# Simplifying Wide Area Coordination of Directional Time Overcurrent Relays Using Automatic Settings Selection

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*Abstract*—**Relay coordination is an extremely difficult, yet vital part of a comprehensive protection strategy for modern power systems. Ensuring that relays in these coupled systems behave in a consistent, predictable manner is a time consuming process which traditionally requires substantial engineer effort with manual analysis of numerous combinations of settings values. Furthermore, there is typically no assurance at the end of the process that a near best solution was found. There is previous work in the literature towards automating this activity, but existing methods have yet to completely automate the workflow and expand it to use on real world power systems.**

**In this paper, we present a framework for the automatic generation of coordinated relay settings for directional time overcurrent relays, which represents one of the most challenging coordination problems engineers face. Our framework extends existing approaches and increases the level of automation by seamlessly interacting with fault simulation software to both provide input to and verify the coordination results of pickup and time dial settings chosen by the setting generator. This advancement is accomplished by designing a general software infrastructure for parameter selection, integrated with techniques developed in our previous work for automated relay settings development [1] and NERC PRC-027-1 coordination [2]. Experimental results on several grids, including a real world example where we have previously created settings manually, are presented to demonstrate the speed and precision of the proposed approach.**

*Index Terms*—**Directional Time Overcurrent, Microprocessor Relays; Time Dials, Wide Area Coordination**

## I. INTRODUCTION

Directional time overcurrent relays (DOCRs) are an integral part of any transmission line protection application. While they are used primarily as backup functions to distance elements, they play a key role in protection redundancy; unlike distance elements, directional time overcurrent relays are unaffected by impedance based faults and provide better sensitivity in cases where distance elements fail to detect faults. One example where DOCRs perform better is during high impedance faults where the distance elements will fail to operate, as there would be minimal voltage depression during an arc fault, in which the fault would fall outside the mho characteristic. In contrast, time overcurrent relays can be set sensitively enough to detect these types of faults without compromising security.

Utilities have differing practices when it comes to calculating the relay pickups and time dials, but they all must find the proper relay coordination between primary and backup pairs. In most transmission applications, coordination is achieved by checking the tripping times of the primary relay against that of the backup relay. The required coordination time interval (CTI) between operation is usually required to be at least 0.33 to 0.5 seconds. In order to make the relay settings more secure, coordination is often further checked under a single, or, N-1 contingency. However, with these more exhaustive studies, coordination might not be attainable in some cases.

In this paper we present a framework that automatically creates pickup and time dial relay settings for directional time overcurrent relays. These settings are based on a specification of the desired constraints on the settings (e.g., CTI and required backup relay response to remote bus faults), coupled with fault current data obtained through automatic interaction with fault simulation packages such as ASPEN Oneliner. We build upon previous work in the field [3], [5]–[8], extending it in practical ways to support the needs of engineers working on real power grids. Examples of this include better support for multiple backups and an arbitrary number of input fault studies to the settings selection module. Importantly, we increase the level of automation in the coordinated settings creation workflow, incorporating advances made in our previous work in [1], [2].

This paper represents an important contribution to the field of system protection, as the amount of studies that must be completed will soon increase dramatically as part of the compliance activities dictated for PRC-027-1 [13]. Furthermore, these studies will need to be performed on a recurring basis, and solutions such as the one presented are necessary to streamline the coordination process so that it does not become overly burdensome or resource intensive for electrical power utilities to complete in a timely manner.

The outline of the paper is a follows: In Section II we give a motivating example of the coordination problem and discuss related work. We then present an overview of the proposed settings generation framework in Section III. Experimental results on three power systems are then presented, followed by conclusions and discussion of directions for future work.

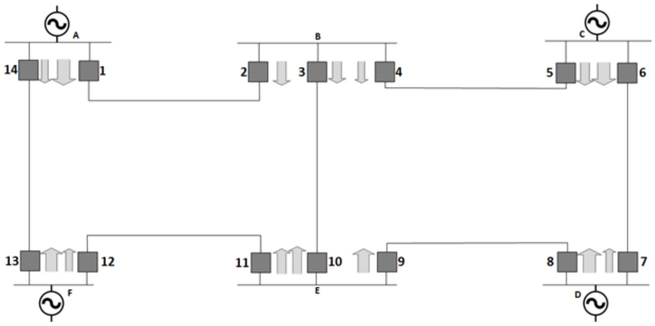

Fig. 1. One line diagram for 6-bus example system.

## II. Background and Related Work

### A. The Challenge of Manual Relay Coordination

For radial systems, coordination is easily achieved between the local and remote terminal since radial lines act like distribution feeders. However, for a non-radial system, the coordination of time overcurrents can get highly complex.

