUS#630:51 relay, farther from the power source, and then the A BUS#610:51 relay. With the CTI fixed at 0.3 seconds [20], tap values of the 51 relay in B BUS#630 are gradually incremented from 5A, 6A, 7A, to 9A, such that, passed through the fixed point, a characteristic curve with less lever setting, i.e., steeper slope, is acquired so as to move the curve away from the crossing position. These tap values are supplied to the relay setting program for computing the corresponding time dial settings and, in turn, the slopes at the fixed point, as shown in Table 2. The tap values and calculated lever settings are fed to OneLiner to plot the characteristic curves of B BUS#630:51 relay associated
Figure 7. Characteristic curves diagram of coordinated 51 relays before adjustment.

Table 2
Adjustment for B BUS#630:51 relay

<table>
<thead>
<tr>
<th>Tap value (A)</th>
<th>Lever setting</th>
<th>Multiples of pickup current</th>
<th>Operation close time (cycle)</th>
<th>Slope at the fixed point</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.23</td>
<td>8.18</td>
<td>45.0</td>
<td>0.01366045</td>
</tr>
<tr>
<td>6</td>
<td>0.21</td>
<td>6.82</td>
<td>45.0</td>
<td>0.01632505</td>
</tr>
<tr>
<td>7</td>
<td>0.19</td>
<td>5.84</td>
<td>45.0</td>
<td>0.01900547</td>
</tr>
<tr>
<td>9</td>
<td>0.16</td>
<td>4.54</td>
<td>45.0</td>
<td>0.02421773</td>
</tr>
</tbody>
</table>
with distinct tap values for finding the candidate one with no intersection occurred, as illustrated in Figure 8, where curve no. 1 is the characteristic curve of C BUS#660:51 relay with a tap value of 5A; curve no. 2 is the characteristic curve of C BUS#610:51 relay with a tap value of 5A; and curves no. 3, no. 4, no. 5, and no. 6 are characteristic curves of B BUS#630:51 relay with tap values of 5A, 6A, 7A, and 9A, respectively. In the figure, we see that curves no. 5 and no. 6 have no intersection with the curves of other relays, so they both are suitable for acceptable coordination while the CTI used is 0.3 seconds. In this study, curve no. 6 with a tap value of 9A is chosen, and its multiple of pickup current, lever setting, and slope at the fixed point are 4.54, 0.16, and 0.02421773, respectively, as depicted in Table 2.

Before regulating the setting of A BUS#610:51 relay, the new obtained setting of 9A/#0.16 for B BUS#630:51 relay is stored into the system data table via the relay setting program. Then, with the CTI fixed at 0.3 seconds, tap values of 5A, 6A, 7A, and 9A for A BUS#610:51 relay are entered to the relay setting program for computing the corresponding time dial settings, and, in turn, the slopes at the fixed point, as shown.

Figure 8. Characteristic curves of B BUS#610:51 relay with various tap values.
Table 3
Adjustment for A BUS#610:51 relay

<table>
<thead>
<tr>
<th>Tap value (A)</th>
<th>Lever setting</th>
<th>Multiples of pickup current</th>
<th>Operation close time (cycle)</th>
<th>Slope at the fixed point</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.97</td>
<td>16.26</td>
<td>48.0</td>
<td>0.00743180</td>
</tr>
<tr>
<td>6</td>
<td>0.91</td>
<td>13.55</td>
<td>48.0</td>
<td>0.00888570</td>
</tr>
<tr>
<td>7</td>
<td>0.85</td>
<td>11.61</td>
<td>48.0</td>
<td>0.01033847</td>
</tr>
<tr>
<td>9</td>
<td>0.76</td>
<td>9.03</td>
<td>48.0</td>
<td>0.01322568</td>
</tr>
</tbody>
</table>

in Table 3. The tap values and calculated lever settings are fed to OneLiner to plot the characteristic curves of A BUS#610:51 relay associated with discriminated tap values for finding the candidate one with no intersection occurred, as illustrated in Figure 9, where curve no. 1 is the characteristic curve of C BUS#610:51 relay with a tap value of 5A; curve no. 2 is the characteristic curve of B BUS#630:51 relay with a tap value of 9A;
and curves no. 3, no. 4, no. 5, and no. 6 are characteristic curves of A BUS#610:51 relay with tap values of 5A, 6A, 7A, and 9A, respectively. In the figure, we see that only curve no. 3 intersects with no. 1 at the spot corresponding to the fault current of 1600A. In this study, curve no. 6 with a tap value of 9A is selected, and its multiple of pickup current, lever setting, and slope at the fixed point are 9.03, 0.76, and 0.01322568, respectively, as exhibited in Table 3.

Figure 10 displays the characteristic curves of coordinated relays with the adjusted settings for B BUS#630:51 relay and A BUS#610:51 relay. It can be found from the figure that, by using the proposed method, all the previous curve intersections have been removed.

3.2. **FPSA for Ground Overcurrent Relays**

The ground fault of transmission lines is isolated by ground overcurrent relays. The protective coordination constructed by ground overcurrent relays is adjusted in terms of single-phase ground fault currents without the resistance of grounding and electric arc
being taken into account. Figure 11 displays the characteristic curves diagram of ground overcurrent relays, plotted by OneLiner, before adjustment, where curve no. 5 is the characteristic curve of A BUS#610:51N relay, curve no. 4 is the characteristic curve of B BUS#630:51N relay, and so on. In the figure, it is noticed that curves no. 5 (A BUS) and no. 4 (B BUS) intersect with curve no. 3 (C BUS#610) at the points having the single-phase ground fault currents of 350A and 500A, respectively.

