Nigerian Research Journal of Engineering and Environmental Sciences 7(1) 2022 pp. 238-249
p ISSN: 2635-3342; e ISSN: 2635-3350

Nigerian Research Journal of Engineering and Environmental Sciences
Journal homepage: www.rjees.com

Original Research Article

Modeling and Simulation of a Coordinated Power System Protection using Overcurrent Relay

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http://doi.org/10.5281/zenodo.6725273

ARTICLE INFORMATION

Article history:
Received 16 Feb, 2022
Revised 06 Apr, 2022
Accepted 14 Apr, 2022
Available online 30 Jun, 2022

Keywords:
Device coordination
Overcurrent relay
Protection
Relay setting
Time-current curve

ABSTRACT

The efficient and reliable operation of a protection system cannot be overemphasized as any shortfall in such system has both huge financial implications and makes the station dangerous and unsafe. The data for the overcurrent relay coordination analysis used in this study was obtained from the Ohiya Umuahia 132/33 kV substation of the Transmission Company of Nigeria (TCN) while the electric transient analyzer program (ETAP) software was used for the analysis. Firstly, a three-phase (3-phase) short circuit test was conducted on the network at the 33 kV busbar. Then, a detailed sequence of operation of the station's overcurrent relays was done for standard inverse relay setting, very inverse relay setting and extremely inverse relay setting characteristics. Results showed that at t = 0 seconds a 3-phase fault of initial symmetrical current root mean square (RMS) of 3.049 kA, peak value of 7.746 kA and a steady state value of 2.615 kA was induced on the 33 kV busbar, which lasted till t = 0.2 seconds upon action of the circuit breaker. Also, results showed that the individual time current curve (TCC) for the three relays indicated a fault current of 7.746 kA which lasted for 3.57, 3.57 and 3.28 seconds on the network respectively. Effective device coordination of the 132/33 kV transmission station is an appropriate sequence of operation of its protective devices.

1. INTRODUCTION

The protection and control of substations and power grids is very essential and they involve selecting suitable actuation settings for different protective devices such as relays (Onah, 2012; Obi *et al.*, 2014). A typical power system such as 132/33 kV transmission substation comprises of numerous protective devices. These devices ought to be well coordinated to ensure that their vital and most essential functions are fulfilled along with the requirement of sensitivity, selectivity, reliability and speed (Weedy *et al*., 2012; Agbontaen and Idiagi 2021). In the process of choosing or setting these protective devices, a juxtaposition is made of the utilization times of all the devices in response to different levels of trip signals (for instance overcurrent). The objective is to design a selectively coordinated electrical power system such that the resulting forced power outage is only limited to the faulty portion of the network in the cause of fault clearing. Considering the above, the job of a protection engineer becomes tedious and rigorous as a new or revised coordination study is required whenever there is a change in the maximum short circuit current of a power station due to the introduction of large loads, replacement of existing equipment with larger equipment, or when fault shuts down a large portion of the power system, or when protective devices are upgraded (Mohammed and Alzuhairi, 2008). With the above challenges, it becomes imperative for computer models to be developed in other to reduce the time and energy spent in manually configuring these protective devices.

Over-current protection is considered as one of the preeminent and common protection schemes in power system as it can detect a sudden build-up of current magnitude that is considered as fault effect. However, the extent of the fault current is in direct relation to the impedance source and fault type. (Rehman, 2020). The impedance source depends on the amount of generating plants that are in operation at a particular point in time and varies occasionally. So, the set point for the difference of the extent of fault current from the typical current in addition to the time of operation of over-current protection can vary from fault to fault, and time to time. This has led protection engineers to think of other principles of power system protection (Schlabbach and Rofalski, 2008; Oza *et al*., 2010; Obi *et al*., 2021).

Overcurrent protection in power system network is carried out with the aid of overcurrent relays which are categorized as instantaneous over-current relays, inverse time over-current relays, definite time over-current relays, inverse definite minimum time (IDMT) over-current relays, very inverse over-current relays, and extremely inverse over-current relays. Among these types of relays, the ones with inverse time-current properties are mostly used in transmission and distribution systems. This is due to their relatively flat time-current properties which allow them to achieve a reasonable and meaningful fast operation over a wide range of short-circuit currents (Parmar, 2013; Sharaf *et al*., 2015; Hari and Daru, 2019; Pankaj *et al*., 2021). Overcurrent relay is a type of relay that operates or picks up when its current surpasses a set value. Overcurrent relays can be instantaneous, that is, with no intentional time delay. Overcurrent relays are the simplest of all relaying devices. Overcurrent relays are not inherently directional, i.e., measuring a current gives no indication of the current direction. One application of non-directional overcurrent relays is on radial distribution systems, where the direction of current flow is always known. In this application, the relays must coordinate with a variety of other types of devices, such as circuit reclosers and fuses (Wadhwa, 2012; Gupta, 2015).

