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PERFORMANCE EVALUATION OF OVERCURRENT RELAY IN A DISTRIBUTION SUBSTATION FOR IMPROVED PROTECTION AND COORDINATION

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Abstract: *The paper examined Overcurrent relay protection and coordination in the Igwuruta distribution system. As power system infrastructure advances in size and complexity, fault current level also increases in the system due to an increase in load demand, and increasing network interconnections. In order to mitigate the fault current level to the barest minimum, and also ensure un-interruption in the power supply it is pertinent to ensure the protection scheme is designed in such a way that the protective relays are properly coordinated to provide both primary and backup protection that can isolate any faulty section and prevent it from escalating in the distribution system. A properly coordinated scheme should ensure the protective device close to the point of fault operates first during fault occurrence and if it fails due to variation in operating time, the backup protection scheme operates to isolate the fault. The network was modeled and simulated in Electrical Transient Analyzer Program ETAP 19.01 Software using over current relay 51 which is one of the most commonly used protection. The result obtained from base case simulation shows that the sequence of operation was not in order as circuit breakers upstream from the point of fault tripped first during a fault in the following sequence CB4: 92ms, CB5: 100ms, CB1: 365ms and CB3: 392ms. However, after fine-tuning the relay setting using the TCC curve, the order of tripping followed sequentially and there was proper backup protection in the following sequence CB1: 92ms, CB3: 100ms, CB4: 365ms, and CB5: 392ms.*

Keywords: Relay, Circuit Breaker, CT Ratio, Fault Current, Distribution System, ETAP

1.0 Introduction

Every distribution system network requires the protection of equipment and it should be designed in such a way that the protective relays isolate the faulted portion of the network. The simplest type of protective device that is suitable is Overcurrent Relays because of its characteristics, setting up and the pick-up values for individual relays is easy. However, the problem arises when each relay has to be coordinated with the other relays in the system (Magnus, 2013).

Relay coordination is a means by which a relay nearest the fault point operates first and if it fails to operate the backup relay operates in sequence to provide backup protection. For a relay coordination study, every series relay from the load upstream to the power supply must be chosen or established (Serge, 2014).

The power system in recent times, has advanced in terms of size and complexity. Hence, the need for a protection scheme that can monitor and control the system efficiently to ensure an un-interruption in the power supply becomes inevitable. However, there is an ambiguity in the proper coordination of the protective scheme with respect to fault isolation in the distribution system which ultimately leads to loss of power supply. Secondly, there have been several reported cases of electrocution that were brought to the public notice which is a clear indication that the distribution system in Nigeria has a protective relay coordination challenge. For the purpose of clarity, a properly coordinated scheme ensures the protective device close to the point of fault operates first during fault occurrence and if the nearest protective device fails due to variation in operating time, the backup protection scheme operates to prevent the fault from escalating in the distribution system which depicts the opposite in this study. In this paper, the performance of the overcurrent relay is optimized in a bid to provide effective relay coordination for proper fault isolation in a distribution system (Ahmed *et al.*,2013)

To achieve the aim of the study, the following objectives were considered.

i. Modeling of the existing distribution system in Electrical Transient Analyzer Program (ETAP 19.01) software.
ii. Performing load flow analysis to determine the steady state condition of the existing distribution system
iii. Performing star protection and coordination analysis to identify the sequence of relay coordination in the existing distribution system.
iv. Performing short circuit analysis to determine the size of protective devices such as circuit breakers, relays, and current transformers.
v. Re-coordinating the relay protection system chosen a satisfied relay parameter from the TCC curve.

2.0 Literature Review

According to Jayesh & Prajapati (2014), the relays in the power system must be properly coordinated in order to offer both main and backup protection while also preventing failure that could cause unnecessary interruption of the healthy section. With backup protection and adequate coordination, the system will be highly protected.

Hima (2015), any power system network protection should be designed so that protective relays isolate the faulted portion of the network as soon as possible. This will help to prevent damage to the equipment and injuries to the operators, as well as to ensure that there is minimal system disruption so that the healthy portion of the network can continue to receive service. When primary relays fail, backup relays come on after a certain amount of discrimination. The protective relay should be able to distinguish between normal, abnormal, and fault circumstances, according to the paper (Serge, 2014).

