# SINGLE LINE TO GROUND FAULT DISTANCE ESTIMATION IN MEDIUM VOLTAGE NETWORK BASED ON MEASUREMENT FROM SECONDARY SIDE OF DISTRIBUTION SUBSTATIONS

by

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| | |
|---|---|
| AI | Artificial Intelligence |
| ANN | Artificial Neural Network |
| ATP-EMTP | Alternative and Electromagnetic Transient Program |
| BPN | Back Propagation Algorithm |
| CFBPN | Cascaded Correlation Feed Forward Network |
| CT | Current Transformer |
| DLG | Double Line to Ground |
| EF | Earth Fault |
| ES | Expert System |
| FL | Fuzzy Logic |
| GA | Genetic Algorithm |
| HHT | Hilbert-Huang Transform |
| hp | Horsepower |
| HVDC | High Voltage Direct Current |
| IED | Intelligent Electronic Device |
| L-G | Line to Ground |
| L-L | Line to Line |
| L-L-L | Line to Line to Line |
| L-L-L-G | Line to Line to Line to Ground |
| MAE | Mean Average Error |
| MV | Medium Voltage |
| MTHVDC | Multi-terminal High Voltage Direct Current |
| nftool | Neural Network Fitting Tool |
| RBF | Radial Basis Function |
| R-ECT | Rogowski coil based Electronic Current Transformer |
| RMS | Root Mean Square |
| SLG | Single Line to Ground |
| STDM | Synchronized Transient Detection Module |
| TDM | Time Domain Reflectometery |
| TDQ | Transient Detection Technique |
| TDOA | Time Difference of Arrival |
| $v_p$ | Propagation velocity |

**ANGGARAN JARAK GAGAL TALIAN TUNGGAL KE BUMI DALAM RANGKAIAN VOLTAN SEDERHANA BERDASARKAN UKURAN DARI BAHAGIAN SEKUNDER PENCAWANG PENGAGIHAN**

## ABSTRAK

Keadaan gagal boleh berlaku di setiap rangkaian sistem kuasa yang terdapat di dunia ini. Ia mungkin terjadi kesan daripada fenomena semulajadi dan juga akibat daripada kecuaian manusia yang mengendalikannya. Keadaan gagal boleh mengakibatkan kerosakan pada sistem dan menyumbang kepada kegagalan sistem tersebut untuk beroperasi dengan sempurna. Gagal bumi adalah antara keadaan gagal yang sering didapati berlaku dalam rangkaian sistem kuasa. Keadaan gagal ini tidak dapat dielak, tetapi kesan akibat berlakunya keadaan gagal ini mampu dikurangkan. Bagi mengurangkan kesan buruk tersebut, pertama sekali, kedudukan di mana gagal berlaku hendaklah dikenalpasti. Terdapat banyak kaedah yang digunakan bagi mengenalpasti kedudukan gagal pada rangkaian, antaranya ialah kaedah asas galangan dan kaedah wavelet. Prinsip kerja bagi kaedah-kaedah tersebut adalah mengenalpasti kedudukan gagal menggunakan sebuah algoritma yang dicipta berdasarkan ciri-ciri rangkaian kuasa tersebut ketika berlaku keadaan gagal. Tujuan projek ini dijalankan adalah untuk membentuk algoritma bagi mengenalpasti anggaran jarak gagal bumi dalam rangkaian voltan sederhana berdasarkan ukuran dari bahagian sekunder pencawang pengagihan. Projek ini dimulakan dengan pemodelan rangkaian voltan sederhana menggunakan perisian ATP-EMTP. Berdasarkan model rangkaian tersebut, ukuran voltan lendut diambil apabila berlaku keadaan gagal bumi pada rangkaian tersebut. Ukuran tersebut diambil dari bahagian sekunder pengubah pengagihan. Keseluruhan data ukuran tersebut dikumpulkan untuk melatih rekaan rangkaian neural (ANN) dalam perisian MATLAB. Berdasarkan rekaan algoritma kedudukan gagal tersebut, menunjukkan bahawa ianya mampu mengenal pasti jarak kedudukan gagal dengan tepat. Purata ralat bagi proses pengenalpastian yang direkodkan adalah kurang dari 0.5km. Ini membuktikan algoritma ini dapat bekerja sebaiknya dalam mengenalpasti kedudukan gagal dalam rangkaian sistem kuasa. Kesimpulannya, algoritma pengenalpastian kedudukan gagal boleh dicipta dengan menggunakan nilai voltan lendut yang telah direkodkan.