Several researchers have investigated power system protection using overcurrent relays. Akhikpemelo *et al.* (2018) in a bid to minimize outages due to ineffective protective relay coordination, designed a MATLAB graphical user interface (GUI) model of overcurrent relay and used different characteristic equation to determine the various operating parameters of the overcurrent relays in various modes such as the extremely inverse, standard inverse and very inverse. The results of the research showed a proper coordination of the different overcurrent relay characteristics. A stable process operation of distributed generation was conducted by Tohid *et al.* (2018) with the aid of optimal coordination of double-inverse overcurrent relay. Ojaghi and Mohammadi (2018) used a clustering topology to minimize the number of various setting for adaptive relays coordination. Sulaiman *et al.* (2018) used the firefly algorithm to resolve the issue of directional overcurrent relay (DOCR) by taking some case studies of the IEEE standard bus system. Non-standard properties of overcurrent relay for maximum protection level and minimum operating time was presented by Hemmati and Mehrjerdi (2019). In the developed model, the initial relay setting is fixed on normal inverse (NI) curve, very inverse (VI) curve, and the third setting is IDMT type of MiCOM P123 overcurrent relay. Overcurrent protection of alternating current (AC) micro grids with the aid of mixed relays characteristic curves was presented by Alam (2019) by considering optimum settings of directional overcurrent relays (DOCRs). An innovative and a novel objective operation method for ideal coordination of overcurrent relays to boost micro grid earth fault protection scheme was discussed by El-Naily *et al.* (2019). In Alam *et al.* (2020), protection coordination strategy for directional overcurrent relays with view of change in network geology and on-load tap changer (OLTC) tap position was done. An ideal stability-aimed protection coordination of smart grid's directional overcurrent relays (DOCRs) established on an optimized tripping properties in double-inverse model was studied in the IEEE 33-bus test system.

The significant limitations of the reviewed literatures including both the numerical and metaheuristic methodologies, is the probability of converging to values which may not be a global optimum but, rather, are stuck at a local optimum. The literatures also failed to inspect the circuit breaker tripping sequence of operations and time value of fault currents. To unravel these issues, a real time transient analysis tool such as the ETAP is examined and used to model a real-life power system for onward simulation of its overcurrent relays in order to obtain the best relay settings for optimal coordination. This research therefore examines the coordination of the General Electric 650 overcurrent relays at Ohiya-Umuahia 132/33 kV transmission power substation for its characteristic settings of standard inverse, very inverse and extremely inverse settings. This is done in order to inspect the circuit breaker tripping sequence of operations and time value of fault current for the protection analysis of the substation. This is because of the physical layout of the substation switchyard which presents a radial arrangement for its outgoing 33 kV feeders. The Ohiya-Umuahia 132/33 kV transmission substation was chosen because of its relevance to power supply to Umuahia - the Abia state capital, Michael Okpara University of Agriculture, Umudike and environs.

2. MATERIALS AND METHODS

2.1. Materials

The following materials were used in the analysis: Data from Ohiya Umuahia 132/33 kV switch yard transmission substation, General Electric 650 relay data, ETAP 19.0 analysis software,

2.2. Methods

The method employed for the modeling and simulation of a coordinated power system protection using overcurrent relay (OCR) of Umuahia 132/33 kV substation is relay coordination and over-current protection analysis of the Umuahia 132/33 kV substation relays.

2.2.1. Inverse definite minimum time (IDMT) overcurrent relay equations

Inverse definite minimum time (IDMT) relay has inverse time characteristic, where the relay time of operation is oppositely symmetrical to the fault current (Tenaga, 2014). IDMT is influenced by the opposite symmetrical correlation between the relay time of operation and the current function. For overcurrent relay there are two adjustments which are plug setting and time dial setting. Plug setting dictates the current at which the relay will initiate operation while time dial setting controls the relay's disc movement.

This inverse time characteristic also can be shifted up or down by adjustment of the time-dial setting (TDS) whereby using the appropriate TDS settings, the grading of protection network system can be achieved where the range of TDS is normally from 0.1 to 1.0. The current or time tripping properties of IDMT relays can be differed with respect to the tripping period required and the properties of other protection devices used in the network. A number of standard relay characteristics are as follows: standard inverse (SI), very inverse (VI), and extremely inverse (EI).