Relays and circuit breakers make up an essential fault-clearing mechanism which consists of an operating coil of the circuit breaker, sensors, wire, relay, and auxiliary power supply that make up the relay protection system. At first, relays with electromechanical mechanisms were used to detect faults in an automated fault-clearing system. When a certain limit had been surpassed, the observed quantity, such as a voltage or current, was converted into the force of motion that actuated the relay. Solid-state relays were created after the invention of semiconductors like transistors and operational amplifiers. By using circuit design, the properties of these relays were put into practice. Modern relays currently are mostly numerical relays (Ahmed *et al.*,2013).

According to a report from the National Electric Power Authority basic protection course P1 training and development program manual (NEPA) (2017), Relay coordination is an essential component of the entire system's protection and is required to:

i. Disconnect the unsafe circuit or equipment from the rest of the system.
ii. Prohibit the normally functioning circuits or equipment next to the faulty circuits or equipment from tripping up.
iii. Avoid unintentional tripping of various functioning circuits or equipment anywhere in the network when a fault arises there.
iv. When a malfunctioning circuit or piece of equipment isn't fixed by its own protective system, it secures the adjacent healthy circuits and equipment.

2.1 Fault in an Electrical System

Faults in an electrical system generally arise from the failure of the insulating medium involving a live-carrying conductor and the earth. The insulation breakdown could be brought on by any of the following: mechanical damage, overheating, voltage spikes due to lightning, intrusion of a conducting medium, ionization of the air, or improper use of the device. If not promptly cleared, fault currents can unleash a tremendous amount of heat that can lead to an electrical fire, severe equipment damage, and electrocution of humans (*Chowdhury et al*., 2019).

2.1.1 Types of Electrical Faults

Faults are classified into two major groups:

i. Symmetrical fault: is a three-phase fault. The fault results in an extremely intense electrical current that is capable of causing an electrical fire.
ii. Un-symmetrical faults: are single line-to-ground faults, double line-to-ground faults, and double line faults.

2.2 Essential Qualities of Protection

Prerequisite requirements for a protective system to isolate a faulty section.

i. Selectivity
ii. Speed of operation
iii. Discrimination

2.2.1 Selectivity

The state of the system allows for the isolation of just the unhealthy part while leaving the other, healthy parts unharmed. Selectivity is relative if it is produced by grading the configuration of protection from various zones that may respond to a specific fault contrary to being absolute if the protection exclusively responds to faults inside its own zone. Unit systems are protective measures that are, in theory, completely selective. Non-unit systems are those whose selectivity is relative (Mohamed, 2016).

2.2.2 Fastness of Operation

A number of factors necessitate a quick response from protective relays:

i. It is best not to go beyond the critical clearance time.
ii. Electrical equipment may sustain damage if it is designed to handle fault currents for an extended period of time.
iii. A prolonged fault will cause a voltage drop, which is capable of prompting industrial drives to overload and crawl.

2.2.3 Discrimination

Protection must be sensitive enough to function consistently under minimal abnormal conditions for a fault inside the zone it protects while maintaining stability under full load, meaning a relay must be able to differentiate between a fault and an overload. When it comes to transformers, the inrush of magnetizing current—which is 5 to 7 times the full load current—may be likened to the entire current. Inrush current shouldn't cause the relay to operate (Chowdhury et al., 2019).

2.3 Coordination of Protective Devices

The coordination assessment of an electrical power system entails a systematic time-current analysis of each device connected from the utility to end-users. In this study, the operating times of several protective devices under various conditions of either typical or unusual current flow are compared (Serge, 2014).

2.3.1 Methods of Coordination

There are a number of Protection relay coordination techniques designed to reduce the impact caused by system irregularities on the system directly. They are;

i. The table's coordination.

ii. the use of the device's characteristic curve

iii. the use of the device time curve

3.0 Materials and Methods

The data used for this study was collected from Port Harcourt Electricity Distribution Company. Table 1 below shows the data used for the study.

Table 1: Data Obtained from PHEDc

S/no	Parameter	Rating
1	Length of line	9.5km
2	Transformer Size	15MVA
3	load on feeder 1	3.96MVA
4	load on feeder 2	5.4MVA
5	Conductor type	AAC
6	Conductor size	150mm²
7	Cable size	240mm²
8	System type	3-phase AC
9	CTRs	600/5, 1200/5
10	CTRs	300/5 600/1
11	Relay type	Over current

Source: PHEDC

3.1 Method Adopted

3.1.1 Load Flow Analysis: was used to determine the steady state operating condition of the network. The Newton Raphson technique was used to run load flow simulation in ETAP19.01 software environment.