An example coordination problem taken from [3] is shown in Figure 1. This is a six-bus system with a total of fourteen terminals. For each terminal, a relay pickup and a time dial must be found that satisfies the coordination criteria. We can start by calculating the pickups and time dials for relay *R13* which is a backup to *R1*. The same procedure is then followed for the rest of the primary / backup pairs. We next move to *R11* which is backup to *R13*, and then to *R3* which a is backup for *R9* as well as *R11*, thereby closing the loop by setting *R1* as backup to *R3* and *R4*. Note that *R1* had already been computed to the initial setup of breaker 13. The changes to *R1* could result in breaking the entire coordination of the rest of the relays in the loop. As a result, the engineer may be required to complete several iterations of this procedure before proper coordination of all terminals can be achieved.

### B. Related Work

The complexity of the coordination problem grows substantially as the number of terminals and relays increases. To address this complexity, algorithms and tools have been proposed to reduce the time and effort required to achieve proper coordination. Here we focus on previous work aimed at automatically created coordinated relay settings which are guided by some measure of solution optimality. Two surveys of existing methods are presented in [3] and [4]. The authors of [5] proposed the use of *optimization theory* to address the problem and subsequent work in [6]–[8] among others has furthered research in this direction.

Other approaches have been proposed, often tracking developments in the field of machine learning and artificial intelligence. For example, [9] proposes an evolutionary approach, based on genetic algorithms. Similarly, authors of [10] use reinforcement learning to find optimal overcurrent relay coordination. Some approaches such as [11] pull from other fields such as graph theory, a natural fit given the graph like structure of the power grid.

## III. Proposed Framework

In this section, we provide an overview of the major components of the settings selection framework and describe how a protection engineer uses it in an integrated workflow for creating coordinated relay settings. The framework is depicted in Figure 2 and the process begins by a formulation of the coordination.

This formulation consists of several inputs to the learner, including the power system to be coordinated, a list of relays whose settings must be calculated, and a list of desired constraints to be considered when developing the time dial and pickup settings. These constraints include things such as the minimum CTI to enforce between primary relays and their backups and how far down remote lines backups must respond to faults. Finally, the valid value ranges of the relay settings to be computed are provided, based on the capabilities of the relays and/or the standards of the utility.

The framework begins by having the *Input Collector* interact with the fault simulation software (e.g., ASPEN) automatically, gathering fault current and other grid information, analyzing constraints and formulating the problem for the *Settings Generator* module which will create candidate settings. This generator is customizable, as it can employ any of the approaches previously discussed. Currently, we're using a settings tuner from the field of optimization theory, drawing heavily from the ideas presented in [5] and [8]. We have further extended with feedback capabilities drawn from unsupervised learning [12], as well as added practical extensions to support an arbitrary number of fault studies and relay backups.

After initial settings are created, the *Coordination Verifier* interacts with the fault simulation software to verify the coordination using the process outlined in [2]. If there are coordination failures, the framework can refine the fault information provided to the *Settings Generator* to create fully coordinated settings. After coordination is achieved, the settings values are presented to the protection engineer for review, who can either accept them after verification, or refine the coordination problem based on their domain knowledge. In the end, this framework automates the tedious and laborious parts of wide area relay coordination, empowering the engineer to more effectively create settings that ensure reliable operation of the power system.

## IV. Experimental Results

In this section, we demonstrate the capability of the framework described in the previous system to calculate pickup ($I_{set}$) and time dial ($TMS$) relay settings on three input grids. The allowable range of these settings varies between the inputs and will be described in the following sections, together with CT ratio and overcurrent curve selection. For all cases, the response times of the backup relays relative to that of primary relay are constrained by a coordination time interval $CTI > 0.3333$. The framework is directed to minimize the

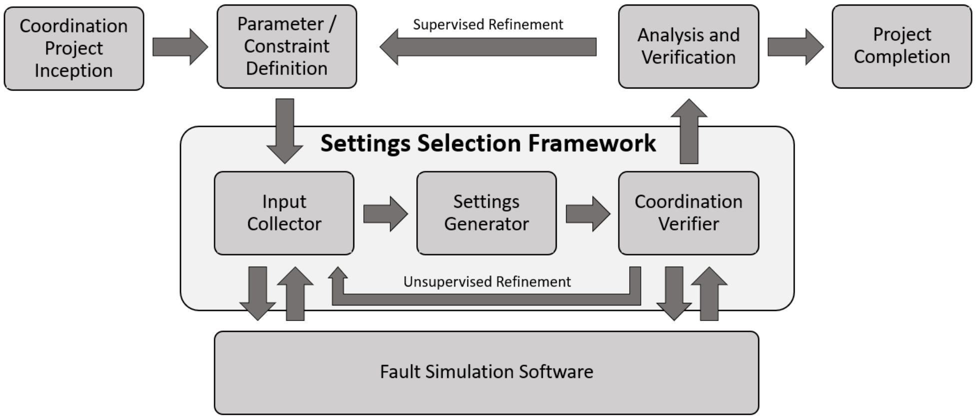

Fig. 2. Workflow for coordinated settings creation.

