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A Review of Short-Circuit Fault Analysis and Novel Fault Detection Methods

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***Abstract*—This paper proposes a comprehensive review of short circuit fault analysis. It presents the different definitions and classifications of faults. It then discusses both symmetrical and unsymmetrical faults in detail and provides the equations used to solve for the fault current during each of these faults. Also, in this research, the causes and effects of short circuit faults are discussed to highlight the importance of understanding the extent of the damage in order to compensate for it. Finally, the paper examines a number of novel fault detection methods in literature.**

Index Terms—Power system analysis, short circuit fault, fault detection, symmetrical faults, unsymmetrical faults.

I. INTRODUCTION

Modern electrical power systems are complex, extensive, and interconnected systems over a large geographical area. These systems are made up of generators, transformers, trans- mission lines, and loads as well as other protective equipment such as relays and circuit breakers. Also, they operate as balanced 3-phase AC power systems such as when they are in their normal conditions, the magnitude of both currents and voltages are equally distributed between each phase. However, a fault in a circuit may occur which will cause a disturbance or a failure that will disrupt these normal operating conditions. Statistics show that almost 50% of power system faults occur in the transmission and distribution networks [1]. Faults are defined as the flow of a huge current through an irregular path which will then cause equipment damage eventually leading to interruption of power supply, human injury, or destabilization of the whole power system. Moreover, voltage levels will alternate between very high and very low levels. As a result, the equipment insulation will be damaged, or it will cause start-up failures of certain equipment if the voltage is below a minimum level [2]. To prevent such events from happening, fault analysis was introduced. Fault analysis is a process consisting of determining the system voltages and line currents during different types of faults, and it is an essential part of power system analysis. These analyses help in evaluating the appropriate safety measures as well as the required protective equipment. For instance, selecting a suitable fuse, the size of a circuit breaker, or the type of a relay [3]. Moreover, the detection of faults is a major issue that should be considered in order to protect the power system and avoid unwanted accidents that could damage equipment or cause blackouts. Hence, faults analysis is of immense significance from an operational and an economic point of view. The rest of the paper is organized as follows: The different definitions and types of faults are discussed in section II. In section III, the causes and consequences of circuit faults will be presented. Section IV will then discuss some of the novel prototypes proposed in literature. Finally, section V concludes the findingsof this review paper.

II. DEFINITIONS AND CLASSIFICATIONS IN SHORTCIRCUIT ANALYSIS

There are different types of short circuit faults that occur in three phase power systems. Generally, these faults are divided into symmetrical faults (balanced) or unsymmetrical faults (unbalanced). A fault which involves all the three phases of the power system is known as a symmetrical fault or a three-phase fault. On the other hand, a fault involving one or two phases is known as an unsymmetrical fault. Furthermore, all short circuit faults are analyzed through the Thevenin equivalent sequence circuits seen from the fault point in power systems [4]. Consequently, during symmetrical faults, the sequence circuits given in are kept independent. However, during unsymmetrical faults, the sequence circuits connect to each other at the fault point and cannot be considered independent. Finally, by utilizing the sequence networks and the symmetrical components concept, the short circuit fault current is computed.

A. Symmetrical Faults

Symmetrical faults are rarely seen, in fact, they account for less than 5% of all short circuit faults [2]. Nevertheless, they are considered the most severe type of faults. Symmetrical faults could be a three-phase short circuit or a three-phase to ground short circuit (which is the most common one) and they are mainly due to insulation failures, or lightning strikes [5]. In a balanced three phase fault, it is only required to determine the positive sequence circuit. Then, the fault current can be given by the following equations:

$$I_f = I^{(1)} = \frac{V_f^{(1)}}{Z^{(1)}} \quad \text{(In the case of a solid fault)} \qquad (1)$$