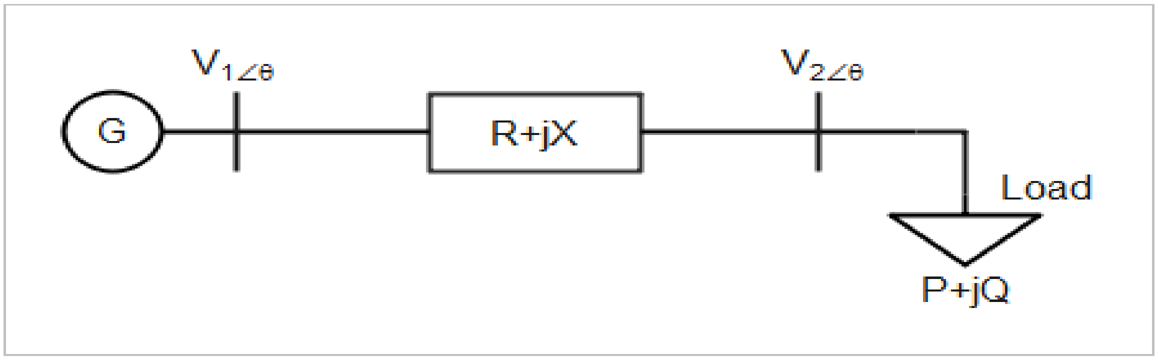

Figure 1: One Line diagram of a two-bus system

Figure1 shows a 2-bus system which consists of a load fed from a source via a transmission line. For any ith bus, the real and reactive power injected in the network is given by

$$S_i = V_i I_i^* = P_i + jQ_i \quad (1)$$

$$I_i = \left(\frac{S_i}{V_i}\right)^* = \frac{P_i - jQ_i}{V_i^*} \quad (2)$$

$$I_i = \frac{P_i - jQ_i}{V_i^*} = \sum_{k=1}^{n} Y_{ik} V_k \quad (3)$$

$$P_i - jQ_i = V_i^* \left(\sum_{k=1}^{n} Y_{ik} V_k\right) \quad (4)$$

$$P_i - jQ_i = V_i^* \left(\sum_{k=1}^{n} Y_{ik} V_k \angle \delta_k + \theta_{ik} - \delta_i\right) \quad (5)$$

$$P_i - jQ_i = \sum_{k=1}^{n} |Y_{ik}||V_i||V_k| \left[\cos(\delta_k + \theta_{ik} - \delta_i) + j\sin(\delta_k + \theta_{ik} - \delta_i)\right] \quad (6)$$

Separating (6) into real and imaginary parts we have,

$$P_i = \sum_{k=1}^{n} |Y_{ik}||V_i||V_k| \cos(\delta_k + \theta_{ik} - \delta_i) \quad (7)$$

$$Q_i = -\sum_{k=1}^{n} |Y_{ik}||V_i||V_k| \sin(\delta_k + \theta_{ik} - \delta_i) \quad (8)$$

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_3 \\ J_2 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \quad (9)$$

Where

J_1,J_2,J_3&J_4 : are element of Jacobian matrix

3.1.2 Short circuit analysis: Impedance method was used to the short circuit impedance value of the grid and transformer upstream from the point of fault.

I. Short circuit impedance of the grid

$$\boldsymbol{Z_r = \frac{U^2}{S_{sc}}} \quad (10)$$

Where

U: phase to phase before point of fault in kV

S_{sc}: short circuit power in MVA

II. Short circuit impedance of transformer

$$\boldsymbol{Z_{tsc} = \frac{U^2}{S_{t1}} * \%Z_t} \quad (11)$$

Where

U: phase to phase before point of fault in kV

S_{t1}: Transformer rating in MVA

Z_{t1}: Transformer impedance in %

III. Total Short Circuit Impedance

$$\boldsymbol{Z_{sc} = Z_r + Z_{tsc}} \qquad (12)$$

IV. Short Circuit Current in kA

$$\boldsymbol{I_{sc}} = \frac{\boldsymbol{U}}{\sqrt{\boldsymbol{3}} * \boldsymbol{Z_{sc}}} * 10^{-3} \qquad (13)$$