**SINGLE LINE TO GROUND FAULT DISTANCE ESTIMATION IN MEDIUM VOLTAGE NETWORK BASED ON MEASUREMENT FROM SECONDARY SIDE OF DISTRIBUTION SUBSTATIONS**

## ABSTRACT

Faults may occur in every power system network in the world. It can be caused by natural phenomenon and also human errors. Faults may cause damage to the system which resulting in system failure. Earth fault is the most common fault that occurrs in power system network. Faults cannot be avoided but the risk of damage caused by faults can be reduced. In order to reduce the risk, locations of fault must first be identified. Many methods can be used to identify fault locations in a network such as impedance-based method and wavelet method. The working principle of these methods are detecting fault locations using an algorithm which was created based on characteristics of the power network during fault events. The purpose of this project is to develop an algorithm regarding single line to ground fault distance estimation in medium voltage network based on measurement from secondary side of distribution substations. This project was done by modelling a medium voltage network using ATP-EMTP software. Based on the network model, measurement of voltage sag was taken when single line to ground fault occurs on the network. The measurement was taken at the secondary side of distribution transformer. All of the measurement data was then collected in order to train in artificial neural network (ANN) in MATLAB. Based on the fault location algorithm developed, it is shown that it was able to estimate the fault location distance accurately. The average error of the detection was less than 0.5 km and this proves that the algorithm works perfectly in detecting fault locations in power system network. Thus, a fault detection algorithm can be developed by using the voltage sag values collected.

# CHAPTER 1 : INTRODUCTION

## 1.1 Background

Electrical power system is one of the most important facilities needed in the world. Electrical power system supplies electricity which were used for the purpose of living. Most of the daily activities done nowadays use electricity as they involve utilization of electrical equipment. In order to ensure the continuity of the supply to meet its purposes, the system needs to work efficiently without any failures. Over the last decades, the growth of electrical power system has increased rapidly resulting in large number of development in transmission lines and substation. As a result, demands for high quality power protections increased as well as the needs of controlling devices and equipment to ensure the stability of the system in order to provide continuous supplies.

Fault can probably be caused by natural phenomenon such as earthquake and lightning strikes. Besides that, human factor such as carelessness in handling an equipment can also cause fault. The most can be done is to clear the fault. The faster the fault can be cleared, the least problem and damage occur. In general, fault location is a process of aiming the location fault with the highest possible accuracies (Saha, Izykowski, & Rosolowski, 2009). Fault location consists of algorithms applied in an equipment called fault locators. To be exact, fault locators are a supplementary protection equipment whereby it applies the algorithms in order to locate fault (Saha et al., 2009). Fault location can be implemented in microprocessor-based relays, digital fault recorders (DFRs), stand-alone fault locators and post-fault analysis programs (Saha et al., 2009).

In this project, fault locating algorithm was built by studying the behaviours of voltage at normal conditions and when fault occurred in power network system. The idea of using the voltage behaviour is because in practical, power utility companies have a maintaining system where they recorded all data in their network all the time. In Malaysia, Tenaga Nasional Berhad (TNB) is the only power utility company. It is responsible to supply power to the entire country. Therefore, a communication system is needed in order to monitor the network for the whole country. TNB have a system called Supervisory Control and Data Acquisition (SCADA) facility. SCADA is a control system that uses graphical user interfaces for the purpose of supervisory management of the power network system. The power network system were equipped with remote terminal unit (RTU) and connected to SCADA. SCADA is able to monitor the system in terms of frequency (Hz), voltage (V), current (A), real power energy flow (kW or MW), reactive power energy flow (kVAR or MVAR), energy meters, breaker status and relay indications. In practical, these recorded data may be used for developing fault location algorithm.

## 1.2 Problem statement

There were a lot of faults that occurred in power distribution system. These faults would damage the system if not cleared quickly. Single line to ground (SLG) fault is the type of fault that usually occurred in transmission line. Generally, an SLG fault on a transmission line occurs when one conductor drops to the ground or comes in contact with the neutral conductor. Such type of failures may occur in power system due to many reasons like high-speed wind, falling off of a tree and lightning (Single Line to Ground Fault). When SLG fault occurs, it results in voltage sag and increase in current value which gives huge impact to the whole system. Some equipment might be wrecked, caused by the huge current flows in the system. Commonly, the method used to locate fault is by searching throughout the entire line. This will consume a lot of time. The longer the time taken, the higher the risk of damages to the system.