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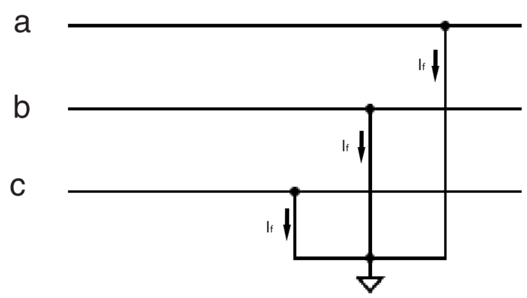

Fig. 1: Representation of a three phase symmetrical fault.

$$I_f = I^{(1)} = \frac{V_f^{(1)}}{Z^{(1)} + Z_f} \text{ (For a fault through an impedance)} \quad (2)$$

Where I_f represents the fault current, $I^{(1)}$ represents the positive sequence current, $Z^{(1)}$ represents the positive sequence Thevenin equivalent impedance, and Z_f is the fault impedance. Fig. 1 shows the schematic representation of a symmetrical fault.

B. *Unsymmetrical Faults*

Unsymmetrical faults are the most common type of faults in power systems. These faults occur under unbalanced operating conditions either through a line or through a fault impedance. The sequence circuits cannot be independent; thus, all three sequence circuits are connected to each other according to the fault type during unsymmetrical faults. Unsymmetrical faults are classified into:

1) Single-Line-to-Ground Fault (SLG):: This type of fault occurs when one of the phases of the transmission line makes a connection with the ground. This could occur due to ice, wind, a falling tree, or any other incident. This type of faults account for 70% of all faults [5]. In a SLG fault, the positive, negative, and zero sequence networks will be connected in series. Then, the fault current can be given by the following equations:

$$I^{(1)} = I^{(2)} = I^{(0)} = \frac{V_f}{Z^{(1)} + Z^{(2)} + Z^{(0)}} \quad (3)$$

$$I^{(1)} = I^{(2)} = I^{(0)} = \frac{V_f}{Z^{(1)} + Z^{(2)} + Z^{(0)} + Z_f} \quad (4)$$

Thus, the fault current can then be given through:

$$I_f = I^{(1)} + I^{(2)} + I^{(0)} = 3I^{(1)} = 3I^{(2)} = 3I^{(0)} \quad (5)$$

Where $I^{(2)}$ represents the negative sequence current, $I^{(0)}$ represents the zero sequence current, $Z^{(2)}$ represents the negative sequence Thevenin equivalent impedance, and $Z^{(0)}$ the zero sequence Thevenin equivalent impedance. Fig. 2 shows the schematic representation of a SLG usymmetrical fault.

2) Line-to-Line Fault (LL):: This short circuit fault takes place when one of the lines makes contact with another line phase. This can be caused by strong wind resulting in the lines touching. In the case of a LL fault, it is only required to determine the positive and negative sequence circuits. Both sequences are then connected in series. Then, the fault current can then be found through these equations:

$$I^{(0)} = 0, \text{ so } I_f = I^{(1)} = -I^{(2)} \quad (6)$$

$$I^{(1)} = -I^{(2)} = \frac{V_f}{Z^{(1)} + Z^{(2)}} \quad (7)$$

$$I^{(1)} = -I^{(2)} = \frac{V_f}{Z^{(1)} + Z^{(2)} + Z_f} \quad (8)$$

Fig. 3 shows the schematic representation of a LL usymmetrical fault.

3) Line-to-Line-to-Ground or Double-Line-to-Ground Fault (LLG): A double line to ground short circuit fault is caused by two phases touching each other while simultaneously establishing a connection with the ground. This fault can be the result of a tree falling onto the transmission line and causing a connection between two lines. For a LLG fault, the positive sequence network is placed in series with the parallel combination of the negative and zero sequence networks. Therefore, the symmetrical components of the fault current can be given by the following equations:

$$I^{(1)} = \frac{V_f^{(1)}}{Z^1 + \frac{Z^{(2)}(Z^{(0)}+3Z_f)}{Z^{(2)}+Z^{(0)}+3Z_f}} \quad (9)$$

$$I^{(2)} = -\frac{V_f - Z^{(1)}I^{(1)}}{Z^{(2)}} \quad (10)$$

$$I^{(0)} = -\frac{V_f - Z^{(1)}I^{(1)}}{Z^{(0)} + 3Z_f} \quad (11)$$

Then, after obtaining the three unbalanced currents, the symmetrical components method is used to find the unbalanced