Where

U: phase to phase before point of fault in kV

Z_{sc}: Total short circuit impedance

V. Circuit Breaker Making Capacity

$$Making\ capacity = 2.5 * I_{sc} \qquad (14)$$

3.1.3 CT Sizing

I. CT Operating current ($\boldsymbol{I_L}$)

The operating current ($\boldsymbol{I_L}$) of the CT is given by

$$\boldsymbol{I_L} = \frac{\boldsymbol{S}}{\sqrt{\boldsymbol{3}} * \boldsymbol{U}} \qquad (15)$$

Where

U: phase to phase in kV

S: Transformer rating in MVA

II. Rated CT Primary Current

$$\boldsymbol{I_{pr} = 1.2 * I_L} \qquad (16)$$

Where

U: phase to phase in kV

S: MVA rating of protected equipment

III. CT Ratio

$$\boldsymbol{CT\ ratio} = \frac{\boldsymbol{I_{pr}}}{\boldsymbol{I_{sr}}} \qquad (17)$$

Where

Ipr: CT rated primary current selected from the nearest value in market

Isr: CT rated secondary current which is 5A for local use and 1A for remote use

3.1.4 Relay Sizing

I. Operating Current (IL)

The operating current ($\boldsymbol{I_L}$) of the relay is given by

$$\boldsymbol{I_L} = \frac{\boldsymbol{S}}{\sqrt{\boldsymbol{3}} * \boldsymbol{U}} \qquad (18)$$

Where

U: phase to phase in kV
S: MVA rating of protected equipment

II. Relay Current Setting

Current setting of a relay is set at 120% of the operating current (IL) which is giving by

$$I_{setting} = 1.2 * I_L \qquad (19)$$

III. Relay Pickup Current (Ipu)

$$I_{pu} = \frac{Relay\ Current\ setting}{CT\ ratio} \qquad (20)$$

IV. Fault in Relay Primary Coil

$$Fault\ in\ Relay\ coil\ = \frac{Short\ Circit\ Fault\ Current\ (kA)}{CT\ ratio} \qquad (21)$$

V. Plug Setting Multiplier (PSM)

$$PSM = \frac{Fault\ in\ Relay\ Coil}{Pickup\ Current} \qquad (22)$$

VI. Relay Time Dial Multiplier

$$TDM = \frac{T}{\left[\frac{A}{(PMS)^{p}-1} + B\right]} \qquad (23)$$

Where
T: operating Time
PMS: plug setting multiplier
A=19.61, B=0.491, P=2 from IEEE very inverse operating curve shown in Table 2 below.

Table 2: IEC/IEEE Operating Curve

Standard	Operating Curve	A	B	C
IEC	Moderately inverse	0.14	0.02	0
	Very inverse	13.5	1	0
	Extremely Inverse	80	2	0
IEEE	Moderately inverse	0.0515	0.02	0.1140
	Very inverse	19.61	2	0.491
	Extremely Inverse	28.2	2	0.1217

4.0 Result and Discussion

The result obtained from simulation of the Igwuruta distribution system in ETAP 19.01 software environment was presented in two scenarios.

Case1: A three-phase fault was simulated on 11kV outgoing feeder in the existing network.

