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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more complicated to analyze due to the simplifying assumption of equal current magnitude in all the phases being no longer applicable.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

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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°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 $t_{ref} = 20^0C$

$(R_t)_{DC}$ = DC Resistance of the line at 40.5^0C, $t = 40^0C$, $t_{ref} = 20^0C$

The DC Resistance of the line per km at a reference temperature $t_{ref} = 20^0C$ as stated by the manufacturer is 0.27018 Ω /km. The AC Resistance $R_{t(AC)}$ /km of the line was obtained from below equation

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

Where $R_{t(AC)}$ /km = AC Resistance of the line /km at 40^0c and $(R_t)_{DC}$ = DC Resistance of the line at 40^0c. 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°C = $(R_{40}{}^0C)_{DC}$ /km

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$$(R_{40}{}^0C)_{DC}/km = (R_{20})_{DC} * \frac{t + 288}{t_{ref} + 288}$$

$$(R_{40})_{DC}/km = 0.27018 * \frac{40 + 288}{20 + 288}$$

$$(R_{40})_{DC}/km = 0.27018 * \frac{328.5}{308}$$

$$(R_{40})_{DC}/km = 0.288163$$

$$(R_{40})_{AC}/km = 0.288163 * 1.05$$

$$(R_{40})_{AC}/km = 0.288163 * 1.05 = 0.3025709$$

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 100m^2 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 Deq is given by

$$D_{eq} = 3\sqrt{}\ D_{ab} * Dbc * D_{ca}$$

$$D_{eq} = 3\sqrt{}\ 0.658 * 0.658 * 1.316$$

$$D_{eq} = 3\sqrt{}\ 0.5697806$$

$$D_{eq} = 0.82902803 \text{ meter}$$

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

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

$$L_o = 10^{-7} * \{0.5 + 2 \log_e \frac{0.82908}{0.00559} .\}$$

$$L_o = 10^{-7} * \{0.5 + 2 \log_e 148.31485\}$$

Lo/ phase/meter = 0.0010312 Henry

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

Reactance of Lagos Road Feeder/phase/kilometer = $2\pi f L_o$

= 0.32400525 ohm

Resistance of Lagos Road Feeder/ phase/kilometer = 0.302570893 ohm

Impedance of the Lagos Road Feeder

Impedance of the Lagos Road Feeder = R + jX_L

The impedance Z, of Lagos Road feeder/kilometer = 0.302570893 + j0.32400525

Therefore impedance Z per kilometer = 0.443 ohm

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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:

$$Zpu = \frac{Z_{(ohms)} \times \text{base MVA}}{\text{base KV}^2} \quad \text{for single phase}$$

$$Zpu = \frac{Z\,(ohms) \times \text{base MVA}}{\sqrt{3}.\ (KV)^2\ \text{base}} \quad \text{for three phase}$$

$$If = \frac{1/Z_{pu} \times \text{base MVA}}{\text{base (KV)}} \quad \text{for single phase}$$

$$If = \frac{1/Z_{pu} \times MVA_{base}}{\sqrt{3}.\ (KV)\ \text{base}} \quad \text{for three phase}$$

$$X\,pu = \frac{X\,(ohms) \times (MVA)\ \text{base}}{(KV)\ \text{base}} \quad \text{for single phase}$$

$$Xpu = \frac{X\,(ohms) \times (MVA)\text{base}}{\sqrt{3}.\ (KV)^2\ \text{base}} \quad \text{for three phase}$$

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.

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At the point of fault, 1/Zpu equivalent = 1/ 0.1903823 = 5.253

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

VA_{fault} = $1/Z_{f.pu}$ × (MVA) base,

VA_{fault} = 5.253 × 15 = 78.795 MVA

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

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

$$= 4.135786\ \text{KA}$$

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/km	MVA	KV	KV	KV Square	Z total*MVA	√3	KV square*√3	ZPU	1/Zpu	1/Zpu *MVA	√3 * 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 0.12 Ω. 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:

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

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

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

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

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

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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	Disconnetion 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

