



Fault Diagnosis Algorithm and Protection of Electric Power Systems in an Alternative Distribution System

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Abstract

In any power systems, protective devices will detect fault conditions and operate circuit breakers in order to disconnect the load from the fault current and limit loss of service due to failure. This fault may involve one or more phases and the ground, or may occur between two or more phases in a three-phase systems. In ground, fault' or 'earth fault, current flows into the earth. In a poly-phase system, a fault may affect each of the three phases equally which is a symmetrical fault. If only some phases are affected, the resulting 'asymmetrical fault' becomes more complicated to analyze due to the simplifying assumption of equal current magnitude in all the phases being no longer applicable. Therefore, the prospective short circuit current of the fault can be calculated for power systems analysis procedures. This will assist in the choice of protective devices like circuit breakers, current transformers and relays. This research work evaluated and analyzed the occurrence of faults in a distribution system. Fault currents were obtained and the maximum tripping time required for the protective devices to operate were determined. Hence, it was possible to select appropriate relay and circuit breaker for effective operation of a distribution system before the occurrence of faults and in the events of faults.

Introduction

Fault is said to occur on a power system when abnormally high current flows due to the partial or complete failure of insulation or electrical components at one or more points. The complete failure is called a short circuit. Weedy et al (2012), Carlos (2011) faults in electric power system can be categorized under several sub headings including *symmetric or balanced fault* affect each of the three phases equally. In transmission lines, the occurrences of faults are symmetric. This is in contrast to an asymmetric fault, where the three phases are not affected equally. In practice, most faults in power system are asymmetric (unbalanced). *An asymmetric or unbalanced fault* does not affect each of the three phases equally. Common types of asymmetric faults and their causes are as follows:

Line – to Line, Line – to – Ground, Double Lines – to – Ground

Earth or Ground Faults, in three phase systems, is a fault that may involve one or more phases and ground. This type of fault is known as earth or ground fault where current flows into the earth. *Transient fault* is a fault that is no longer present if power is disconnected for a short time. Many faults in overhead power lines are transient in nature. At the occurrence of this type of fault, power system protection operates to isolate area of fault. A transient fault will then be

cleared and the power line can be returned to service immediately. *Persistent fault* does not disappear when power is disconnected. Faults in underground power cables are often persistent. Underground power lines are not affected by trees or lightning. So, faults, when they occur, are probably due to damages. In such cases, if the line is reconnected, it is likely to be only further damaged. It is therefore better if such faults are traced and repairing crew mobilized to the point of fault for repair operations.

Fault Current and Impedance of the Distribution Line

Lerkervi and Holmes (1997) define electrical fault as an unfavorable event which usually leads to discontinuation of supply of electricity to final consumers in a particular area. Fault causes most power quality and reliability problems (Deshmukh et al, 2013; Azam et al, 2004; De Almeida, 2003). It can also lead to the damage of equipment, burning and destruction of life and properties (Schneider, 2011; Bernstein, 1991; Parise & Parise, 2013). Fault current calculation is a sensitive aspect of electrical design for electrical distribution systems in commercial and industrial installations. The value of fault current obtained determines the highest available current at a given point of fault along a distribution or transmission line (Noe & Steurer, 2007; Ekici, 2012).

In this research work, fault currents in the events of faults were determined, the maximum allowable tripping time for the protective device to trip off were also determined. Hence, over-current protection equipment such as instrument transformers, relays, circuit breakers and fuses can then be selected. If a breaker or fuse is not rated to handle the maximum available fault current it might receive, it may not operate normally; its internal parts could even melt or fuse together. Hence, the device may blow up under such destructive fault condition. This will lead to serious injury, and destruction of life and properties. This is the reason why the relay chosen for each protection system must be selected in accordance with the minimum and maximum values of fault current expected. Also, the relay must sense the fault, compare the fault current within the shortest possible time and initiate a trip or disconnection which will make the circuit breaker to open or close the system based on relay and auto re-closer command.