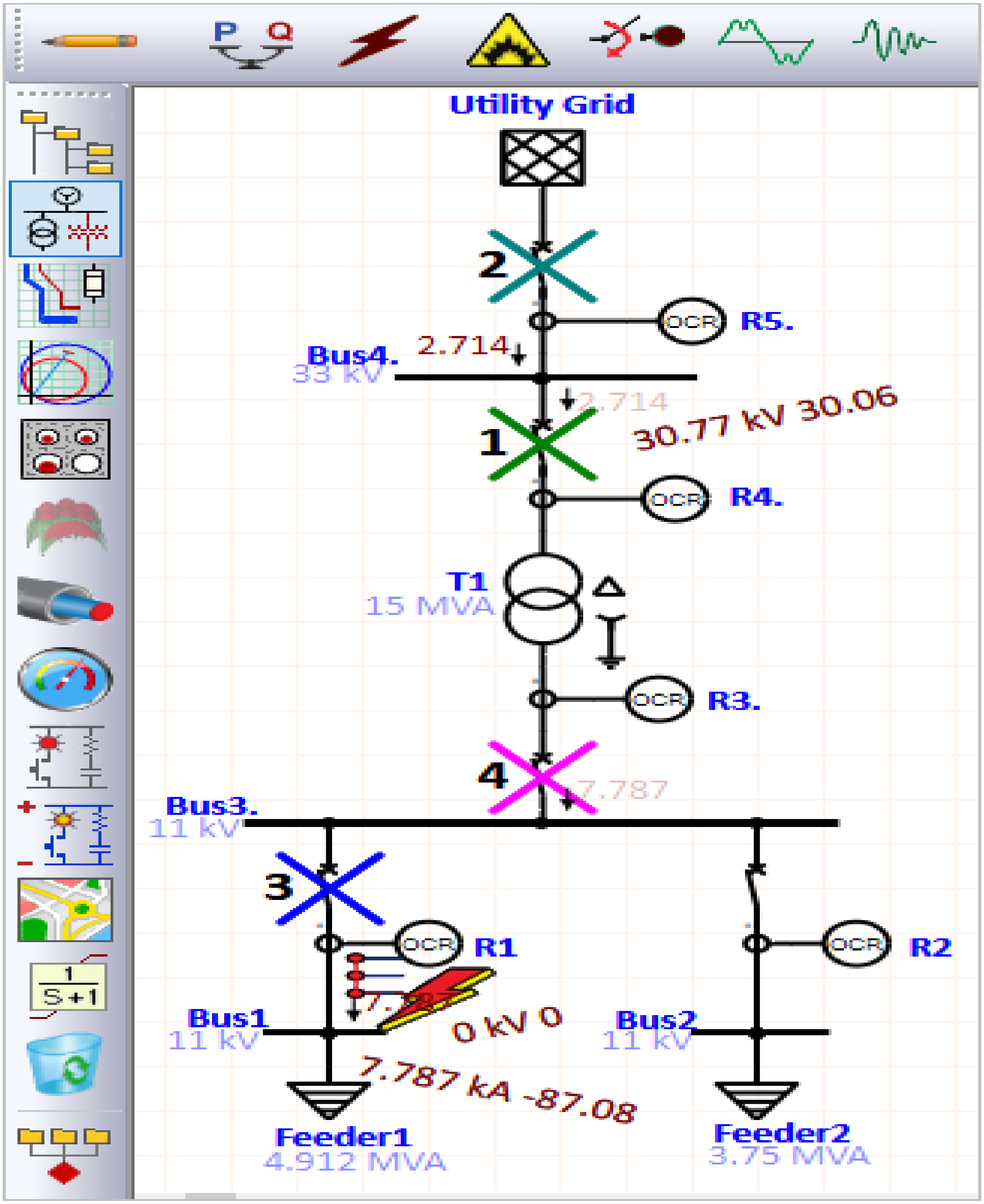

Figure2: Relay Sequence Operation for Existing Network

Figure 2 above shows the sequence of operation for three-phase fault on bus1 11kV outgoing feeder. The sequence of operation was violated due to miscoordination of the protection relay. A quick look at Figure 2 shows that the

Circuit breakers (CB4) followed by (CB5) upstream from the point of fault on the primary side of T1A tripped before (CB1) which is closer to the fault location and the backup (CB3). It would be difficult to locate the point of fault quickly. In a properly coordinated scheme, the protective device close to the point of fault operate first during fault occurrence and if the nearest protective device fails due to variation in operating time, the backup protection scheme operates to prevent the fault from escalating in the distribution system. case1 is not true backup protection. Table 3 shows the order of operation and tripped time for the existing case.

Table 3: Coordination with Fault on Bus 1

Protective Device	Tripped by	Tripped Sequence	Tripped Time (ms)
CB4	OCR 4	1	92
CB5	OCR 5	2	100
CB1	OCR 1	3	365
CB3	OCR 3	4	392

Case2: A three-phase fault was simulated on 11kV outgoing feeder in the improved network.