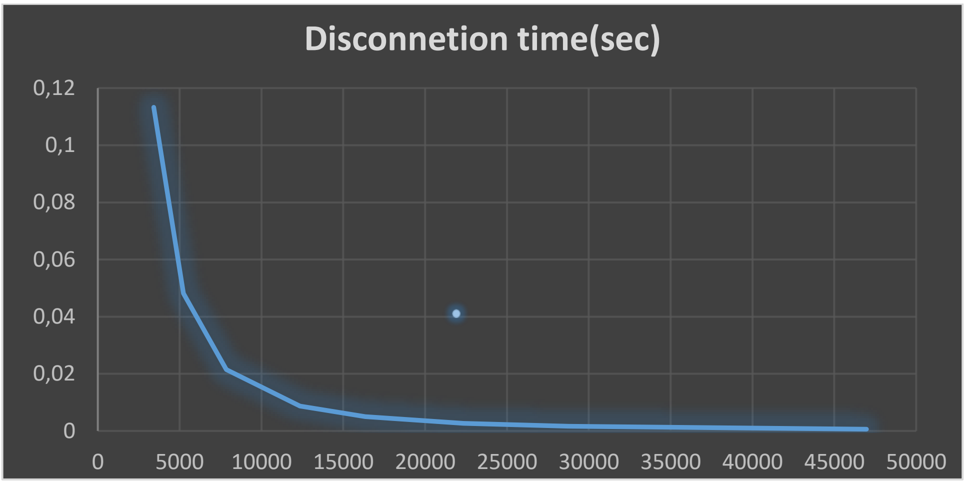

Figure 1. Disconnection time (sec) and the Fault Current (Ampere) characteristics I

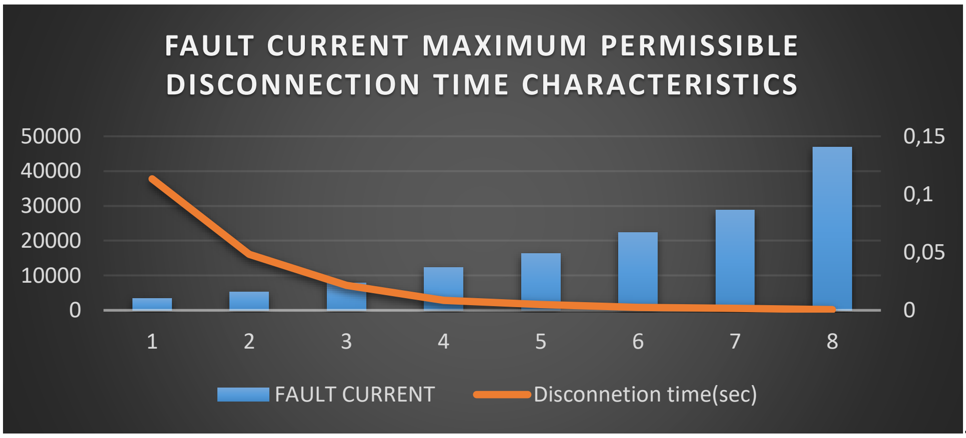

Figure 2. Disconnection time (sec) and the Fault Current (Ampere) characteristics II

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 $100mm^2$ PVC Mineral Insulated Copper cables short circuited when connected to an 11 kV

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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	Disconnetion 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

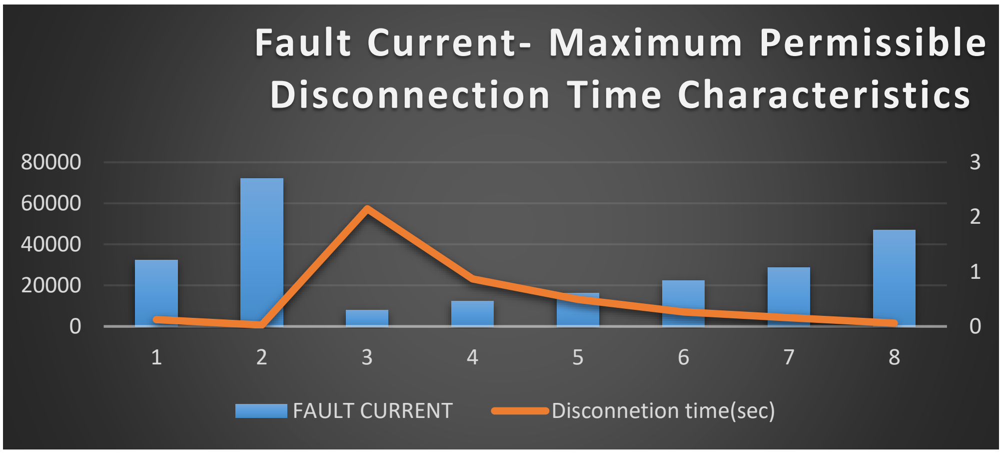

Figure 3. Maximum Permissible Disconnection Time of Protective II

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).

