Overcurrent relays coordination: comparison characteristics standar inverse, very inverse and extremly inverse

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Abstract. This study discussed the coordination of working time of Over Current Relay (OCR) incoming and OCR feeders on a substation with a 60 MVA transformer, 150/20 kV which supplies 4 feeders. OCR working time coordination was done to compare the performance of OCR using 3 time characteristics: standard inverse (SI), very inverse (VI) and extremely inverse (EI). OCR feeder 1 (OCR F1) was chosen to coordinate work time with OCR incoming because feeder 1 (F1) is the longest (6.10 km) between the 4 feeders so that it has the largest impedance. Phase to phase short-circuit current was calculated at a distance of 0% (bus 20 kV), 1%, 25%, 50%, 75% and 100% length of feeder 1. The short-circuit current was used to calculate the time multiplier setting (tms) also working time (tOCR) OCR incoming and OCR feeder 1 with time characteristics SI, VI and EI. From the comparison analysis of OCR incoming and OCR feeder working time coordination, it was proven that the time characteristics of SI had the best performance by considering OCR feeder working speed and OCR incoming work speed as back up.

1. Introduction
Most of power outages are triggered by distribution circuit failure [1]. It is important to tackle and enhance customer reliability [2]. Overcurrent relays (OCR) are frequently utilized in the power feeder [3]. OCR can prevent over-current flow owing to short circuit, phases failures [4]. This can reduce system failure and to guarantee ongoing power delivery [5]. Overcurrent protection was created to minimize damage to transformer, circuit and helpful to operate the economic distribution system [6]. The basic protective function is fulfilled with the conditions of sensitivity, selectivity, reliability and speed [7].

It is a standard procedure of using more than one OCR in the distributed energy system whereby one acts as main protection function and the other as backed up protection [8]. Back-up protection should operate after the main protection. It should use to remove the defective component in the event of failure of main protection [9]. Protective relay layout must guarantee that relays can identify unusual or unwanted circumstances and then acts to disconnect the impacted area [10]. In order to guarantee continuity of electrical distribution, protection alignment between the relays is a significant element. Proper relay coordination often prevents excessive interruptions of the network [11].

Coordination of protection needs to analyze load flow and short circuit to protect the relay setting [12]. For precise relay configuration and implementation, the real knowledge of the fault current at each portion of the power scheme is required. Maximum short-circuit current, transformer impedance in p.u., single-line power scheme diagram, and highest peak load current [13] are essential information required for precise power system.

The trip time is inversely proportional to the fault currents and are described as normal inverse, very inverse and highly inverse by separate equations. Selecting overcurrent relay features usually begins
with selecting the right features to be used for each relay, accompanied by selecting the present relay settings [14,15].

To boost reliability, "backup" protection must be provided for "main" controls, which should only work if one of the main systems crashes. In this study, we are studying the comparison of time coordination between OCR incoming as back-up protection and OCR feeder 20 kV delivery system using distinctive normal inverse, very inverse and highly inverse in bus 20 kV and feeder range from bus 20 kV to fault position. Line-to-line faults are the 2nd most prevalent form [16]. Positive (Z1) and negative (Z2) impedance affect the value of phase-to-phase fault current.

This study discussed the coordination of incoming Over Current Relay (OCR incoming) work as a back up OCR feeder in a 20 kV primary distribution system. OCR work time coordination was done to compare the coordination performance of OCR incoming dan OCR feeder using 3 time characteristics : standard inverse (SI), very inversion (VI) and extremely inverse (EI). The purpose of this study is to get the best work time coordination of OCR incoming dan OCR feeder by comparing the use of time characteristics SI, VI and EI to protect the 20 kV primary distribution system from phase-phase short circuit.

2. Research Method
The applied method in this study is the calculation method. Calculations were performed on the longest feeder, feeder (F1), 6.10 km length, as a representative of four feeders (see figure 1) to get :

a. short circuit current value occurred in the 0% (in the bus bar 20 kV), 1%, 25%, 50%, 75% and 100% feeder length from the 20 kV bus towards the down stream feeder.
b. OCR incoming and OCR feeder 1 current settings.
c. compared coordination performance OCR incoming and OCR feeder 1 for the phase to phase fault current occurring at 0% (bus bar 20 kV), 1%, 25%, 50%, 75% and 100% feeder length using working time characteristics SI, VI and EI. The study will base on figure 1.