Resistance of Lagos Road Feeder

The length of each of the sections was obtained as shown below

$$L = S * 50$$

Where S = number of span, 50 = Average length span

DC Resistance $(R_t)_{DC}$ per km of any line at temperature $t = 40.5^\circ\text{C}$ can be obtained using below Equation

$$(R_t)_{DC} = (R_{ref})_{DC} * \frac{t + 288}{t_{ref} + 288}$$

Where $(R_{ref})_{DC}$ = DC Resistance of the line per km at a reference temperature $t_{ref} = 20^\circ\text{C}$

$(R_t)_{DC}$ = DC Resistance of the line at 40.5°C , $t = 40^\circ\text{C}$, $t_{ref} = 20^\circ\text{C}$

The DC Resistance of the line per km at a reference temperature $t_{ref} = 20^\circ\text{C}$ as stated by the manufacturer is $0.27018 \Omega / \text{km}$. The AC Resistance $R_{t(AC)} / \text{km}$ of the line was obtained from below equation

$$R_{t(AC)} / \text{km} = (R_t)_{DC} * 1.05$$

Where $R_{t(AC)} / \text{km}$ = AC Resistance of the line /km at 40°C and $(R_t)_{DC}$ = DC Resistance of the line at 40°C . 1.05 is the factor used to multiply the DC resistance in order to obtain the AC resistance. It represents the addition resistance due to skin effects.

The DC resistance of the line at $40^\circ\text{C} = (R_{40^\circ\text{C}})_{DC} / \text{km}$

$$\begin{aligned}
(R_{40}^0C)_{DC}/km &= (R_{20})_{DC} * \frac{t + 288}{t_{ref} + 288} \\
(R_{40})_{DC}/km &= 0.27018 * \frac{40 + 288}{20 + 288} \\
(R_{40})_{DC}/km &= 0.27018 * \frac{328.5}{308} \\
(R_{40})_{DC}/km &= 0.288163 \\
(R_{40})_{AC}/km &= 0.288163 * 1.05 \\
(R_{40})_{AC}/km &= 0.288163 * 1.05 = 0.3025709
\end{aligned}$$

Hence, the resistance of the line per kilometer = 0.3025709 ohm.

Inductance of Lagos Road Feeder

The inductance of conductors per phase per meter can be obtained from below equation

$$= L_o = 10^{-7} * \left\{ 0.5 + 2 \log_e \frac{D_{eq}}{r} \right\}$$

$$\text{Where } D_{eq} = \sqrt[3]{D_{ab} * D_{bc} * D_{ca}}$$

and r = Radius of the 100mm² Aluminium conductor

Radius of the 100mm² Aluminum conductor = r

$$r = 0.00559m$$

The distances between the pairs of conductors are $D_{ab} = 0.658$, $D_{bc} = 0.658$, and $D_{ca} = 1.316$.

The equivalent distance of the conductor D_{eq} is given by

$$\begin{aligned}
D_{eq} &= \sqrt[3]{D_{ab} * D_{bc} * D_{ca}} \\
D_{eq} &= \sqrt[3]{0.658 * 0.658 * 1.316} \\
D_{eq} &= \sqrt[3]{0.5697806} \\
D_{eq} &= 0.82902803 \text{ meter}
\end{aligned}$$

Inductance/phase/meter of the lines were obtained as follows:

$$\begin{aligned}
L_o &= 10^{-7} * \left\{ 0.5 + 2 \log_e \frac{D_{eq}}{r} \right\} \\
L_o &= 10^{-7} * \left\{ 0.5 + 2 \log_e \frac{0.82908}{0.00559} \right\} \\
L_o &= 10^{-7} * \{ 0.5 + 2 \log_e 148.31485 \} \\
L_o/\text{phase/meter} &= 0.0010312 \text{ Henry}
\end{aligned}$$

These values were obtained by calculation. Microsoft excel algorithm was used to analyze the results.

$$\begin{aligned}
\text{Reactance of Lagos Road Feeder/phase/kilometer} &= 2\pi f L_o \\
&= 0.32400525 \text{ ohm}
\end{aligned}$$

$$\text{Resistance of Lagos Road Feeder/ phase/kilometer} = 0.302570893 \text{ ohm}$$

Impedance of the Lagos Road Feeder

$$\text{Impedance of the Lagos Road Feeder} = R + jX_L$$

$$\text{The impedance } Z, \text{ of Lagos Road feeder/kilometer} = 0.302570893 + j0.32400525$$

$$\text{Therefore impedance } Z \text{ per kilometer} = 0.443 \text{ ohm}$$

The incessant electric power supply problems facing the existence of industries in Nigeria is a pointer to the fact that there is great need for fault evaluation and protection of power system in the country. In view of this, a traditional analytical method is developed to access the occurrence of faults and outages along each of the individual consumer point in a feeder, as well as optimizes the performances of the generation, transmission and distribution system. In view of this, it will be possible to clear faults, ensuring adequate protection of the distribution system that is, bringing a steady uninterrupted power supply to consumers. The present study investigates the evaluation of the occurrence of faults on distribution lines, estimates fault currents along a distribution line, determines the maximum tripping time required for the protective devices to operate and establishes a method for selecting appropriate relay and circuit breaker for effective operation of a distribution system before the occurrence of faults and in the events of faults