Plug setting multiplier (PSM): This refers to how hazardous the fault is and in what time period it should be cleared. It is the ratio of the fault current in the relay to its pick up current is as shown in Equation (1).

$$PSM = \frac{\text{Fault current in relay Coil}}{I_{(pick\ up\ current)}} \tag{1}$$

$$PSM = \frac{\text{Fault current in relay coil}}{\text{Rated CT secondary current} \times \text{current setting}} \tag{2}$$

Plug setting for each relay is determined by the fault current (Almas *et al*., 2012). In accordance with ANSI/IEEE standard, the properties of IDMT relays are represented in Equation (3).

$$t = \frac{C}{(\frac{I}{Is})^{\alpha} - 1} \times TMS + L \tag{3}$$

Where CT is the current transformer, t is the relay operation time (tripping time) in secs, C is a constant for relay characteristic, Is is the relay pick-up current setting, I is the fault (actual) secondary CT current (A), α is a constant representing inverse time type (α> 0), TMS is time multiplier setting.

Standard inverse relay (SIR): These are relays whose working time is nearly inversely symmetrical to the fault current near the pick-up value and becomes noticeably constant a bit above the relay pick-up value. The properties of SIR are represented in Equation (4) (Akhikpemelo *et al.,* 2018).

$$t_{SIR} = \frac{0.0515}{(\frac{I}{Is})^{0.02} - 1} \times TMS + 0.114 \tag{4}$$

Very inverse relay (VIR): The very inverse relay types are applied in feeders and lengthy sub transmission lines protection. The relay time current properties is inverse over a remarkable range of time and it moves to definite time at the end of saturation. It is notably productive with ground faults because of its stiff properties. This is represented in Equation (5).

$$t_{VIR} = \frac{19.61}{(\frac{I}{Is})^{2.0} - 1} \times TMS + 0.491 \tag{5}$$

Extremely inverse relay (EIR): The relay operating time of these type is roughly inversely proportional to the current square. It is often applied when fault current depends on fault point. The properties of EIR are shown in Equation (6).

$$t_{EIR} = \frac{28.2}{(\frac{I}{Is})^{2.0} - 1} \times TMS + 0.1217 \tag{6}$$

By using appropriate TMS settings, the grading of a protection network system can be achieved.

2.2.2. Data for the analysis

The single line diagram for the Ohiya 132/33 kV transmission substation under study is shown in Figure 1. The substation comprises of two T-off 33 kV busbar with twenty-two (22) multifunction and overcurrent relays connected to their respective circuit breakers, thereby transmitting power to the five (5) feeders covering Umuahia and environs in Abia State.