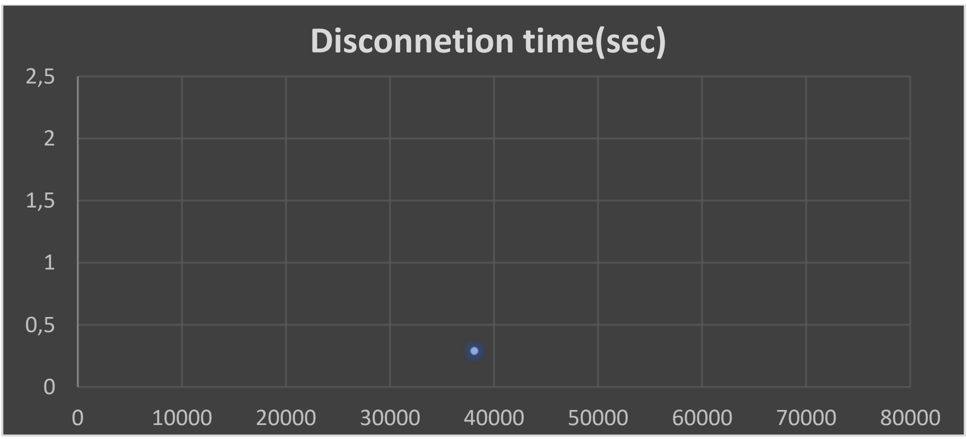

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Figure 4. Maximum Permissible Disconnection Time of Protective Devices III

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	Disconnetion 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

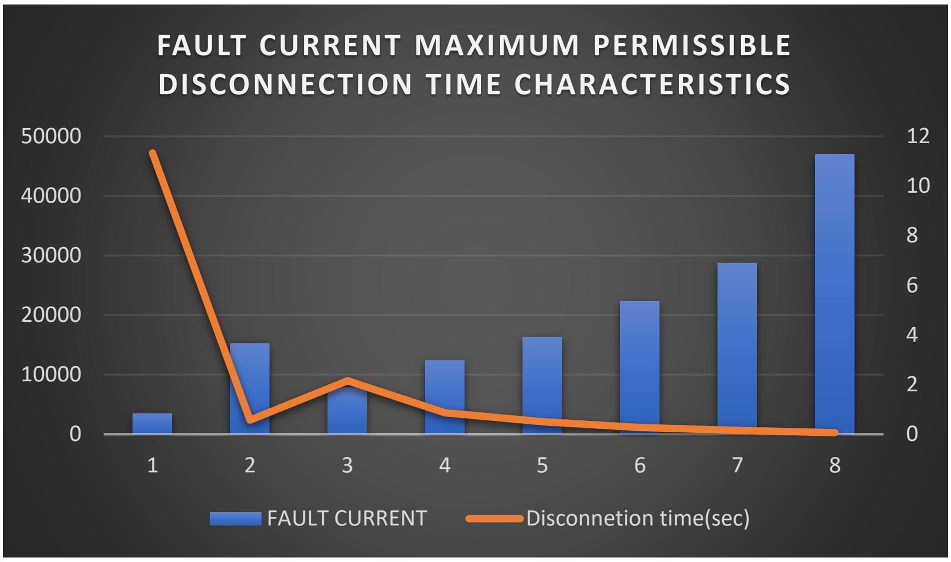

Figure 5. Fault Current and the maximum permissible Disconnection time for the chosen protective device I

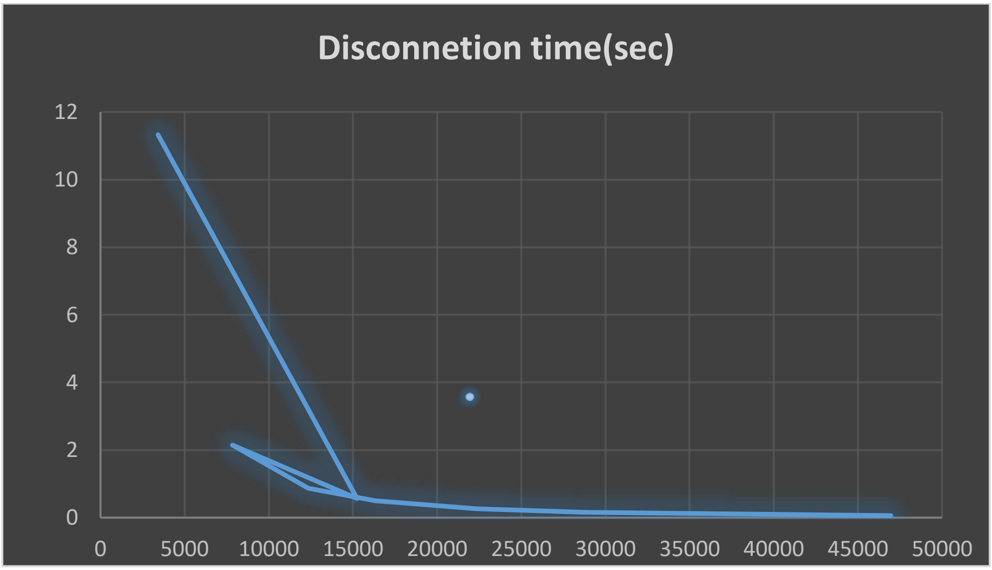

Figure 6. Fault Current - disconnection time characteristics curve.

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)

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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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