Methods

The study area is the 132/33 kV, 2 X 60MVA Secondary Transmission Sub Station located in Ikorodu, Lagos State, Nigeria. The power distribution system in the area consists of the 132kV power transmission line grid which has been stepped down via two 132/33 kV, 60 MVA power transformers. The 33kV feeders were used to feed some factories and other industrial loads, while the 33 kV sub-transmission lines were further stepped down through (4) four 33/11kV, 15MVA transformers for distribution through the following 11kV feeders, as shown in fig.1.1 to 1.3. The lagos road feeder includes Ayangburen feeder, Ijebu Ode feeder, Eyita feeder, Igbogbo feeder, Ladega feeder, Agric feeder, Isawo feeder, and Oriokuta feeder. The per unit impedance (MVA_{base}), fault current (I_f), (KV) $_{base}$, (VA) fault, per unit reactance (X_{pu}) are related as shown in the equations below:

$$\begin{aligned} Z_{pu} &= \frac{Z_{(ohms)} \times \text{base MVA}}{\text{base KV}^2} && \text{for single phase} \\ Z_{pu} &= \frac{Z_{(ohms)} \times \text{base MVA}}{\sqrt{3} \cdot (\text{KV})^2 \cdot \text{base}} && \text{for three phase} \\ I_f &= \frac{1 / Z_{pu} \times \text{base MVA}}{\text{base (KV)}} && \text{for single phase} \\ I_f &= \frac{1 / Z_{pu} \times \text{MVA}_{base}}{\sqrt{3} \cdot (\text{KV}) \cdot \text{base}} && \text{for three phase} \\ X_{pu} &= \frac{X_{(ohms)} \times (\text{MVA})_{base}}{(\text{KV})_{base}} && \text{for single phase} \\ X_{pu} &= \frac{X_{(ohms)} \times (\text{MVA})_{base}}{\sqrt{3} \cdot (\text{KV})^2 \cdot \text{base}} && \text{for three phase} \end{aligned}$$

Results and Discussion

Analysis and Calculations of Fault Currents

Fault currents were estimated based on the data collected from Ikorodu Electricity Distribution Network along 11KV Lagos Road and other feeders. From these data, calculations and analysis were made and fault currents along the distribution line were obtained. From the results obtained the ratings of the protective devices such as: current transformers, relays, circuit breakers and fuses that would be required for the protection of the distribution line and equipment were obtained. Thus the protective devices selected was be able to withstand the large values of fault current which occurred as a result of faults. With this development, the protection of lines, equipment, lives and properties can be guaranteed and safeguarded by proper setting of choice relays. Fault currents along the outgoing 11kV Lagos Road feeder were calculated and the results obtained were presented in table 1.

At the point of fault, $1/Z_{pu}$ equivalent = $1/0.1903823 = 5.253$

$$\frac{1}{Z_p} = \frac{1}{0.1903823} = 5.253 \text{ pu}$$

$$VA_{\text{fault}} = 1/Z_{f,pu} \times (\text{MVA}) \text{ base,}$$

$$VA_{\text{fault}} = 5.253 \times 15 = 78.795 \text{ MVA}$$

$$I_f = \frac{1/Z_{pu} \times (\text{MVA}) \text{ base}}{KV \times \sqrt{3}}$$

$$= \frac{5.253 \times 15}{11 \times \sqrt{3}}$$

$$= 4.135786 \text{ KA}$$

Excel software Algorithm for point of fault and fault current calculation along Lagos Road 11kV feeder will be useful for Power System Engineers in the choice of Protective devices to be installed along the feeder. This is because the protective device must be able to withstand the maximum fault current in the event of fault.