Fault cannot be prevented; therefore, the location of fault occurred should be detected as fast as possible to reduce the risk. In order to achieve target, various methods had been proposed regarding sensitivity of equipment and its accuracy of detecting faults. Since power distribution system nowadays had increased rapidly caused by high demands from customers, the protection system also needs to evolve rapidly to ensure stability of the system and means of supply continuity. Therefore, the previous methods proposed can still be improved to achieve better results. Besides that, no previous method had collected data at secondary side of distribution substations regarding characteristic of network during fault events. Based on that reason, this project will be designing a medium voltage (MV) network and creating fault location algorithm based on voltage measurement at secondary side of distribution system.



## 1.3 Project Objectives

The aim of this project is to study the characteristics of voltage during fault events in power system network can be used to create a fault locating algorithm. In order to fulfil the aim of this project, the objectives are as stated:

1. To model a medium voltage (MV) network using Electromagnetic Transient Program (ATP-EMTP) software.

2. To analyze the impact on voltages at secondary side of distribution system when single line to ground fault (SLG) occurs at several different locations in MV network transmission line.

3. To develop fault locating algorithm based on artificial neural network (ANN) technique for single line to ground (SLG) fault in MV network using the voltages at secondary side distribution transformer.

## 1.4 Project Scopes

This project aims to develop an algorithm for locating fault in power distribution system. The scope of this project is analysing the characteristic of the whole system when fault occurs in MV network based on measurement of voltage at secondary side of distribution system.

Based on MV network circuits designed using ATPDraw, SLG fault were injected to the circuit at different locations in the MV network. All data regarding the voltage measurement at pre-fault and during-fault will be collected.

From the data collected, an algorithm will be developed using artificial neural network (ANN) tools in MATLAB software. The developed algorithm should then tested the performances and the accuracy of detecting fault locations.

## 1.5 Thesis Outline

This report consists of five chapters which contain information that explains and helps to understand single line to ground (SLG) fault in medium voltage network. Besides that, the information collected was used to develop an algorithm that can detect the locations of fault in the network. The first chapter is about the introduction and a little knowledge on single line to ground (SLG) fault including problem statement, project objectives, project scope, and project's flowchart overview.

Chapter two explains more on the types of fault in power system network and their characteristics including the consequences. This chapter also shares the knowledge regarding previous method used to detect fault locations.

In chapter three, it will discuss the process in obtaining data regarding the voltage characteristics during (SLG) fault events on a model network constructed using ATPDraw. Furthermore, this chapter shows the process of constructing an algorithm to detect locations of fault using the previous data collected.

Chapter four shows the results of the algorithm developed. All the data collected will be shown in this chapter including tables and graphs. Discussions had been made in this chapter regarding the effectiveness of the developed algorithm in locating faults occurred in power system network.

Lastly, a conclusion is included in chapter five. This chapter will conclude all the data from the results and also discuss on the potential of this project to be commercialize. Besides, this chapter also explains the advantages and disadvantages of the project.

# CHAPTER 2 : LITERATURE REVIEW

## 2.1 Type of Faults and Its Characteristics

Presence of abnormal conditions in electrical networks such as electrical equipment failures is an example that causes faults in a power system. Besides, lightning, winds and tree falling on lines also could cause faults to occur. When faults occur, there will be some changes on the characteristics of the system such as abnormal values of voltage, current and impedance. Faults also cause over-current, under-voltage, unbalance of the phases, reversed power and high voltage surges which results in abnormal operations in the network, equipment failures and electrical fires (Types of Faults in Electrical Power Systems, 2017).

Faults that occur in power system can be divided into two categories which are symmetrical and unsymmetrical fault. Symmetrical faults are the types of faults that infrequently occurred in the system. Line to line to line to ground (L-L-L-G) and line to line to line (L-L-L) are two types of symmetrical faults. These types of fault can also be called as balanced faults. When these types of faults occur, the system remains in balanced condition but results in severe damage towards the equipment involved. Figure 2.1 and 2.2 shows the two types of balanced faults in electrical power system.