aggregate response time of all relays to a close in end open fault on the primary line of protection.

In addition to the computed pickups and time dials, we report the response time of each relay with their respective settings to a line end fault. This gives context to the chosen parameters and gauges the overall quality of the answer by showing a lower bound on possible response times to a common fault for the given coordination problem. In deployed relay settings, this response may need to be increased (in the problem specification to our framework), if other protective functions (i.e., Zone 2 distance) are desired to respond before the overcurrent elements.

For the fault simulation and coordination checking, ASPEN Oneliner V14.6 is used together with the automation tools described in [1] and [2]. Studies were run on a desktop PC with an Intel Core i3-4160 processor and 8GB of RAM.

Finally, the coordination study to verify the framework's parameter selection performs a series of three phase faults on each protected line, including a close in, line end, remote bus, and intermediate faults at every 10% of the line. The study ensures that no CTI violates the defined threshold and that backups respond to all faults required by the input specification to the framework (described in the follow subsections).

### A. 3-bus System

We began our experiments with a simple 3 bus system shown in Figure 3 and described in [5]. This allowed us to validate the approach and quickly verify the results.

For this configuration, the CT ratios are as defined in the original paper and are used with parameter ranges $I_{set} \in [0.5 ... 15]$ and $TMS \in [0.1, 5]$. The relay's response time is modeled as in [5] with the following equation:

$$T_{response} = 0.14 * TMS_r / ((I_{fault}/I_{set})^{.02} - 1)$$

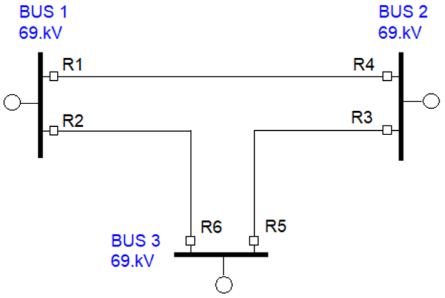

Fig. 3. One line diagram for 3-bus system.

The framework provided the autotuner with fault current data for each relay and its backups to primary line close in, close in end open, and line end faults. In this study, we configure the framework to require a response from backup relays to all faults along the primary line (which thus dictates a more sensitive pickup parameter. The computed parameters and associated line end fault response times are shown in Table I.

TABLE I
CACULATED SETTINGS AND RESPONSE FOR 3-BUS SYSTEM

| **Relay** | $I_{set}$ | $TMS$ | $T_{LE}$ (s) |
|---|---|---|---|
| R1 | 8.0822 | 0.1000 | 0.7141 |
| R2 | 5.0535 | 0.1004 | 0.6818 |
| R3 | 8.8867 | 0.1191 | 0.6512 |
| R4 | 5.6694 | 0.1351 | 0.5918 |
| R5 | 7.8411 | 0.1023 | 0.6843 |
| R6 | 6.1111 | 0.1267 | 0.6125 |

The autotuner computed the settings in less than a second. Together with the generation of its fault current inputs for each relay and the subsequent full validation of the coordination in ASPEN, the total computation time is less than 15 seconds. The maximum response time of a relay to a line end fault was 0.7141 seconds, well within the standard required response time (1 second) used by many electrical utilities.

### B. 9-bus System

In Figure 4, we show a 9 bus one line diagram, derived from a sample power system model that ships with ASPEN.

This system, while still relatively small, represents a significantly more difficult coordination problem that would take a protection engineer a significant amount of time to coordinate from scratch. In this case, pickups were allowed to be in the range $I_{set} \in [0.25...16]$ and time dials could vary as $TMS \in [0.5, 15]$. These ranges are taken from that allowed for relay configuration in a SEL 421 Relay [17]. The CT ratios were set in a straightforward manner, targeting a 20 amp secondary fault current for a close in fault. Finally, the relay's response time is modeled with a standard ANSI U3 (very inverse) curve as shown below:

$$T_{response} = TMS_r * (0.0963 + 3.88/((I_{fault}/I_{set})^2 - 1))$$

The same fault studies and required backup response were provided to the framework as in the 3 bus case. The computation time for the autotuner was also similar to that case, with the overall framework computation time running in less than 30 seconds. Again the maximum response time to a line end fault remains below 1 second, with the maximum being 0.7861 seconds by relay *R15*.