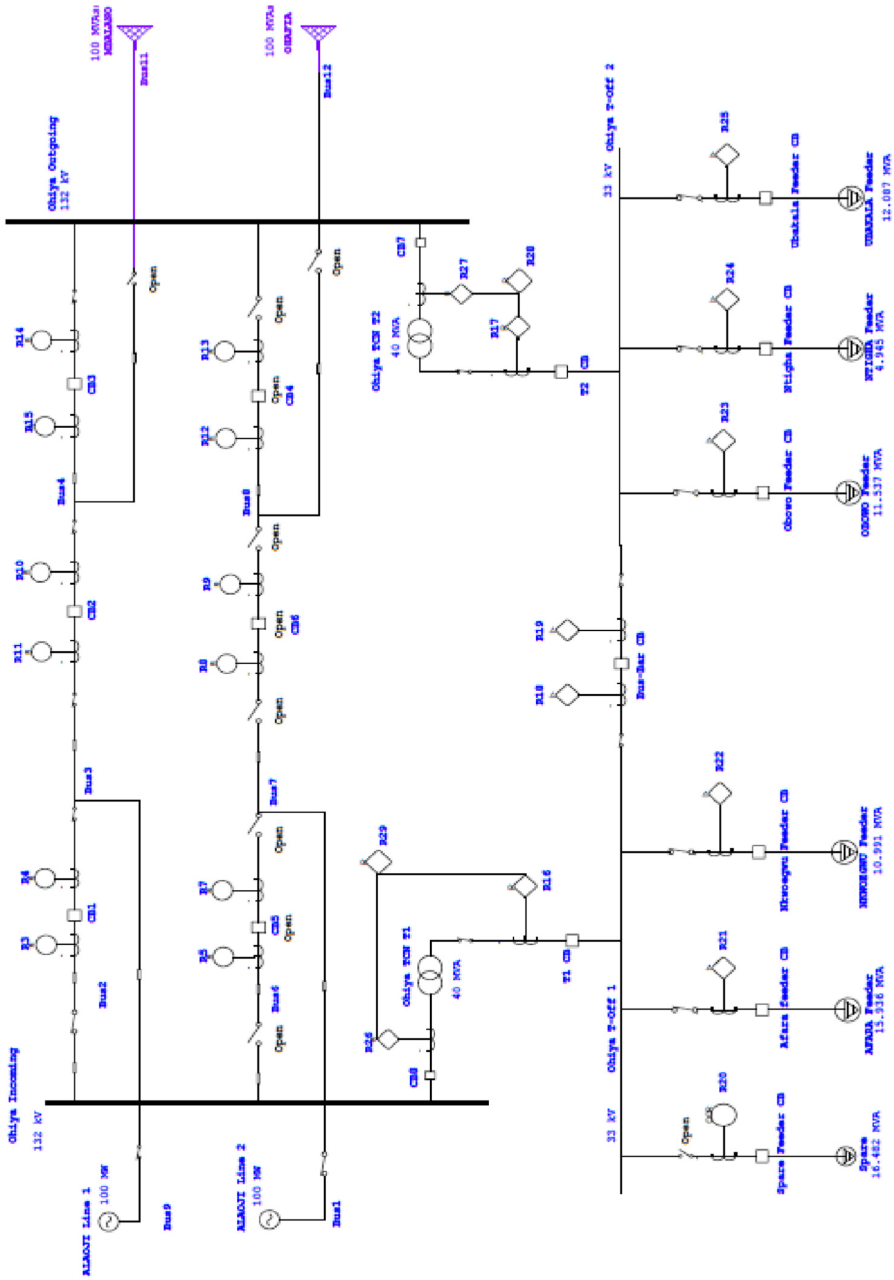

Figure 1: Single line diagram of Ohiya 132/33 kV sub-station

3. RESULTS AND DISCUSSION

3.1. Results of Three Phase Short Circuit Analysis

Table 1 shows the RMS values of the initial symmetrical current, the peak current and the RMS values of the steady state current of a three-phase short circuit fault on 33 kV bus side of the network. Proper relay coordination in any electrical power installation can be achieved by first determining the maximum possible short circuit current in the installation. At t = 0 seconds, fault was introduced on the 33 kV busbar, a 3-phase fault of initial symmetrical current RMS of 3.049 kA, peak value of 7.746 kA and a steady state value of 2.615 kA was obtained and the waveforms for the three-phases A, B and C are shown in Figure 2. It shows the transient three phase short circuit waveforms form t = 0 to t = 0.2 seconds when the circuit breakers T1 CB and busbar CB in Figure 1 act. The overall maximum 3- phase short circuit current of 7.711 kA was obtained when fault was introduced at the 33 kV bus feeder. Thus, this value which is the highest in the station becomes the short circuit current of the station, from which the protective relays are set.

Table 1: Three-phase short circuit fault results at different locations.

Fault location	33 kV bus 3-phase
Initial symmetrical current (kA, RMS)	3.049
Peak current (kA)	7.746
Steady state current (kA, RMS)	2.615