Table 1. Excel software Algorithm for point of fault and fault current calculation along Lagos Road 11kV feeder

| S/N | Z/km | Total = Z ohm | MVA | MVA*/Z/k m | MVA | KV | KV | KV Square | Z total*/MVA | $\sqrt{3}$ | KV square*/ $\sqrt{3}$ | ZPU | 1/Zpu | 1/Zpu *MVA | $\sqrt{3} * \text{KV}$ | Fault Current in KA | Point of Fault in km |
|-----|---------|---------------|-----|------------|-----|----|----|-----------|--------------|------------|------------------------|----------|----------|------------|------------------------|---------------------|----------------------|
| 1 | 0.44332 | 0.44332 | 15 | 6.6498 | 15 | 11 | 11 | 121 | 6.6498 | 1.732 | 209.572 | 0.03173 | 31.51553 | 472.733 | 19.052 | 24.81278 | 1 |
| 2 | 0.44332 | 0.88664 | 15 | 6.6498 | 15 | 11 | 11 | 121 | 13.2996 | 1.732 | 209.572 | 0.063461 | 15.75777 | 236.3665 | 19.052 | 12.40639 | 2 |
| 3 | 0.44332 | 1.32996 | 15 | 6.6498 | 15 | 11 | 11 | 121 | 19.9494 | 1.732 | 209.572 | 0.095191 | 10.50518 | 157.5777 | 19.052 | 8.270925 | 3 |
| 4 | 0.44332 | 1.77328 | 15 | 6.6498 | 15 | 11 | 11 | 121 | 26.5992 | 1.732 | 209.572 | 0.126922 | 7.878884 | 118.1833 | 19.052 | 6.203194 | 4 |
| 5 | 0.44332 | 2.2166 | 15 | 6.6498 | 15 | 11 | 11 | 121 | 33.249 | 1.732 | 209.572 | 0.158652 | 6.303107 | 94.5466 | 19.052 | 4.962555 | 5 |
| 6 | 0.44332 | 2.65992 | 15 | 6.6498 | 15 | 11 | 11 | 121 | 39.8988 | 1.732 | 209.572 | 0.190382 | 5.252589 | 78.78884 | 19.052 | 4.135463 | 6 |
| 7 | 0.44332 | 3.10324 | 15 | 6.6498 | 15 | 11 | 11 | 121 | 46.5486 | 1.732 | 209.572 | 0.222113 | 4.502219 | 67.53329 | 19.052 | 3.544682 | 7 |
| 8 | 0.44332 | 3.54656 | 15 | 6.6498 | 15 | 11 | 11 | 121 | 53.1984 | 1.732 | 209.572 | 0.253843 | 3.939442 | 59.09163 | 19.052 | 3.101597 | 8 |
| 9 | 0.44332 | 3.98988 | 15 | 6.6498 | 15 | 11 | 11 | 121 | 59.8482 | 1.732 | 209.572 | 0.285573 | 3.501726 | 52.52589 | 19.052 | 2.756975 | 9 |
| 10 | 0.44332 | 4.4332 | 15 | 6.6498 | 15 | 11 | 11 | 121 | 66.498 | 1.732 | 209.572 | 0.317304 | 3.151553 | 47.2733 | 19.052 | 2.481278 | 10 |
| 11 | 0.44332 | 4.87652 | 15 | 6.6498 | 15 | 11 | 11 | 121 | 73.1478 | 1.732 | 209.572 | 0.349034 | 2.865049 | 42.97573 | 19.052 | 2.255707 | 11 |
| 12 | 0.44332 | 5.31984 | 15 | 6.6498 | 15 | 11 | 11 | 121 | 79.7976 | 1.732 | 209.572 | 0.380765 | 2.626295 | 39.39442 | 19.052 | 2.067731 | 12 |
| 13 | 0.44332 | 5.76316 | 15 | 6.6498 | 15 | 11 | 11 | 121 | 86.4474 | 1.732 | 209.572 | 0.412495 | 2.424272 | 36.36408 | 19.052 | 1.908675 | 13 |
| 14 | 0.44332 | 6.20648 | 15 | 6.6498 | 15 | 11 | 11 | 121 | 93.0972 | 1.732 | 209.572 | 0.444225 | 2.25111 | 33.76664 | 19.052 | 1.772341 | 14 |

Analysis of the Maximum Permissible Disconnection Time

A 10mm^2 PVC Mineral insulated copper cables short circuited when connected to a 410 V supply is considered along Arisendo, Lagos Road feeder. The impedance of the short-circuit path is 0.12Ω . A 100A B-type MCB was installed to protect the system. The maximum permissible disconnection time required for the Miniature Circuit Breaker to meet the requirement was evaluate as shown below:

$$I = \frac{V}{Z \text{ of short circuit path}} = \frac{410}{0.12} = 3416.67 \text{ A}$$

