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OPTIMIZING AUTOMATED RELAY SETTINGS: A COMPARATIVE ANALYSIS USING SIMULATION-BASED PROTECTION SCHEMES

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ABSTRACT

Protection of the electrical power system is vital to ensure reliability of operations by automatically detecting faults and acting quickly. The reliability of modern power networks with increasingly complex composition, coupled with escalating energy requirements, has made it a challenge for protection engineers to determine the relay configurations as well as ensure effective coordination among the relays. This paper proposes an overcurrent (OC) protection coordination strategy that considers both directional and non-directional relays, evaluated through simulation-based methods. The suitability of the suggested scheme is analyzed by applying it to a 132/33 kV substation as a case study, subject to further extension to a 33 kV multi-sources network. The ETAP (Electrical Transient Analysis Program) package has been utilized in simulating as well as investigating actual relay as well as breaker tripping times. Short-circuit as well as load flow analysis were conducted to determine pickup as well as plug setting multipliers (PSMs). The result verifies that the use of simulation tools can vastly minimize the process of relay configuration, ensuring a reliable as well as efficient solution for complex power networks.

Keywords: Relay Setting, Relay Coordination, Short Circuit Analysis, Load Flow Analysis

1. INTRODUCTION

Electrical faults can occur at any point and at any time in the electrical power system. In case such faults go undetected and unresponded to by high-voltage circuit breakers and protection relays, faults can cause significant damage to high-value assets in a power system, such as current and power transformers Dy et al. (2018), Rahmania et al. (2019). For system security, faults must be cleared in a timely manner, and rapid and selective protection techniques become critical. Overcurrent protection is regarded as primary protection for 11 kV, 33 kV medium voltage feeders and a backup protection for 132 kV, 400 kV high voltage transmission lines.

Coordination between primary and backup protections must work effectively to discriminate between them Farkhani et al. (2019) since backup protection takes over in case of failure of primary protection, and continuity in a system is maintained Kamoona et al. (2020).

The growing complexity and expansion of modern power networks have prompted developing an effective mechanism for achieving protection device coordination in an efficient manner. It keeps the dependability and integrity of the power system intact and minimizes downtime and loss due to faults Almuhsen and Sultan (2020), Abd and Sultan (2020). With increased expansion and integration of modern technology in modern power networks, efficient and computerized protection coordination is a must in managing its complexity and operational efficiency.

Effective relay coordination studies involve both simulation software and manual calculation. The studies Nayanatara et al. (2020), Bui et al. (2021) integrate complex protection techniques, including dynamic algorithms and hybrid tripping techniques, for fault-clearing times and dependability improvement. Micro-grid protection is handled through new coordination techniques with the use of ETAP simulations Saini (2022). Hybrid and adaptive techniques also follow an evolutionary path, with new tripping behavior proposed in Idris and Mohamed, (2022), Singh et al. (2022). Optimized algorithms including modified firefly, grey wolf, and particle swarm make relay coordination even more complex, as considered in Alasali et al. (2022) – Seng et al. (2023). Certain techniques use methods such as particle swarm optimization for coordination in complex, distributed networks Reski et al. (2023).

This study delineates a structured methodology to address the intricacies of overcurrent relay coordination within complex power systems, leveraging the analytical capabilities of ETAP simulation software. The research rigorously assessed and verified the proposed framework's efficacy by systematically comparing manually derived relay settings against simulation-generated data to evaluate precision and robustness in both primary and backup protection schemes using a verification test system. Next, the proposed method was applied to a complex system for future assessment. The investigation emphasizes the challenges inherent to multi-fed power networks, with a detailed examination of fault conditions impacting feeders and busbars, thereby highlighting the practical utility of simulation-driven coordination strategies in enhancing system reliability.