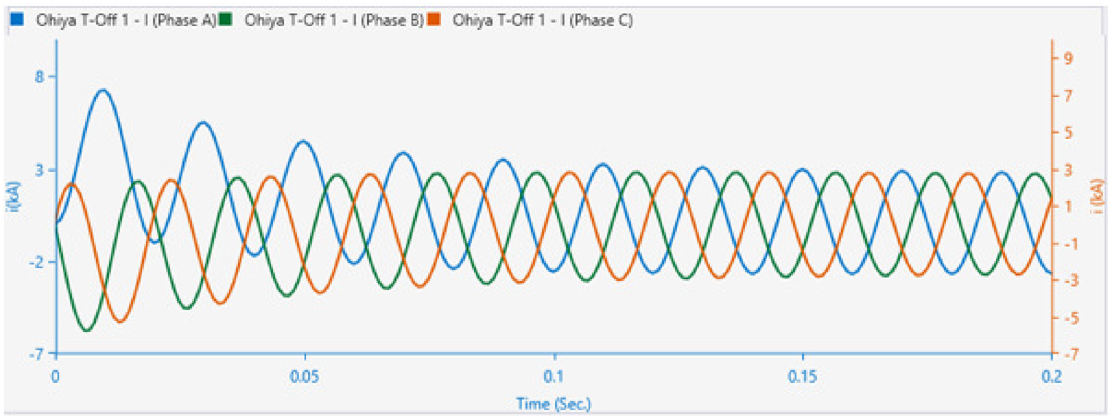

Figure 2: Three phase short circuit fault on 33 kV busbar

3.2. Results for Relay Coordination Operation for Fault on 33 kV Busbar

The model diagram of relay coordination operation is shown in Figure 3 for a three-phase symmetrical fault incident on 33 kV bus with standard inverse relay characteristics. This shows a one-line diagram of the sub-station's protective system, in which a fault is incident on the 33 kV T-off busbar and the circuit breakers sequence of opening are shown and marked as 1, 2 and 3 in the Figure.

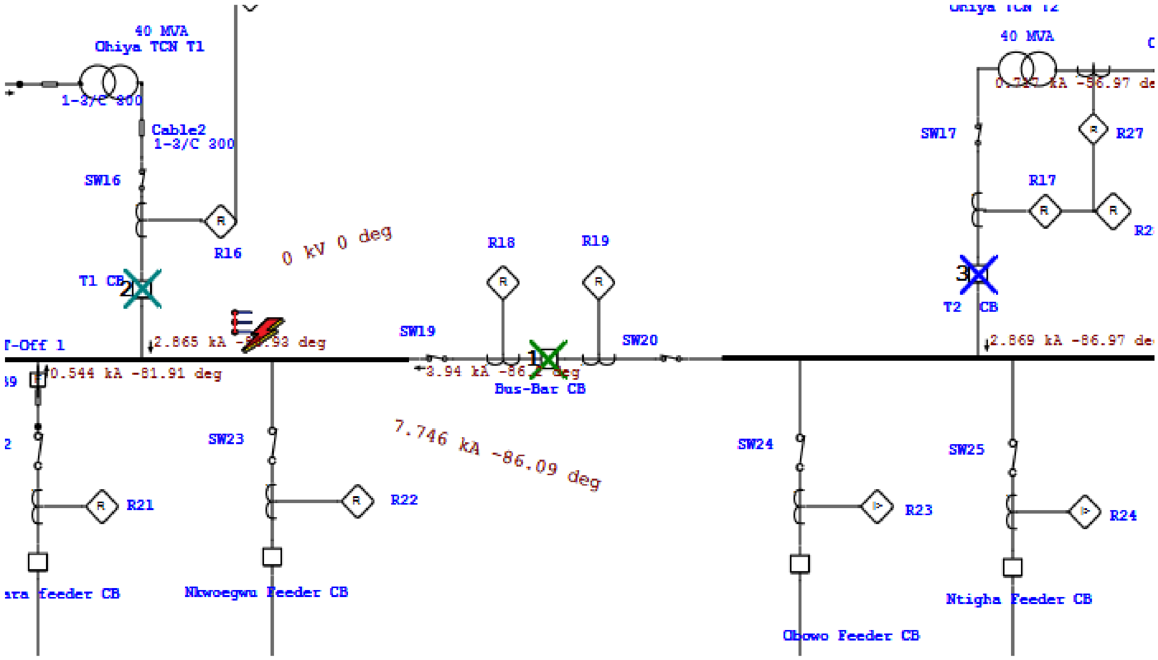

Figure 3: Relay coordination for fault on 33 kV bus

3.2.1. Standard inverse setting

Table 2 shows the sequence of operation of relays R16, R17, R18 and R19 shown in Figure 3 for a three-phase symmetrical fault incident on 33 kV bus with standard inverse relay characteristics. Relay R18 sees a fault current of 3.941 kA in 0.010 seconds and then triggers the busbar circuit breaker to trip on instantaneous overcurrent (OC1-50) in 0.31 seconds.

Table 2: Sequence-of-operation event summary report for standard inverse setting

Time (ms)	ID	Symmetrical 3-phase fault at Ohiya T-Off 1	
		If (kA)	Condition
10.0	R18	3.941	Phase - OC1 – 50
78.1	R16	2.865	Overload Phase – Thermal
78.1	R17	2.869	Overload Phase – Thermal
287	R19	3.941	Phase - OC1 – 51
310	Busbar CB		Tripped by R18 Phase - OC1 – 50
378	T1 CB		Tripped by R16 Overload Phase – Thermal
378	T2 CB		Tripped by R17 Overload Phase – Thermal
587	Busbar CB		Tripped by R19 Phase - OC1 – 51
2324	R17	2.869	Phase - OC1 – 51
2332	R16	2.865	Phase - OC1 – 51
2624	T2 CB		Tripped by R17 Phase - OC1 – 51
2632	T1 CB		Tripped by R16 Phase - OC1 – 51