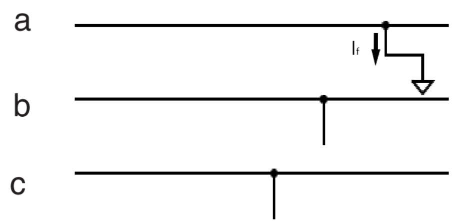

Fig. 2: Representation of a solid line to ground unsymmetrical fault.

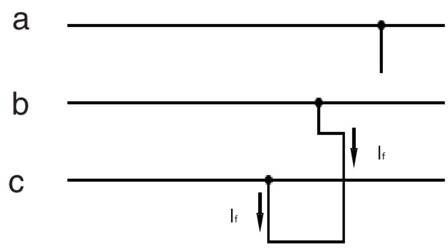

Fig. 3: Representation of a line to line unsymmetrical fault.

currents $I^{(b)}$ and $I^{(c)}$. Finally, the fault current is found through:

$$I_f = I^{(b)} + I^{(c)} \tag{12}$$

Fig. 4 shows the schematic representation of a LLG fault.

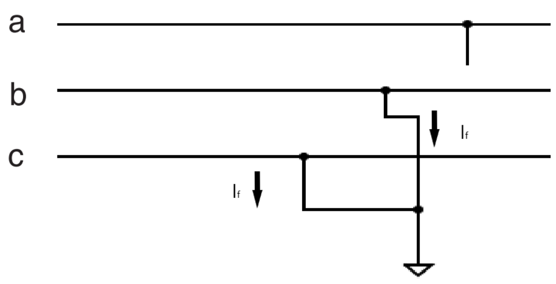

Fig. 4: Representation of a double line to ground unsymmetrical fault.

III. Causes and Effects of Short Circuit Faults

Short circuit faults may be the result of natural causes such as extreme weather or falling trees. However, it can also be induced by human error when handling power system equipment. Hence, investigating these factors will assist in preventing and avoiding these unwanted conditions. Moreover, the consequences of short circuit faults should also be understood in order to determine the extent of damage inflicted on the equipment, and thus, the measures that should be taken to nullify and compensate for this damage.

A. Causes of Short Circuit Faults

1) Human Error: Short circuit faults may sometimes be caused by human error and negligence. Such errors include selecting an improper rating of a certain equipment or device, placing metallic conductive materials near machines after servicing or maintenance, or switching the circuit while it is still under service.

2) Weather Conditions: As discussed in the previous section, unfortunately, nature has a high chance of causing faults. These causes include faults induced by lightning strikes, heavy rain and wind, snow or ice accumulating on the transmission lines, and finally insulation contamination due to salt or any other pollutants.

3) Lack of Safety Measures: Many of the electrical equipment which are part the power system may cause short circuit faults due to them malfunctioning, aging, having internal failures. Thus, if fuses and circuit breakers are not up to par with what the facility requires, then these faults will occur. Therefore, safety measures should be checked regularly so that they are evaluated to determine if they can handle a fault if it occurs.

B. Effects of Short Circuit Faults

The extent of damage caused by short circuit faults heavily depends on the type of fault. Generally, the type of fault dictates the manner of how the power system operation is affected. Some faults may only cause mild disturbances or damages to equipment, while others will induce a power outage.

1) Human Injury: One of the many results of short circuit faults is arcing fault currents which generate very high temperatures that reach up to 20000°K [6]. This can cause human injuries as such burns or in extreme cases, death.

2) Equipment Damage: Many equipment sustain a lot of damage in the case of shirt circuit faults. Faults induce the flow of abnormally huge currents. These fault currents will usually burn the winding and insulation of equipment such as generators and transformers.