2. OVERCURRENT PROTECTION AND SETTING

This type of protection relay is used for overload and fault protection. It compares the measured current with the set pickup value to detect normal or abnormal system conditions. There are several classes of OC relays, and the one selected for this study is the normal inverse relay. Each inverse relay has a time-current characteristic curve, where the relation between current and time is inversely proportional. As the current increases, the relay operation time decreases. With advancements in electronics and software, numerical relays have emerged, capable of performing multiple functions in a single relay.

The OC relay configuration is almost exclusively determined with two values: Plug Setting (PS) and Time Multiplier Setting. TMS value is inserted in the relays for offering selectivity, and PS value is computed with consideration for the maximum allowable normal loading of the feeder. PS value can be computed through a load flow analysis for calculation of current in any section of the system. PS is used for calculation of Plug Setting Multiplier (PSM), and PS is calculated through short circuit calculation for calculation of fault current. With a computed value of PSM, relay operating time can be calculated. The procedure of the setting and coordination of OC relays is summarized as follows

- **Load Flow Study:** The load flow study calculates the steady-state voltage, current, and power flow in the system. This helps determine the pickup current (I_p) for each relay.
- **Pickup Current Calculation:** I_p is typically calculated as a percentage of the rated current of the relay:

$$I_p = \frac{S}{\sqrt{3}\,V_{LL}} * CT\ Ratio \qquad (1)$$

Where: S is apparent power (in kVA or MVA), V_{LL} is Line-Line voltage (in kV) and CT Ratio is the Current Transformer ratio.

- **Short Circuit Study:** This study helps to determine the fault current (I_f). These values are critical for setting the PSM and TDS.
- **PSM:** The PSM is the ratio of the fault current to the relay's pickup current:

$$\text{PSM} = \frac{I_f}{\text{plug setting} \times I_p} \qquad (2)$$

- **Relay Operating Time Calculation:** The operating time of the relay is calculated based on its Time-Current Characteristics (TCC). For overcurrent relays, the standard inverse characteristic equation is:

$$t = \frac{TMS}{\left(\frac{I_f}{I_p}\right)^n - 1} \qquad (3)$$

Where: t is the relay operating time (in seconds), n is a constant based on relay type (e.g., 0.02 for standard inverse and 1 for very inverse)

- Alternatively, the (Time - PSM) curve can be used for the relay to determine the time, which is then used to calculate the actual relay time as follows:

$$t = Time\ from\ curve\ \times TMS \qquad (4)$$

The discrimination time, also known as the time margin, is a fixed value ranging from 0.2 to 0.4 seconds. It is used to ensure selectivity between relays and depends on various factors, including the relay type, circuit breaker time, relay overshoot time, and time error in the operation of the primary relay Kuriakose and Balamurugan (2023), Adnan et al. (2024).

3. SIMULATION RESULT AND DISCUSSION

The work involves two test stages. First, the proposed method is verified by comparing it to the manual relay setting using a radial 132/33 kV test system. After verification, the same procedure is applied to a complex multi-fed system, as described below.

1) Verification case study:

The process at this stage includes test system modelling, load flow and short circuit analyses to outline the system operation for relay settings computation.

- **System Modelling:** Figure 1 illustrates a single-line diagram of a substation containing two 132/33 kV step-down transformers, both rated at 60 MVA. These transformers are supplied by a 132 kV power grid with a short circuit level of 2500 MVA. Each transformer feeds a 33 kV busbar, which accommodates three outgoing feeders through the incoming feeder. The total system load amounts to 66 MVA. To cater for emergencies such as maintenance or defects, the two transformers are interconnected on the 33 kV side through a bus section. The circuit breaker of the bus section is only closed when one of the transformer breakers is switched off, allowing the load to be maintained through the other transformer.