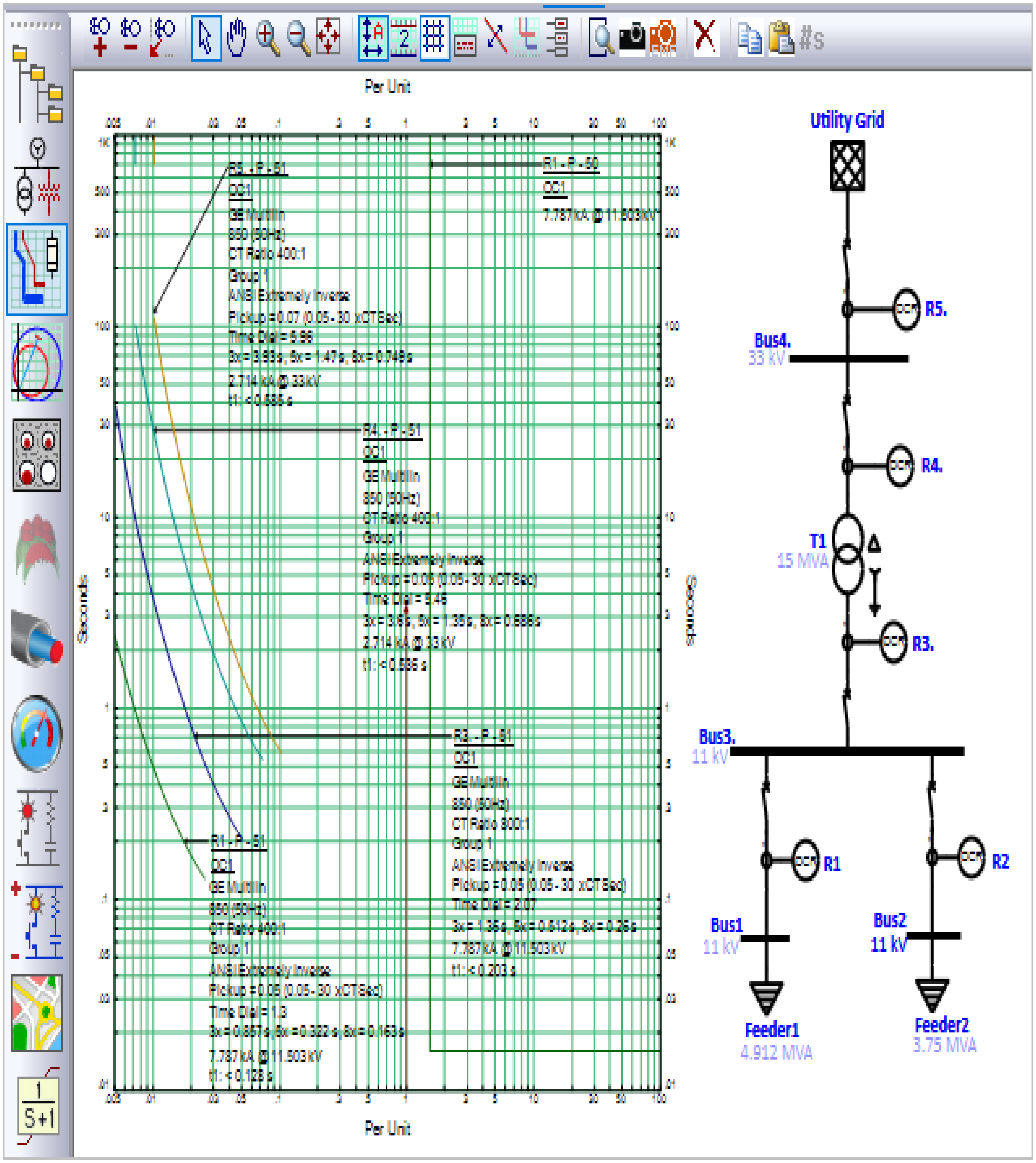

Figure3: TCC Curve of Protective Device

Figure 3 shows the time current curve (TCC) plot of protective device in distribution network. The curve is important in achieving proper protection coordination among the protection devices in the network as it shows graphically the response of the device to various levels of overcurrent. The TCC curve in figure 3 shows the protective devices on the distribution system and was used to fine tune the relay settings for properly coordination of the protective devices.