Therefore the fault current expected is 3416.67 A and Constant, $K = 115$

$$\text{Maximum permissible disconnection time} = \frac{K^2 S^2}{I^2} = \frac{115^2 10^2}{3416.67^2}$$

$$= \frac{1322500}{11673633.9} = 0.113\text{sec or } 113 \text{ milisec}$$

Where: t = duration in second, S = cross sectional area of the conductor in square millimeter, I = short circuit current in millimeter, k = a constant dependent upon the conductor metal and type of insulation.

The results in Figure 1. shows that the device will operate maximum permissible disconnection time require. Table 1. shows the results of the variation of the fault current and the disconnection time for the selected 100 A Miniature Circuit Breaker. From this analysis, it was

possible to make appropriate choice of protective devices with respect to the fault current and the tripping time required.

Table 2. The result of the protective device disconnection time in relation to the fault current characteristics was obtained:

| S/N | FAULT CURREN | CSA | K | I Square | CSA squar | K square | K . CSA squa | Disconnection time(sec) |
|-----|--------------|-----|-----|-----------|-----------|----------|--------------|-------------------------|
| 1 | 3416.67 | 10 | 115 | 11673634 | 100 | 13225 | 1322500 | 0.113289487 |
| 2 | 5240.46 | 10 | 115 | 27462421 | 100 | 13225 | 1322500 | 0.048156716 |
| 3 | 7842.44 | 10 | 115 | 61503865 | 100 | 13225 | 1322500 | 0.021502714 |
| 4 | 12,348.50 | 10 | 115 | 152485452 | 100 | 13225 | 1322500 | 0.008672959 |
| 5 | 16,330.98 | 10 | 115 | 266700908 | 100 | 13225 | 1322500 | 0.004958738 |
| 6 | 22,346.11 | 10 | 115 | 499348632 | 100 | 13225 | 1322500 | 0.00264845 |
| 7 | 28,751.26 | 10 | 115 | 826634952 | 100 | 13225 | 1322500 | 0.00159986 |
| 8 | 46962.48 | 10 | 115 | 2.205E+09 | 100 | 13225 | 1322500 | 0.000599644 |

Disconnection Time (Sec) And The Fault Current (Ampere) Characteristics Curve For Johnson And Philip Fuses, J And P Fuses

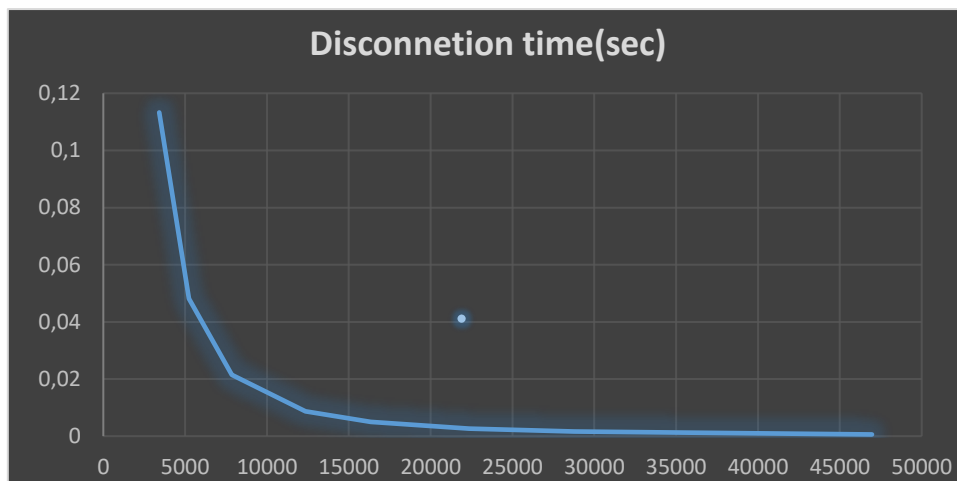


Figure 1. Disconnection time (sec) and the Fault Current (Ampere) characteristics I