Figure 1

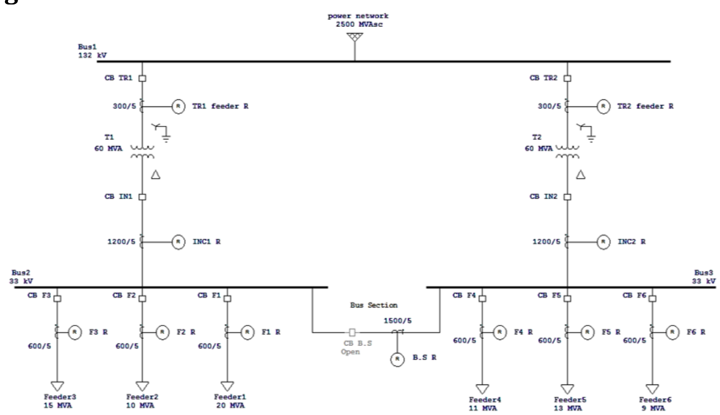

Figure 1 Single Line Diagram of 132/33 kV Substation in ETAP

Generally, the relay coordination study begins from the lower system point of low voltage, specifically the outgoing feeder, and progresses towards the power grid. This approach ensures that the grading starts with the feeder relay, followed by the bus section relay, the incomer relay, and finally the transformer feeder relay, as depicted in Figure 2 The feeder relay is regarded as the primary protection for a fault occurring in the feeder, while all other relays are considered backup protection.

Figure 2

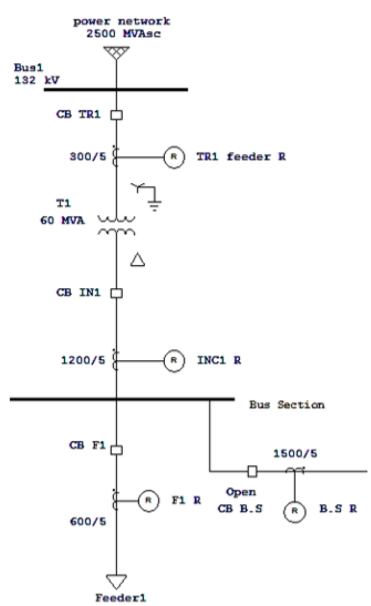

Figure 2 Grading of Feeder1 Transformer 1

2) Load Flow and Short Circuit Analysis

As mentioned earlier, the relay's PS and PSM can be determined through load flow and short circuit analysis, respectively. The load flow analysis provides information about the current and voltage at each bus in the system. In the coordination study, the focus is on Feeder 1. A portion of the load flow analysis results for the corresponding system section, as depicted in Figure 2, is presented in Table 1 It is important to note that the bus section circuit breaker is typically open during the analysis.

Table 1

Table 1 Load Flow Analysis Results

Branch	Load current (A)
Transformer feeder 1	192.5
Incomer 1	771.3
Feeder 1	342.8

With ETAP short circuit analysis, a three-phase short circuit was performed at Feeder 1. The fault current observed by the relay at Feeder 1 was determined to be 9.2 kA, while it was 2.3 kA at the transformer feeder for Feeder 1. This information is crucial for calculating the PSM for the relays.

3) Relay Coordination

- **Relay setting calculation**

Referring to Figure 2, the first step in relay grading will start with the Feeder 1 relay (F1 R), which receives the minimum TMS. Next, the bus section relay must operate if F1 R fails (in the event of the bus section circuit breaker being closed). This is followed by the operation of the incomer relay and then the transformer feeder relay. The grading sequence is structured in this manner to ensure relay selectivity.

In this model, normal inverse numerical relays have been used, allowing the TMS to be set to any desired value. The grading time between relays is set at 0.2. Table 2 displays the CT ratios that supply the relays, which are necessary for the calculations based on the relay setting equations.