3) Destabilization of the power system: When a short circuit current occurs, the power system faces stability issues. As discussed before, a fault will interrupt the operation and flow of the power system, thus, causing the power system to be unstable or completely blackout [7].

IV. Proposed methods of fault detection in recent literature

In order to ensure an efficient and reliable power supply to consumers, power systems should be maintained and protected against faults at all times. The most practiced method currently is the use of relays to detect fault currents and isolate the affected zone. Consequently, in recent research, fault detection methods have been widely studied with the performance criteria for these methods being the speed at which the fault is detected, and the accuracy of locating the fault zone. In this section, several of these methods will be examined.

A. Fault Detection Methods in Transmission Lines

One of the most frequent issues for power transmission is fault occurrence in transmission lines. Therefore, the accurate detection of fault location is very vital for utility companies. The authors in [8] propose an efficient approach to locate SLG faults using post fault currents and voltages waveforms from one terminal and it also depends on line parameters. They utilize the SimPowerSystems toolbox of simulink to model a transmission line in which a low pass filter is used to filter out harmonic components from fundamental components in order to detect fault location. This method requires only source terminal data for fault location and has an error percentage of less than 2%. Nevertheless, the accuracy of this method is heavily affected by the fault impedance Z_f and the error increases significantly as the impedance increases. The reference in [9] presents a protection algorithm that diagnoses fault currents and their type by making use of alienation coefficients of current signals. The model used was a parallel transmission system, with voltage and frequency ratings of 19kV and 50Hz. It was proven that this detection scheme is able to quickly and accurately classify the type of fault as well as its location with little to no error. However, the scheme found difficulty in differentiating LL and LLG faults, by utilizing alienation coefficients alone since the alienation coefficients of faulty phases in both the cases show no apparent difference. Nevertheless, by assessing the value of the zero sequence current the type can then be differentiated (LLG having a higher value for zero sequence current than LL).

B. Fault Detection Methods in Power Distribution Network

For a power distribution network, fault currents may occur due to several factors such as overloading, over voltage, and power swings. Consequently, when a fault occurs protection equipment are initiated such as relays and circuit breakers in order to isolate the faulted part. Hence, rapid detection of the fault will assist in protecting the distribution equipment from any significant damage. Robert A. Sowah et. al [10] developed a prototype data collecting device to collect data during different faulted conditions in a single-phase distribution network. They employ and compare the use of 3 machine learning algorithms: K-Nearest Neighbor (KNN), Decision Trees (DT), and Support Vector Machines (SVM) to predict both fault location and classification. The results obtained show that DT was better compared to KNN and SVN. In fact, it had the fastest training time (2ms) as well as being the most accurate (at 99.42%). In [11], authors provide a decentralized fault detection technique for power distribution systems with an objective of detecting SLG and identifying the faulty feeder within three cycles of the occurrence of the fault. In this paper, the algorithm was tested on both an IEEE test system and a practical SimPowerSystems test system. The algorithm detects the fault based on its neutral voltage displacement. Then, the fault phase can be found through utilizing the pre- and post-fault voltages. Finally, by using both the zero sequence current and the faulty phase voltage, the faulty feeder (location) is obtained. From the case studies done in the paper, it is seen that the proposed technique can detect and identify the faulty phase and feeder within 15ms.

V. CONCLUSION

To sum up, electric power systems nowadays consist of many different machines connected together and are expected to operate in relatively normal conditions. These normal conditions are disturbed and destabilized when a short circuit fault occurs. Moreover, short circuit faults are classified into two types: Symmetrical faults, and unsymmetrical faults which depend on how many phases are connected and involved in a certain fault. Hence, studying and understanding short circuit analysis assists in fixing these faults. In addition, the causes and effects of short circuit faults were discussed and highlighted in order to understand the extent of those effects and how to recompense the system based on said effects. Finally, four novel methods of fault detection were examined and studied depending on the speed of fault detection, and the accuracy of locating the fault zone.

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