![Figure 1. OCR incoming and OCR feeder](image)

2.1. Phase to phase fault current calculation
Figure 1 showed a substation single line diagram with transformer 150/20 kV, 60 MVA, supplied feeders 1,2,3 and 4. The network MVA short circuit (MVA_sc) is 3481.422 MVA, both positive and
negative sequence impedance of feeder \((Z_1 = Z_2)\) is \(0.137 + j 0.396 / \text{km}\). Calculation of phase to phase short circuit current requires data of network impedance \((X_{S150kV})\), transformer impedance \((X_t)\) and feeder impedance \((X_f)\) at fault location. \((X_{S150kV})\) obtained from the calculation:

\[
X_{S150kV} = \frac{(kV)^2}{MVA_{hs}} = \frac{(150)^2}{3481.422} = 0.114 \Omega
\]

so from figure 2, the network impedance 20 kV \((X_{S20kV})\) is:

\[
X_{S20kV} = \frac{(kV20)^2}{(kV150)^2} \cdot X_s = \frac{20^2}{150^2} \cdot 6.463 = 0.114 \Omega
\]

Transformer impedance \((X_t)\) calculated by:

\[
X_t = \frac{(kV)^2}{MVA} \cdot Z_T = \frac{(20)^2}{60} \cdot 12.49\% = 0.832 \Omega
\]

The feeder impedance is influenced by the feeder length. The length was from the bus 20 kV to the fault in the feeder. The F1 feeder was chosen as representative of four feeder existing because the longest (6.10 km). Table 1 shows the calculation of the feeder impedance at a distance of 0% (bus bar 20 kV) and 1% of the length of the F1 feeder.

| % Length | Feeder impedance \((Z_1, Z_2)\) ohm |
|----------|-----------------------------------|
| 0        | 0                                 |
| 1        | 1 % x 6.10 x (0.137 + j 0.396) = 0.008 + j 0.024 |

The equivalent impedance in the fault location is calculated in series: \(Z_{1eq} = Z_{2eq} = X_s \text{ (20 kV)} + X_t + X_{F1} = j0.114 + j0.832 + X_{F1} = j 0.946 + X_{F1}\), so the number of impedances from the network to fault location 0% and 1% of feeder length 1 as in table 2.

| % Length | Equivalent Impedance \(Z_{1eq} (Z_{2eq})\) ohm |
|----------|-----------------------------------------------|
| 0        | j 0.946                                       |
| 1        | j 0.946 + (0.008 + j 0.024) = 0.008 + j 0.970 |

Phase to phase short circuit current \((I_{sc})\) in the feeder is affected by positive and negative sequence of equivalent impedance \((Z_{1eq} \text{ and } Z_{2eq})\) at fault location:

\[
I_{sc} = \frac{V}{Z_{1eq} + Z_{2eq}} = \frac{V}{2Z_{1eq}}
\]

; with \(V\) = phase to phase voltage.
Result calculation of short circuit current at a distance of 0%, 1%, 25%, 50%, 75% and 100% of feeder length 1 is shown in table 3.

| Feeder length (%) | Short circuit current |
|-------------------|-----------------------|
| 0                 | 10570.82              |
| 1                 | 10308.93              |
| 25                | 6393.75               |
| 50                | 4557.50               |
| 75                | 3535.60               |
| 100               | 2886.52               |

2.2. Current setting OCR incoming
The current transformer (CT) ratio used 2000/5 A is shown in figure 5. The current setting (I_{set}) of the OCR relay is 1.2 of the lowest nominal current (I_n) equipment installed. The lowest installed equipment is the transformer (1732.05 A). Selected 1.2 x I_n was intended for maximum load tolerance.

\[ I_{set} = 1.2 \times I_n = 1.2 \times 1732.05 = 2078.46 \text{ A} \] (primer side)

2.3. Current Setting OCR feeder
Feeder (outgoing) used CT ratio 400 / 1 A. The current setting (I_{set}) of the OCR relay is 1.2 of the lowest nominal current (I_n) equipment installed (CT) 400 A.

\[ I_{set} = 1.2 \times I_n = 1.2 \times 400 = 480 \text{ A} \] (primer side)

3. Result and Analysis
Based on the calculation results, the data of impedance and phase to phase short circuit current were used to compare the coordination of OCR incoming and OCR feeder working time characteristics SI, VI and EI.