Table 2

Table 2 Relays CT Ratio

Branch	Relay	CT ratio
Feeder 1	F1 R	600/5
Bus section	B.S R	1200/5
Incomer 1	INC1 R	1200/5
Transformer Feeder 1	TR1 feeder R	300/5

The setting of F1 R: using data from load flow and short circuit study

The plug setting is 20% more than the load current

$$\text{PS} = \frac{410}{600} \times 100\% = 68\ \%$$

$$SM = \frac{9.2\ kA}{68\% \ \times 600} = 22.24$$

The TMS for the feeder is selected of minimum value equal to 0.05

Actual operation time (t) $= \frac{0.14}{(22.24)^{0.02}-1} \times 0.05 = 0.108$ sec

The setting of bus section relay (B.S R):

PS = 80 %

$$PSM = \frac{9.2\ kA}{80\% \ \times 1200} = 9.58$$

t = 0.108 + 0.2 = 0.308   relay operation time

$$TSM = \frac{0.308\ (9.58)^{0.02}-1}{0.14} = \ 0.1$$

In the same way, the setting for the other relays can be calculated as shown in Table 3

Table 3

Table 3 Relays Setting Parameter

Relay	PS %	PSM	TMS	Operation time t (sec)
F1 R	**68**	**22.5**	**0.05**	**0.108**
B.S R	80	9.58	0.1	0.308
INC1 R	77	9.95	0.17	0.508
TR1 feeder R	80	9.7	0.23	0.708

- **Relay Coordination by ETAP**

Overcurrent relays can be coordinated using the star view feature in ETAP. It provides a time-current curve for all relays in the system, allowing for a comprehensive view of the relay grading. With this tool, the relay curves can be adjusted and modified by dragging them, enabling easy modification of relay settings to achieve proper coordination.

The relay coordination process is facilitated by ETAP. Figure 3 depicts the star view of the relay grading, starting from the F1 R and progressing to TR1 feeder R. It is evident that all relays can function as primary or backup protection depending on the location of the fault.

The star view feature also includes the ability to provide the relay operation time and simulate circuit breaker (CB) operation sequences for various faults as shown in Table 4 and Figure 4 Two scenarios are considered: one with the bus section CB open and another with it closed. The calculated relay operating times closely align with those obtained from EATP simulations. In the same way, the setting and grading of the other feeder relays and the neighbouring section relays can be obtained.

Table 4

Table 4 Operation Time of Relays for Fault in Feeder1 Using ETAP

Relay	Operation time t (sec)
F1 R	0.113
B.S R	0.303
INC1 R	0.506
TR1	0.692
feeder R	