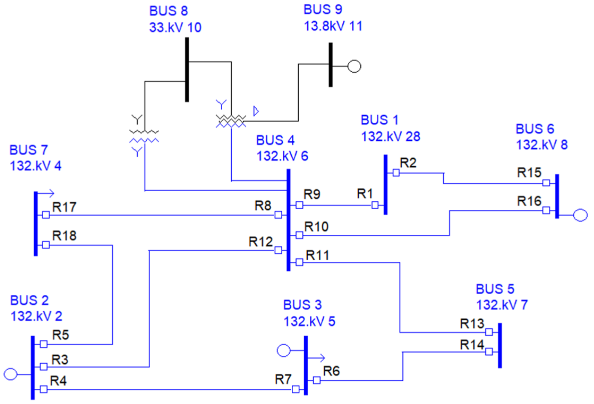

Fig. 4. One line diagram for 9-bus system.

### C. Real World System

The final power system we consider is a real world interconnected system located in Texas, with fourteen relays as depicted in Figure 5. It introduces some complexities into the coordination effort not present in the previous experiments, notably parallel lines between *Bus 3* and *Bus 8*, each of which has a length in excess of 100 miles. Pickup and time dial settings ranges are the same as with the 9-bus case, and the CT ratios for the relays are the same as those of the relays currently in use for this power system. An ANSI U3 curve is again used in this experiment.

Due to the length of the parallel lines, we have relaxed the requirement that backup relays must respond to line end faults on the primary line, as the fault current seen by the backups in this case is negligible. Instead, we only require backups to respond to close in, close in end open, and intermediate faults up to 10% of the remote line. Ideally, the framework should allow the engineer to specify minimum fault current filters in a more selective manner. We intend to explore this option as part of our future work.

TABLE II
CACULATED SETTINGS AND RESPONSE
FOR 9-BUS SYSTEM

| **Relay** | $I_{set}$ | $TMS$ | $T_{LE}$ *(s)* |
|---|---|---|---|
| R1 | 1.4059 | 4.1602 | 0.4779 |
| R2 | 2.8317 | 0.8774 | 0.4610 |
| R3 | 2.4526 | 0.5383 | 0.3302 |
| R4 | 2.7968 | 0.5219 | 0.4155 |
| R5 | 4.0043 | 0.5000 | 0.6830 |
| R6 | 5.0245 | 0.5059 | 0.5838 |
| R7 | 2.1344 | 0.8517 | 0.3568 |
| R8 | 6.7189 | 0.5190 | 0.5435 |
| R9 | 6.2713 | 0.5748 | 0.4715 |
| R10 | 4.0927 | 0.9471 | 0.3364 |
| R11 | 5.5285 | 0.5000 | 0.5382 |
| R12 | 1.9652 | 0.9592 | 0.3238 |
| R13 | 4.0366 | 1.0660 | 0.4193 |
| R14 | 4.1494 | 0.9338 | 0.4113 |
| R15 | 3.8561 | 0.5053 | 0.7861 |
| R16 | 3.6525 | 1.1543 | 0.3068 |
| R17 | 5.3283 | 1.2443 | 0.4269 |
| R18 | 2.0971 | 1.5784 | 0.4628 |

TABLE III
CALCULATED SETTINGS AND RESPONSE
FOR REAL WORLD SYSTEM

| **Relay** | $I_{set}$ | $TMS$ | $T_{LE}$ *(s)* |
|---|---|---|---|
| R1 | 7.5871 | 0.5000 | 0.1355 |
| R2 | 2.6634 | 1.3937 | 0.1616 |
| R3 | 0.2500 | 0.5000 | 0.0482 |
| R4 | 0.2500 | 0.5000 | 0.0486 |
| R5 | 1.9895 | 1.2070 | 0.1478 |
| R6 | 5.5834 | 0.5327 | 0.1801 |
| R7 | 4.1376 | 4.3878 | 0.4701 |
| R8 | 4.1309 | 4.4059 | 0.4718 |
| R9 | 5.7930 | 0.5593 | 0.1686 |
| R10 | 0.2500 | 0.5000 | 0.0483 |
| R11 | 3.7933 | 0.5252 | 0.1581 |
| R12 | 4.8413 | 0.5363 | 0.1737 |
| R13 | 2.4660 | 0.9348 | 0.1031 |
| R14 | 2.4612 | 0.9256 | 0.1020 |