Determination of time multiplier setting (T_{ms}) and working time (t_{OCR}) based on the short circuit current on 20 kV bus. The working time the characteristics of the Inverse Standard (SI), Very Invers (VI) and Extremely Inverse (EI) according to the calculation of T_{ms} and fault currents as follows:
Standar Invers:  
\[ T_{ms} = \frac{I_{f20}}{I_{set}}^{0.02} - 1 \cdot \text{to20} \quad (1) \]

Very Invers:  
\[ T_{ms} = \frac{I_{f20}}{I_{set}}^{13.5} - 1 \cdot \text{to20} \quad (3) \]

Extremely Invers:  
\[ T_{ms} = \left( \frac{I_{f20}}{I_{set}} \right)^2 - 1 \cdot \text{to20} \quad (5) \]

with:
- \( I_{f20} \): phase to phase fault current on feeder
- \( I_{set} \): OCR current setting
- \( \text{to20} \): OCR working time when fault on 20 kV bus

3.1. OCR working time coordination characteristic standard inverse
Calculation of \( T_{ms} \) and \( t_{OCR} \) OCR incoming and OCR feeder used equations (1) and (2).

3.1.1. \( T_{ms} \) OCR incoming. \( T_{ms} \) was variable for adjusting relay operation time. Before determining \( T_{ms} \), \( \text{to20} \) must be determined, in this case \( \text{to20} = 1 \) s. This value was chosen to give an opportunity for the OCR at Feeder to work first.

\[ T_{ms} = \frac{I_{f20}}{I_{set}}^{0.02} - 1 \cdot \text{to20} = \frac{10570.82}{2078.46}^{0.02} - 1 \cdot 1 = 0.236 \]

3.1.2. Working time OCR incoming
\[ t_{OCR} = \frac{0.14}{I_{set}}^{0.02} \cdot T_{ms} \]

\[ t_{OCR} = \frac{0.14}{I_{set}}^{0.02} \cdot \left( \frac{I_{f20}}{I_{set}} \right)^{0.02} - 1 \]

\[ t_{OCR} = \frac{0.14}{2078.46}^{0.02} \cdot \left( \frac{10570.82}{2078.46} \right)^{0.02} - 1 = 1.0 \, s \]

3.1.3. \( T_{ms} \) OCR feeder 1. OCR working time when fault on 20 kV bus be determined 0.5 so that the OCR feeder would not trip due to transformer inrush current.

\[ T_{ms} = \left( \frac{I_{set}}{I_{set}} \right)^{0.02} - 1 \cdot \text{to20} = \left( \frac{10570.82}{2078.46} \right)^{0.02} - 1 \cdot 0.5 \]
3.1.4. Setting of OCR feeder working time when fault current was 10570.82 A:

\[
t_{OCR} = \frac{0.14}{T_{ms}} \cdot \frac{I_{OCR}}{I_{set}} - 1 = \frac{0.14}{0.228} \cdot 0.228 = 0.5 \text{ s}
\]

Calculation with the same procedure was carried out for fault at a distance of 1%, 25%, 50%, 75% and 100% the feeder length using time characteristics of SI, VI, and EI. The results were tabulated in Table 4.

**Table 4. Work time of OCR incoming and OCR feeder 1 characteristic of SI, VI, and EI**

| Fault location (%) | Working time OCR incoming (s) | Working time OCR F1 (s) | Δt (s) |
|--------------------|-------------------------------|------------------------|--------|
| SI | VI | EI | SI | VI | EI | SI | VI | EI |
| 0 (bus 20 kV) | 1.00 | 1.00 | 1.00 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| 1 | 1.02 | 1.03 | 1.05 | 0.50 | 0.51 | 0.53 | 0.51 | 0.52 | 0.53 |
| 25 | 1.45 | 1.97 | 2.94 | 0.60 | 0.85 | 1.37 | 0.85 | 1.12 | 1.57 |
| 50 | 2.09 | 3.43 | 6.53 | 0.69 | 1.24 | 2.71 | 1.39 | 2.19 | 3.82 |
| 75 | 3.09 | 5.83 | 13.14 | 0.78 | 1.65 | 4.54 | 2.31 | 4.18 | 8.59 |
| 100 | 5.01 | 10.52 | 26.79 | 0.87 | 2.10 | 6.88 | 4.14 | 8.42 | 19.91 |

Table 4 showed that coordination of OCR with standard inverse (SI) characteristics better than very inverse (VI and extremely inverse (EI) time characteristics because:

a. able to work quickly protecting the distribution system from phase to phase short circuit current that occurs in the feeder in the time between 0.5 s.d. 0.87 seconds.

b. OCR incoming function as back up OCR feeder will operated between 0.5 - 4.14 seconds.

Figure 4 showed camparison the graphic working time OCR feeder 1 and OCR incoming as backed up for fault current along feeder 1.
4. Conclusion
Coordination of OCR with standard inverse (SI) characteristics better than very inverse (VI) and extremely inverse (EI) time characteristics because OCR feeder as main protection and OCR incoming as backed up able to work faster protecting the distribution system from phase to phase short circuit current that occurs in the feeder. The longer fault location, the longer working time OCR because smaller fault current.

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