Figure 3

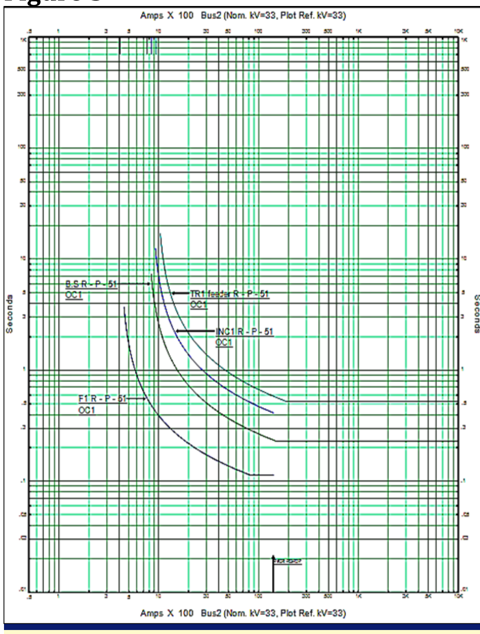

Figure 3 Relay Grading of Feeder1

Figure 4

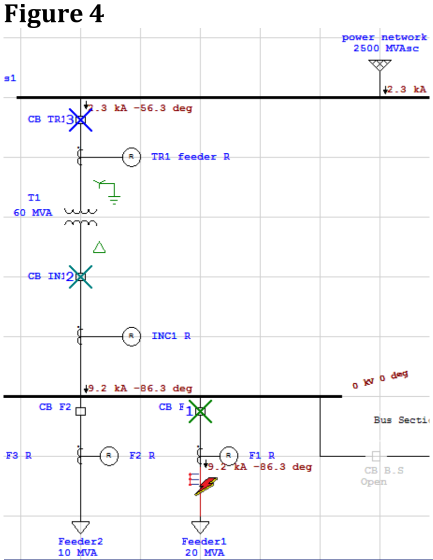

Figure 4 CB operating sequence for F1 fault, B.S CB open

Referring to the relay's operation time which has been presented in Tables 3 and 4, we can compare this result to show the effectiveness of using ETAP as an alternative to other coordination methods. Figure 5 shows that there is a negligible slight difference between manual calculation time and automated results. ETAP setting procedure will be applied to a more complex system to show its efficacy.

Figure 5

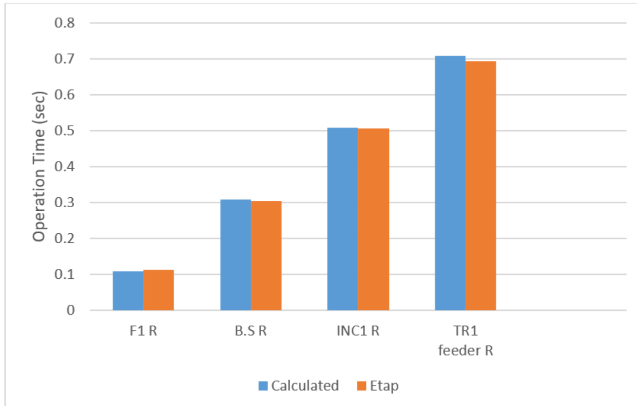

Figure 5 CB Operating Sequence for F1 Fault, B.S CB Closed

4) Multi-feed test system

The system in Figure 6 was used to apply the proposed automated relay setting through ETAP simulation. As the system has two feeding points the OC relays used are directional relays with two sets of forward (RF) and backward (RB) relays. The system is subjected to a cumulative load of 80 MVA with two infeed of 100 MVA generation and power grid supply. A load flow has been conducted through the simulation environment to specify the relay plug setting.

All relays have been coordinated using the star view feature of ETAP, Figures 8 and 9 show the relay operation curves for both RF and RB respectively.