Unlike the previous systems, this is not an isolated power system but is interconnected with that of other utilities in Texas. Hence, backup for some of the relays (such as the one on the right side of *Bus 2* in Figure 5) are outside the main area of interest in the coordination study. For the purpose of these experiments, we include such *boundary* relays within the coordination, but do not include their backups unless they lie within this single tier boundary of the power system of interest. In reality, some more restrictive constraint on adjusting these settings would likely be necessary, as adjusting settings on these relays would require an inter-system settings adjustment request. Again, extending the framework to support restrictions (including not allowing these settings to change at all) is a clear direction for future work.

Table III shows the results obtained for the real world grid. An additional fault current study at 10% of each protected line

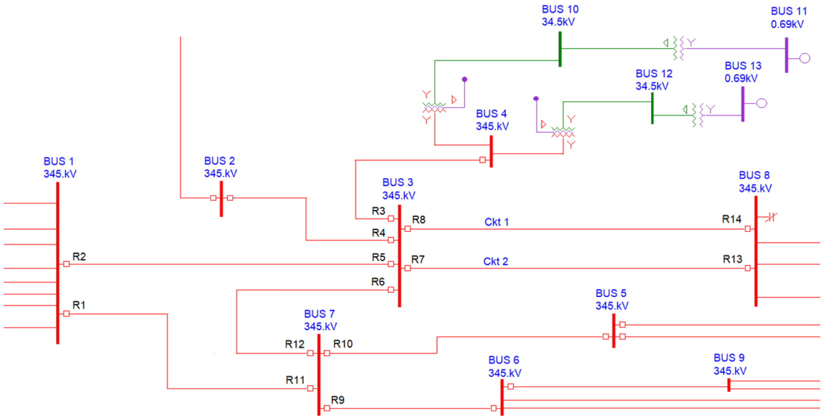

Fig. 5. One line diagram for real world system.

was provided to the framework in addition to those described previously. The autotuner took approximately 3.5 seconds to converge to the solution, though the total computation time including coordination verification remained at less than 30 seconds. Note in the results the generally faster response time to line end faults than in the previous cases (with relays *R7* and *R8* on the long parallel lines being the slowest). This is likely due to the added flexibility in pickup and time dial parameter selection allowed by the relaxation of the remote line end fault response requirement present in the 3-bus and 9-bus experiments.

## V. CONCLUSIONS AND FUTURE WORK

In this paper, we have described a process which streamlines the wide area coordination of directional overcurrent relays by minimizing the manual handling of fault current and settings data by the engineer as well as reducing the tedious, iterative settings adjustments typically required in the process. By designing a customizable framework for the automatic tuning of pickup and time dial settings, we have significantly reduced the chance for error and the labor required to complete this critical protection activity. Furthermore, we have provided a simplified path to demonstrating compliance with regulatory requirements such as the imminent deadline for NERC PRC-027-1 and the recurring studies that utilities will be required to perform.

There are several ways in which the process outlined in this paper can be extended or improved. First, we wish to explore other autotuning coordination approaches as mentioned in Section II, incorporating them into an adaptive selection framework based on an inspection of the characteristics of the input power grid. Next, the inclusion of other relays (i.e., distance) into the framework represents a further step towards better addressing the complexity that protection engineers are faced with in real-life wide area coordination scenarios. Finally, previous approaches primarily aim to optimize the aggregate operation time of relays, preferring coordination solutions that minimize this metric. However, utilities will likely, for practical considerations, prefer coordination solutions that optimize for other metrics, such as those that require the minimal amount of changes to existing, deployed relay settings. We believe implementing alternative optimization goals are achievable within our framework and are currently investigating the incorporation of this feature.

The rapid development of tools and techniques that address the growing complexity of system protection is crucial to empower engineers tasked with ensuring the reliability of this critical infrastructure. We believe the approach presented in this paper is a significant contribution towards this goal, as it directly addresses wide area coordination, one of the primary areas of concern in modern power systems.

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## VI. AUTHOR BIOGRAPHIES

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**Joe Perez** received his B.S. degree in Electrical Engineering from Texas A&M University in 2003. Joe is the author of many relay application notes and has presented technical papers at WPRC, Texas A&M, and Georgia Tech Relay Conferences. Joe is the owner of SynchroGrid, a registered professional engineer in the state of Texas and a member of PSRC, IEEE, and PES. Joe resides in the Bryan/College Station area. He can be contacted at jperez@synchrogrid.com.