At the same instance, relays R16 and R17 see a fault current of 2.865 kA and 2.869 kA respectively in 0.078 seconds and trip T1 and T2 secondary CBs on instantaneous over current (OC1-50) in 0.378 seconds. The R19 standard inverse characteristic (OC1-51) time of operation was found to be 0.287 seconds for a fault current of 3.941 kA which then trips the busbar circuit breaker in 0.587 seconds. Also, the R17 standard inverse characteristic (OC1-51) time of operation was found to be 2.324 seconds for a fault current of 2.869 kA which then trips the T2 circuit breaker in 2.624 seconds. Similarly, the R16 standard inverse characteristic (OC1-51) time of operation was found to be 2.332 seconds for a reduced fault current of 2.865 kA which then trips the T1 circuit breaker in 2.632 seconds. The time current curve (TCC) in Figure 4 shows the standard setting relay curve for relays R16, R17, R18 and R19 indicating the time at which the three-phase fault value of 1.0 pu (7.746 kA) cuts the relay curve and lasts for 3.57 seconds on the network.

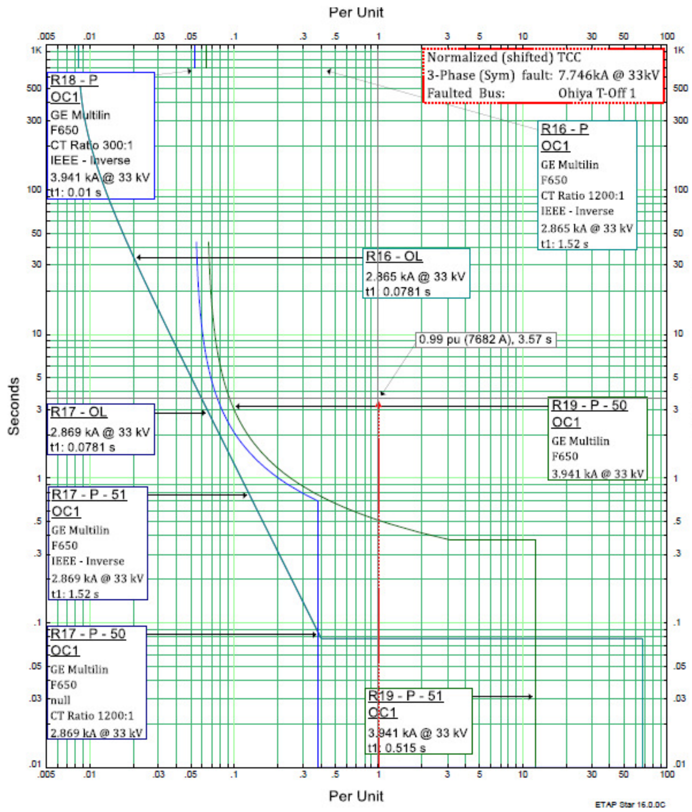

Figure 4: TCC curve of relay 16, 17, 18 and 19 for standard inverse setting

3.2.2. Very inverse setting

Table 3 shows the sequence of operation of relays R16, R17, R18 and R19 for a three-phase symmetrical fault incident on 33 kV bus with very inverse relay characteristics. Relay R18 sees a fault current of 3.941 kA in 0.010 seconds and then triggers the busbar circuit breaker to trip on instantaneous overcurrent (OC1-50) in 0.31 seconds. At the same instance, relay R16 and R17 see a fault current of 2.865 kA and 2.869 kA respectively in 0.078 seconds and trip T1 and T2 secondary CBs on instantaneous over current (OC1-50) in 0.378 seconds. The R19 very inverse characteristic (OC1-51) time of operation was found to be 0.287 seconds for a fault current of 3.941 kA which then trips the busbar circuit breaker in 0.587 seconds. Also, the R17 very inverse characteristic (OC1-51) time of operation was found to be 2.324 seconds for a fault current of 2.869 kA which then trips the T2 circuit breaker in 2.624 seconds. Similarly, the R16 very inverse characteristic (OC1-51) time of operation was found to be 2.332 seconds for a reduced fault current of 2.865 kA which then trips the T1 circuit breaker in 2.632 seconds. The time current curve (TCC) in Figure 5 shows the standard setting relay curve for relays R16, R17, R18 and R19 indicating the time at which the three-phase fault of 1.0 pu (7.746 kA) cuts the relay curve and last for 3.57 seconds on the network.