Figure 6

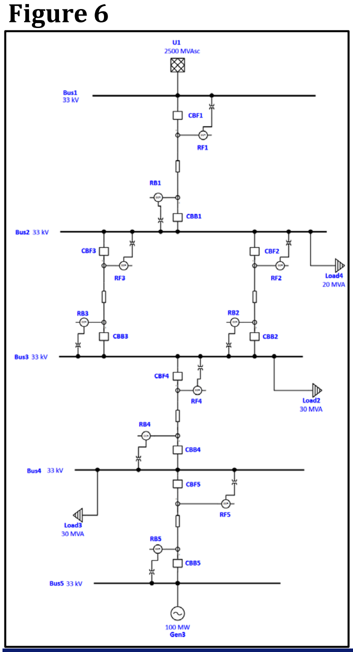

Figure 6 Multi-Feed Test System with Directional OC Relay

Figure 7

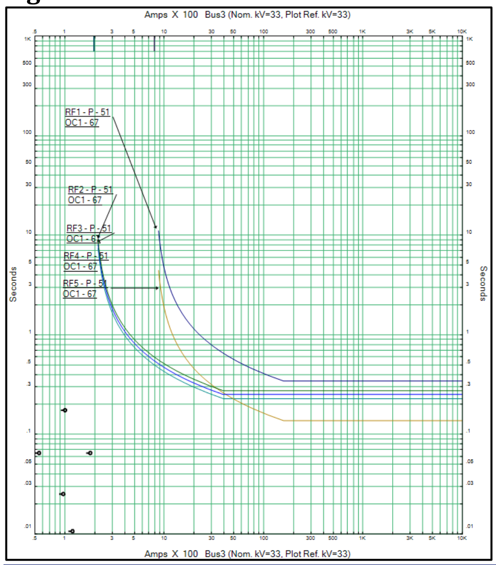

Figure 7 Relay Grading in the Forward Direction

Figure 8

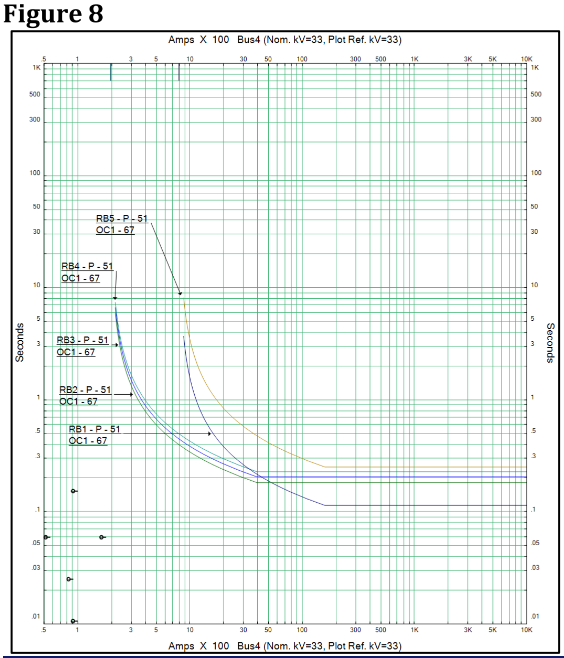

Figure 8 Relay Grading in the Backward Direction

Two scenarios were created to evaluate the proposed relay settings. In the first scenario, a fault was applied at bus 3 of the system, and the corresponding relay operation times are presented in Table 5 In the second scenario, a fault was applied at bus 4, with the relay operation times shown in Table 6

Table 5

Table 5 Operation Time of RF and RB Relays for Fault at Bus3 using ETAP

FAULT AT BUS 3			
FORWARD RELAYS (RF)	OPERATION TIME (msec)	BACKWORD RELAYS(RB)	OPERATION TIME (msec)
RF1	393	RB4	227
RF2	272	RB5	367
RF3	249		

Table 6

Table 6 Operation Time of Relays for Fault at Bus4 using ETAP

FAULT AT BUS 4			
FORWARD RELAYS (RF)	OPERATION TIME (msec)	BACKWORD RELAYS(RB)	OPERATION TIME (msec)
RF1	478	RB5	315
RF2	286		
RF3	262		
RF4	227		

According to the simulation results for both cases, the relays clear the fault effectively and in a short time. Therefore, the proposed method can be applied to a wide range of system configurations and will significantly improve relay coordination.

4. CONCLUSION

The coordination of overcurrent protection in power networks has become increasingly complex and time-consuming due to network expansion. The accurate grading of overcurrent relays is crucial for providing effective primary and backup protection and preventing unnecessary system tripping. ETAP offers a valuable solution with its virtual interaction relay coordination method using star-view. This feature allows for the comprehensive visualisation of all relays' time-current characteristic curves in a single diagram, facilitating the adjustment of relay TMS and PS through intuitive dragging of the curve to achieve optimal relay grading. This study focused specifically on the relay coordination of 33 kV feeders in a 132/33 kV substation. Load flow and short circuit analyses were conducted to acquire the necessary data for precise relay setting calculations. The coordination process involved a combination of manual analysis and the utilization of EATP software. The results demonstrated a high degree of agreement between the two methods, validating the effectiveness of the approach. Moving forward, the substation coordination methodology can be further enhanced to achieve faster relay operation times by harnessing the advantages offered by numerical relays with different setting groups. These advancements can lead to improved system reliability and enhanced protection against faults and abnormal conditions.

CONFLICT OF INTERESTS

None.

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