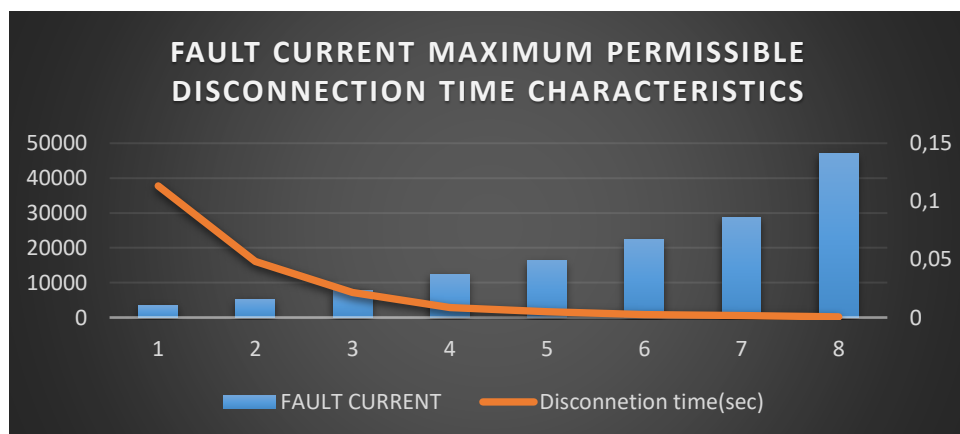


Figure 2. Disconnection time (sec) and the Fault Current (Ampere) characteristics II

The characteristics curve in figure 1 and 2 shows that the selected protective device will operate within permissible disconnection time if the fault current is above 20 kA. Therefore, another protective device (Johnson and Philip Fuses, J and P fuses) must be selected for the point of faults (2 to 14 km along the feeder) where fault currents less than 20 kA are expected. Also, a 100mm² PVC Mineral Insulated Copper cables short circuited when connected to an 11 kV

supply along Lagos Road feeder was evaluated. The impedance of the short-circuit path varies with respect to the length. An SF6 Circuit Breaker (CB) was installed to protect the system and the maximum permissible disconnection time required for Circuit Breaker to meet the requirement was evaluate as shown below. The results show that SF6 Circuit Breaker (CB) installed to protect the system against fault current will operate within the maximum permissible disconnection time when the fault current is above 46 kA as shown in figures 4.3 to 4.6 and table 4.3 to 4.4. For fault current greater than 20 kA but less than 46 kA, 100A B-type MCB or Johnson and Philip Fuses (J and P fuses) should be installed. While Johnson and Philip Fuses (J and P fuses) will operate within the permissible disconnection time when the fault current expected is below 20 kA.

Table 3. Maximum Permissible Disconnection Time of Protective Device I

| S/N | FAULT CURRENT | CSA | K | I Square | CSA squar | K square | K . CSA squa | Disconnection time(sec) |
|-----|---------------|-----|-----|-----------|-----------|----------|--------------|-------------------------|
| 1 | 32416.67 | 100 | 115 | 1.051E+09 | 10000 | 13225 | 132250000 | 0.12585164 |
| 2 | 72,234.55 | 100 | 115 | 5.218E+09 | 10000 | 13225 | 132250000 | 0.025345784 |
| 3 | 7842.44 | 100 | 115 | 61503865 | 10000 | 13225 | 132250000 | 2.150271364 |
| 4 | 12,348.50 | 100 | 115 | 152485452 | 10000 | 13225 | 132250000 | 0.867295851 |
| 5 | 16,330.98 | 100 | 115 | 266700908 | 10000 | 13225 | 132250000 | 0.495873828 |
| 6 | 22,346.11 | 100 | 115 | 499348632 | 10000 | 13225 | 132250000 | 0.264845023 |
| 7 | 28,751.26 | 100 | 115 | 826634952 | 10000 | 13225 | 132250000 | 0.159985977 |
| 8 | 46962.48 | 100 | 115 | 2.205E+09 | 10000 | 13225 | 132250000 | 0.05996442 |