To solve these two intersections, the setting of B BUS#630:51N relay is adjusted first, followed by that of A BUS#610:51N relay. With the CTI fixed at 0.3 seconds, tap values of 1A, 1.2A, 1.4A, and 1.6A are entered to the relay setting program and the calculated results of B BUS#630:51N relay and A BUS#610:51N relay are exhibited in Tables 4 and 5, respectively. In this study, the new settings of 1.6A/#0.19 and 1.6A/#0.84 corresponding to B BUS#630:51N relay and A BUS#610:51N relay, respectively, are chosen as the solution, for their associated curves are no longer crossed with curve no. 3.

Figure 12 is the characteristic curves of coordinated 51N relays with the adjusted settings.
Table 4
Adjustment for B BUS#630:51N relay

<table>
<thead>
<tr>
<th>Tap value (A)</th>
<th>Lever setting</th>
<th>Multiples of pickup current</th>
<th>Operation close time (cycle)</th>
<th>Slope at the fixed point</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.23</td>
<td>9.90</td>
<td>42.0</td>
<td>0.00404596</td>
</tr>
<tr>
<td>1.2</td>
<td>0.22</td>
<td>8.25</td>
<td>42.0</td>
<td>0.00429998</td>
</tr>
<tr>
<td>1.4</td>
<td>0.20</td>
<td>7.07</td>
<td>42.0</td>
<td>0.00468216</td>
</tr>
<tr>
<td>1.6</td>
<td>0.19</td>
<td>6.19</td>
<td>42.0</td>
<td>0.00489330</td>
</tr>
</tbody>
</table>

Table 5
Adjustment for A BUS#610:51N relay

<table>
<thead>
<tr>
<th>Tap value (A)</th>
<th>Lever setting</th>
<th>Multiples of pickup current</th>
<th>Operation close time (cycle)</th>
<th>Slope at the fixed point</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.03</td>
<td>12.90</td>
<td>56.0</td>
<td>0.01200498</td>
</tr>
<tr>
<td>1.2</td>
<td>0.96</td>
<td>10.75</td>
<td>56.0</td>
<td>0.01337805</td>
</tr>
<tr>
<td>1.4</td>
<td>0.89</td>
<td>9.21</td>
<td>56.0</td>
<td>0.01443170</td>
</tr>
<tr>
<td>1.6</td>
<td>0.84</td>
<td>8.06</td>
<td>56.0</td>
<td>0.01552290</td>
</tr>
</tbody>
</table>

for B BUS 630:51N relay and A BUS#610:51N relay, where the two intersections of characteristic curves shown in Figure 11 are disappeared.

Figure 13 shows the simulated radial subtransmission network of six buses with the adjusted relay settings indicated by “***”, including settings of B BUS#630:51 and A BUS#610:51 phase overcurrent relays for three phase short-circuit fault protection, as well as settings of B BUS#630:51N and A BUS#610:51N ground overcurrent relays for single-phase ground fault protection. The real case simulation of Taiwan Power Company reveals that, with the proposed FPSA approach, the coordination problem caused by the crossing of characteristic curves is completely fixed. Therefore, the method proposed in this study indeed can construct sound protective coordination of relays to enhance reliability of power supply.

4. Conclusion

Although overcurrent relays are the most well known and the cheapest, they are actually the most difficult relays to set. This article proposes an effective practical technique to solve the coordination problem of overcurrent relays in radial subtransmission systems resulting from the crossing of characteristic curves, so as to relieve the protection engineers of much routine, tedious, and time-consuming work.

A slope adjustment equation for a selected point on the characteristic curve is derived from the ANSI/IEEE standard characteristic curve equation of digital overcurrent relays. Then, centered on the slope adjustment equation, a dedicated software program is developed to compute the corresponding values for relay settings with different tap...
Figure 12. Characteristic curves diagram of coordinated 51N relays after adjustment.

Figure 13. Relay setting diagram of the radial subtransmission system after adjustment.
values in order that, passed through the selected point, another curve with a steeper slope of that relay is chosen. Finally, incorporating the graphical capability of the commercial OneLiner into the proposed slope adjustment procedure for drawing the relay coordination curves after adjustment, the intersection problem of overcurrent relay characteristic curves in upstream and downstream can thus be readily eliminated, so that the undesired situations such as the upstream overcurrent relays being picked up earlier than the downstream ones, which cause the blackout outside the faulty zone, can be avoided.

In addition, an actual case of a radial network with six buses in Taiwan Power Company is simulated to validate the feasibility as well as the excellence of the method proposed, which demonstrates the practical value suitable for application in the power industry.

In a future study, we will work on resolving the coordination curves crossing problem in more complicated systems, such as single-loop and multi-loop multi-source subtransmission networks. In addition, the software program will be enhanced by developing the GUI user interface module to provide user-friendly environment for interaction, and the characteristic curve drawing module to replace the role of ASPEN’s OneLiner commercial package acted in this article.

Acknowledgment

The authors would like to thank Yuang-Jiang Peng, senior protection engineer in Department of Power Supply of Taiwan Power Company, for his useful discussions contributed to the original version of this document.

References