Table 3: Sequence-of-operation event summary report for very inverse setting

Time (ms)	ID	Symmetrical 3-phase fault at Ohiya T-Off 1	
		If (kA)	Condition
10.0	R18	3.941	Phase - OC1 – 50
78.1	R16	2.865	Overload Phase – Thermal
78.1	R17	2.869	Overload Phase – Thermal
287	R19	3.941	Phase - OC1 – 51
310	Busbar CB		Tripped by R18 Phase - OC1 – 50
378	T1 CB		Tripped by R16 Overload Phase – Thermal
378	T2 CB		Tripped by R17 Overload Phase – Thermal
587	Busbar CB		Tripped by R19 Phase - OC1 – 51
2324	R17	2.869	Phase - OC1 – 51
2332	R16	2.865	Phase - OC1 – 51
2624	T2 CB		Tripped by R17 Phase - OC1 – 51
2632	T1 CB		Tripped by R16 Phase - OC1 – 51

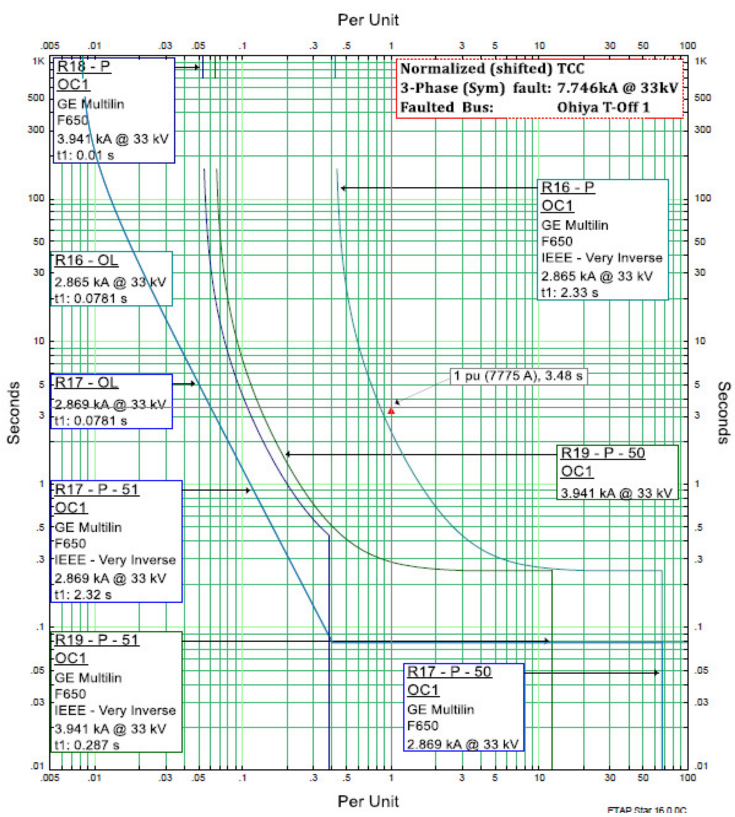

Figure 5: TCC curve of relay 16, 17, 18 and 19 for very inverse setting

3.2.3. Extremely inverse setting

Table 4 shows the sequence of operation of relays R16, R17, R18 and R19 for a three-phase symmetrical fault incident on 33 kV bus with extremely inverse relay characteristics. Relay R18 sees a fault current of

3.941 kA in 0.010 seconds and then triggers the busbar circuit breaker to trip on instantaneous overcurrent (OC1-50) in 0.31 seconds.

Table 4: Sequence-of-operation event summary report for extremely inverse setting

Time (ms)	ID	Symmetrical 3-phase fault at Ohiya T-Off 1	
		If (kA)	Condition
10.0	R18	3.941	Phase - OC1 – 50
78.1	R16	2.865	Overload Phase – Thermal
78.1	R17	2.869	Overload Phase – Thermal
120	R19	3.941	Phase - OC1 – 51
310	Busbar CB		Tripped by R18 Phase - OC1 – 50
378	T1 CB		Tripped by R16 Overload Phase – Thermal
378	T2 CB		Tripped by R17 Overload Phase – Thermal
420	Busbar CB		Tripped by R19 Phase - OC1 – 51
3050	R17	2.869	Phase - OC1 – 51
3062	R16	2.865	Phase - OC1 – 51
3350	T2 CB		Tripped by R17 Phase - OC1 – 51
3362	T1 CB		Tripped by R16 Phase - OC1 – 51