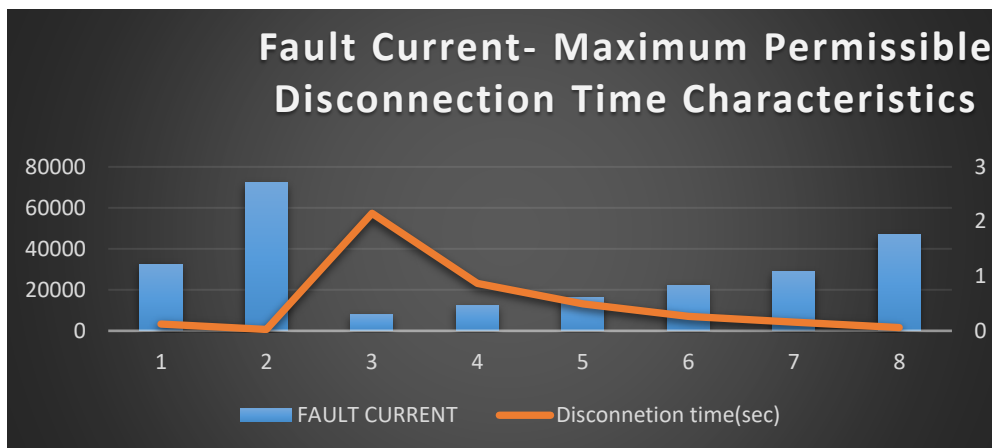


Figure 3. Maximum Permissible Disconnection Time of Protective II

Protective devices must operate with very few micro second. Therefore, the result shown in figure 4.4 revealed that this protective device 100 A, Miniature Circuit Breaker will not be suitable for fault current which lie between 7,842.44A and 32,416.67 A. This is because the tripping time is too high (2.1503 seconds).

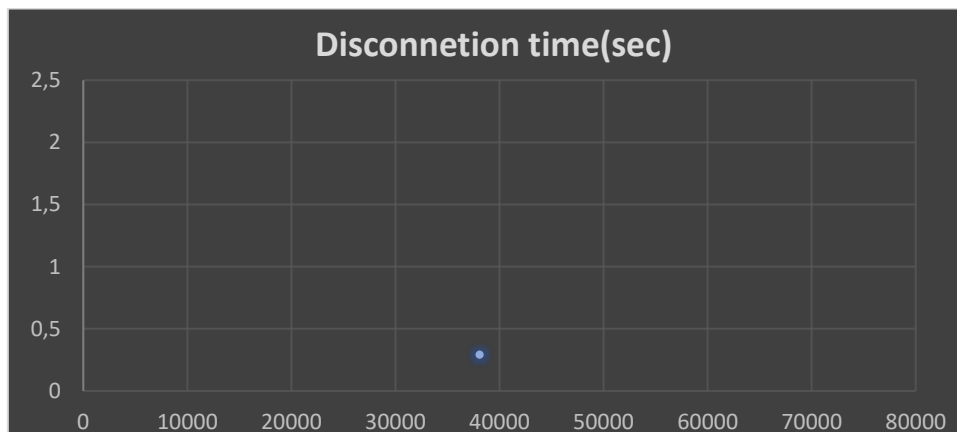


Figure 4. Maximum Permissible Disconnection Time of Protective Devices III

Table 4. Maximum Permissible Disconnection Time of Protective Device IV

| S/N | FAULT CURRENT | CSA | K | I Square | CSA squar | K square | K . CSA squa | Disconnection time(sec) |
|-----|---------------|-----|-----|-----------|-----------|----------|--------------|-------------------------|
| 1 | 3416.67 | 100 | 115 | 11673634 | 10000 | 13225 | 132250000 | 11.32894875 |
| 2 | 15,240.46 | 100 | 115 | 232271621 | 10000 | 13225 | 132250000 | 0.569376489 |
| 3 | 7842.44 | 100 | 115 | 61503865 | 10000 | 13225 | 132250000 | 2.150271364 |
| 4 | 12,348.50 | 100 | 115 | 152485452 | 10000 | 13225 | 132250000 | 0.867295851 |
| 5 | 16,330.98 | 100 | 115 | 266700908 | 10000 | 13225 | 132250000 | 0.495873828 |
| 6 | 22,346.11 | 100 | 115 | 499348632 | 10000 | 13225 | 132250000 | 0.264845023 |
| 7 | 28,751.26 | 100 | 115 | 826634952 | 10000 | 13225 | 132250000 | 0.159985977 |
| 8 | 46962.48 | 100 | 115 | 2.205E+09 | 10000 | 13225 | 132250000 | 0.05996442 |