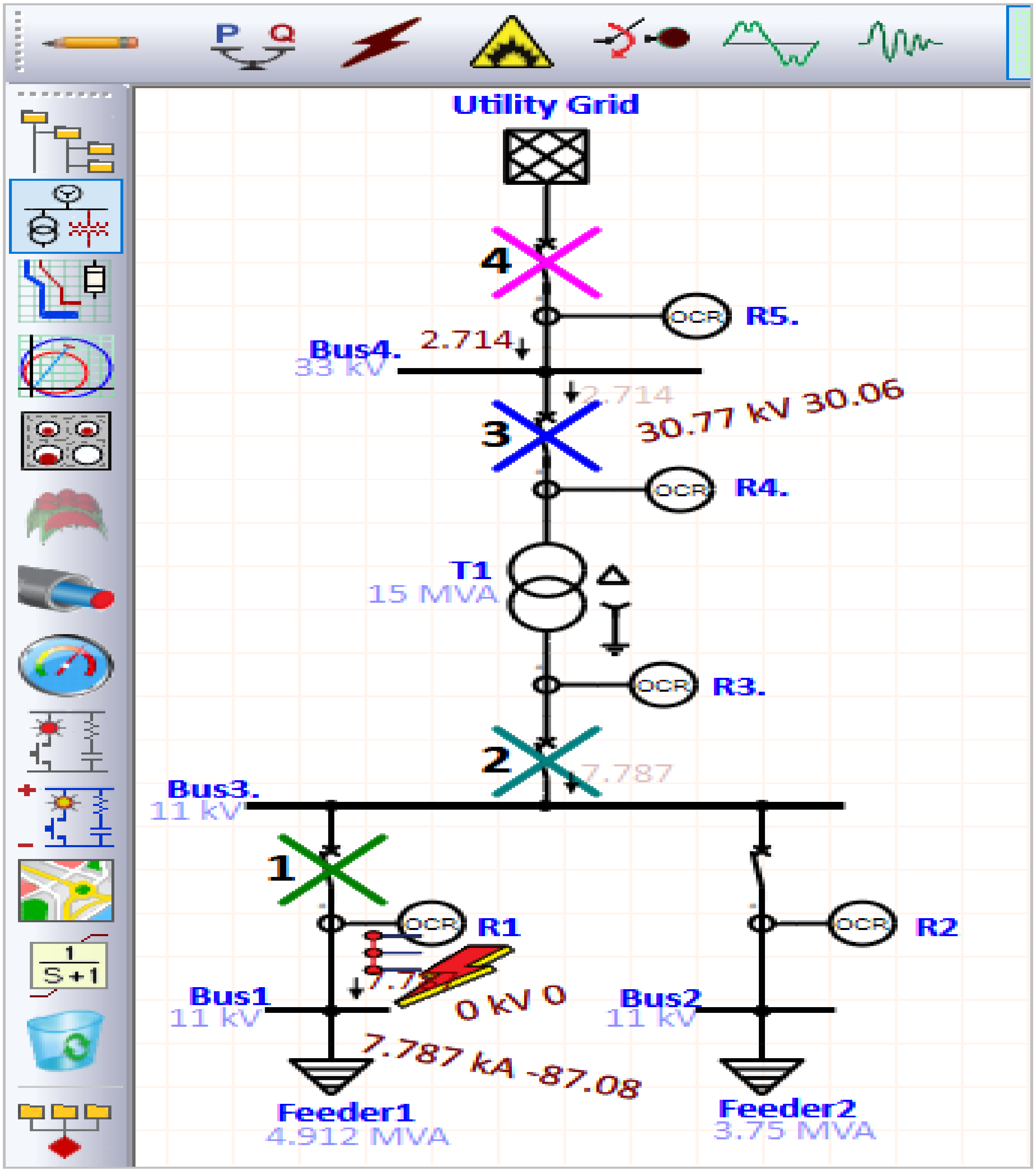

Figure3: Relay Sequence Operation for Improved Network

Figure 4 shows the sequence of operation for three-phase fault on bus1 11kV outgoing feeder. The protective device settings are fine-tuned on the TCC curve and sequence of operation in order for proper coordination. A quick look at Figure 4 shows that the Circuit breakers (CB1) which is closer to the fault location tripped first followed by (CB3), then (CB4) and lastly (CB5) upstream on the primary side of transformer T1. The order of tripping followed sequentially and there was proper backup protection. Table 4 shows the order of operation and tripped time for the improve case.

Table 4: Coordination with Fault on Bus 1

Protective Device	Tripped by	Tripped Sequence	Tripped Time (ms)
CB1	OCR 1	1	82
CB3	OCR 3	2	98
CB4	OCR 4	3	125
CB5	OCR 5	4	207

5.0 Conclusion

This study analyzes the performance of overcurrent relay in a distribution substation for improved protection and coordination during fault on the distribution system. when the primary protection fails, backup protection must intervene to isolate the fault, and if the backup protection fails, the fault may likely transcend to end-users either damage equipment's or electrocute personals. From the above conclusions the following are recommended:

a) Power network system planning stages should include faults analysis and coordination studies for protection.

b) To determine load growth, routine tests, and system functionality should be assessed every five years.

c) Depending on how crucial the electrical grid network is, 100% necessary resiliency should be offered.

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