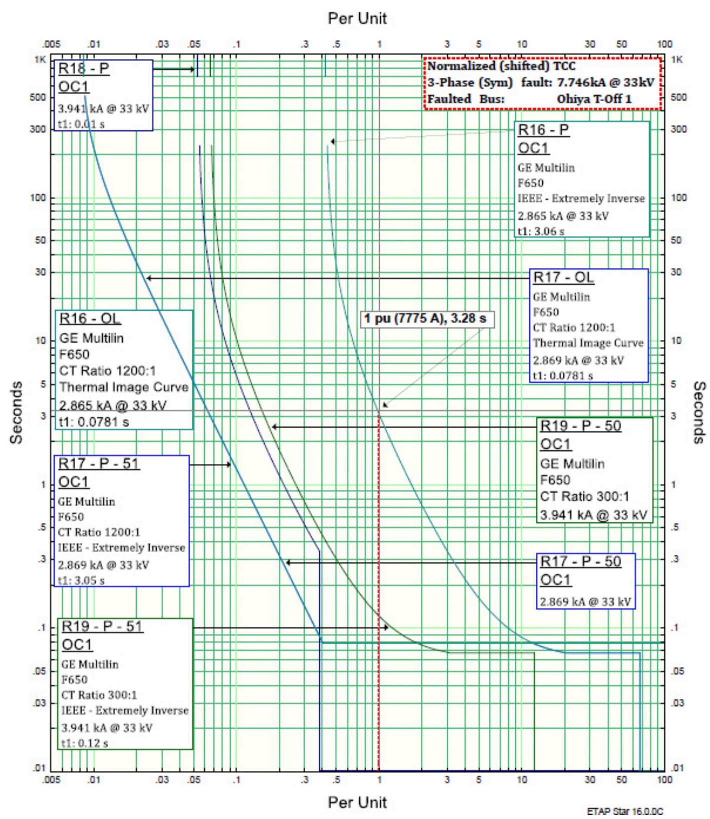

Figure 6: TCC curve of relay 16, 17, 18 and 19 for extremely inverse setting

At the same instance, relays R16 and R17 see a fault current of 2.865 kA and 2.869 kA respectively in 0.078 seconds and trip T1 and T2 secondary CB on instantaneous over current (OC1-50) in 0.378 seconds respectively. The R19 extremely inverse characteristic (OC1-51) time of operation was found to be 0.12 seconds for a fault current of 3.941 kA which then trips the busbar circuit breaker in 0.42 seconds. Also, the R17 extremely inverse characteristic (OC1-51) time of operation was found to be 3.050 seconds for a fault current of 2.869 kA which then trips the T2 circuit breaker in 3.350 seconds. Similarly, the R16 extremely inverse characteristic (OC1-51) time of operation was found to be 3.062 seconds for a reduced fault current of 2.865 kA which then trips the T1 circuit breaker in 3.362 seconds. The time current curve (TCC) in Figure 6 shows the extremely inverse setting relay curves for R16, R17, R18 and R19 indicating the time at which the three-phase fault value of 1.0 pu (7.746 kA) cuts the relay curve and last for 3.28 seconds on the network.

4. CONCLUSION

A typical 132/33 kV transmission substation is an expensive infrastructure as it is the interface between transmission and distribution sector in the Nigerian electricity industry. In this paper, a short circuit current study was conducted at the Ohiya-Umuahia 132/33 kV transmission substation by introducing a three-phase fault at the 33 kV bus section which indicated maximum short circuit current value of 7.746 kA. The simulations produced the sequence of operations of the over current relays at the 33 kV busbar faulted locations. Three relay characteristics, namely standard (normal) inverse, very inverse and extreme inverse were analyzed. The results indicate that for the standard inverse and very inverse relay characteristics, the sequence of operation were 10.0 ms for a three phase fault current of 3.941 kA, 78.1 ms for a three phase fault current of 2.895 kA and 2.869 kA and 287 ms for a three phase fault current of 3.941 kA for relays R18, R16, R17, and R19 respectively. For the extremely inverse relay characteristics, the sequence of operation were 10.0 ms for a three phase fault current of 3.941 kA, 78.1 ms for a three phase fault current of 2.865 kA and 2.869 kA and 120 ms for a three phase fault current of 3.941 kA for relays R18, R16, R17, and R19 respectively. From these results, the sequence of operation of the overcurrent relays are in coordinate and during the sub-station's protection coordination analysis selectivity was not lost in course of sensitivity.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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