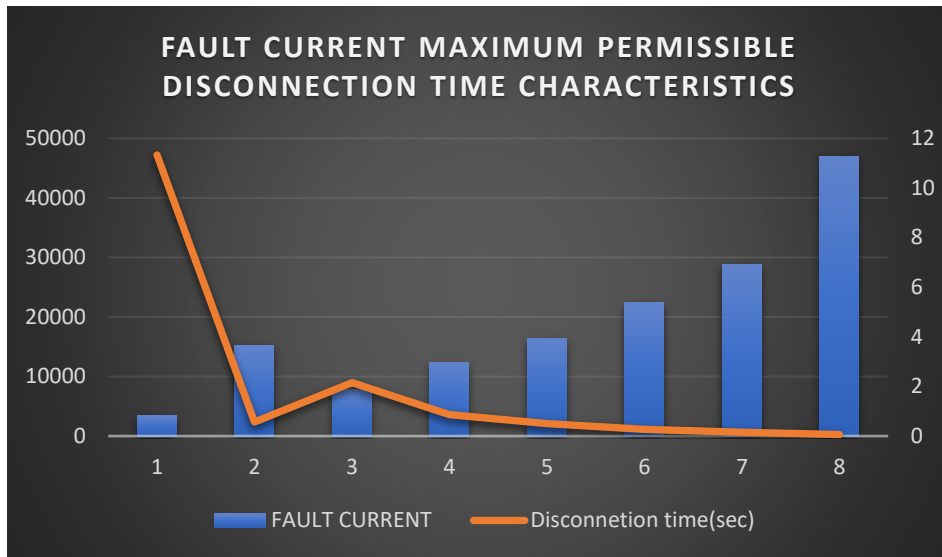


Figure 5. Fault Current and the maximum permissible Disconnection time for the chosen protective device I

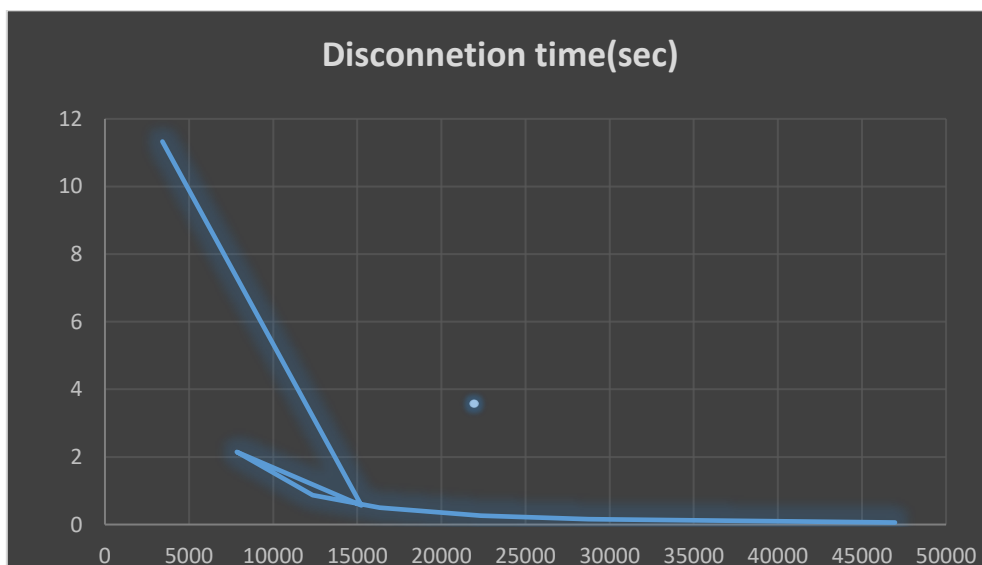


Figure 6. Fault Current - disconnection time characteristics curve.

This curve shows that the protective device, 100 A, Miniature Circuit Breaker selected will not be suitable for fault current that is less than 20,000 A. This is because the disconnection time is too high. However, it will be suitable for fault current greater than 25,000 A (25 kA)

Conclusion

This research work analyze evaluated the occurrence of faults on distribution lines. Fault currents were obtained and the maximum tripping time for the operation of the protective devices were determined. Hence, it was possible to select appropriate relay and circuit breaker for effective operation of a distribution system before the occurrence of faults and in the events of faults. A mathematical model for determining the values of the impedance (Z) in ohms up till the point of fault was developed. From the research result, if the per km impedance of any distribution line is known, the distance (that is the length of line) where fault occurs or repair operations should be carried out can be obtained. This will be useful in fault location, speed repair operations and improve the performance of the system.

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