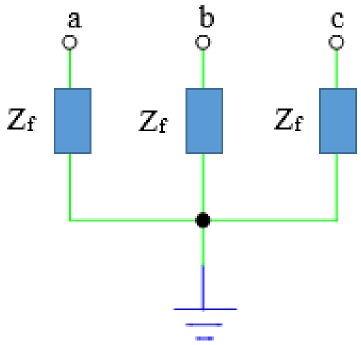


Figure 2.1: (L-L-L-G) fault

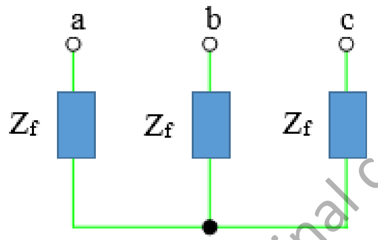


Figure 2.2: (L-L-L) fault



Other than those two types of fault, unsymmetrical faults are line to ground (L-G), line to line (L-L) and double line to ground (L-L-G) faults. Among these three types of fault, (L-G) fault is the most frequent fault that occur in power system which is nearly 70%. These types of faults result in unbalanced of the system. The unbalanced term was used here because these kinds of faults are causing different value of impedance and current flow between phases. Figure 2.3 shows simple illustrations on the types of unsymmetrical faults.

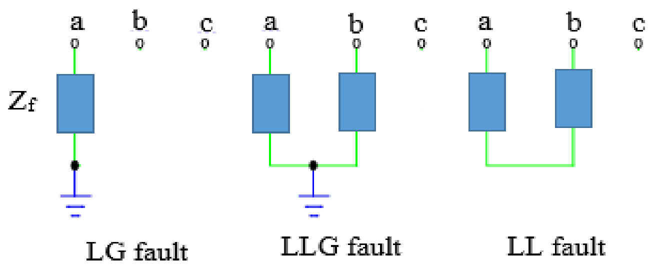


Figure 2.3: Types of unsymmetrical fault

## 2.2 Fault Location Determinations

Generally, the technique of locating fault can be divided into travelling-wave technique, impedance based technique and knowledge based technique (Ghimire, 2014). Besides, there were also other methods such as wavelet method, zero-sequence-component-based method and also composite fault location method. The next section will discuss more about methods of locating fault in power system.

### 2.2.1 Travelling-wave Technique

Travelling-wave technique was proposed by Rohrig in the year 1931. This technique was used to detect the locations of fault on transmission line by detecting an electrical pulse (surge) generated by the fault. The pulse disseminated away from the fault point on both sides and returned to the source. The time taken for the pulse to return represented the distance to the fault point (Ghimire, 2014). There was also a research based on travelling wave theory proposed by Dommel and Michels which was then being improved by McLaren (McLaren & Rajendra, 1985). McLaren developed a correlation-based techniques which estimated the transient signal's time travel from relays to fault point. He formulated a cross correlation between forward and backward travelling waves (Magnago & Abur, 1998). At the time when fault occurred, the incident and reflected waves produced summation of voltage and current. The summation of current and voltage waves can be summarize as shown in equation 2.1 and 2.2 (Reuters, 2015). By assuming a total number of *n* lines connected to a bus bar, the summated waves would be:

$$\text{Summated voltage wave} = \frac{2}{1+n} \tag{2.1}$$

$$\text{Summated current wave} = \frac{2n}{1+n} \tag{2.2}$$

Based on equation in (2.1) and (2.2), conclusion can be made, where when the total number of *n* lines connected to the bus bar increases, the value of summated voltage will decrease and approaching zero, whereas the summation current will be doubled, thus, resulting in very high current production in network system during fault events.

Travelling-wave method depends on the time of disturbance to reach the end of the line. This can be performed by comparing the difference in time of the signals to reach the end of line between each side and the position of fault occurred can be detected. Travelling-wave methods is recognised to have five different types of locators which are Passive Single-Ended Fault Location, Passive Dual-Ended Fault Location, Active Single-Ended Fault Location, High Accuracy Time Tagging At All Terminals, and lastly, Single-Ended Mode (Reuters, 2015).

Passive single-ended fault location is conducted by measuring the time differences between the arrivals and reflected of the first propagated wave. The differences is then divided into half. This is called the propagation velocity ($v_p$). Based on the result, the distance to fault location can be calculated using the formula in Equation (2.3).

$$D_{fault} = v_p \times \frac{\Delta t}{2} \tag{2.3}$$

Where;

$D_{fault}$ distance to fault location

$v_p$ propagation velocity of the travelling wave in the transmission line

$\Delta t$ time differences between arrival and reflected of the propagated wave

Figure 2.4 shows a Bewley-lattice diagram which illustrates the operation principal for passive single-ended method. Passive dual-ended method measures the difference of travelling wave arriving time from fault location to local and remote terminal. There is a delay in time between the arriving and stop signals. The delayed time is then being subtracted from the total difference time and results in time difference of the arrival waves at terminals. From result, an equation can be computed as in equation (2.4)

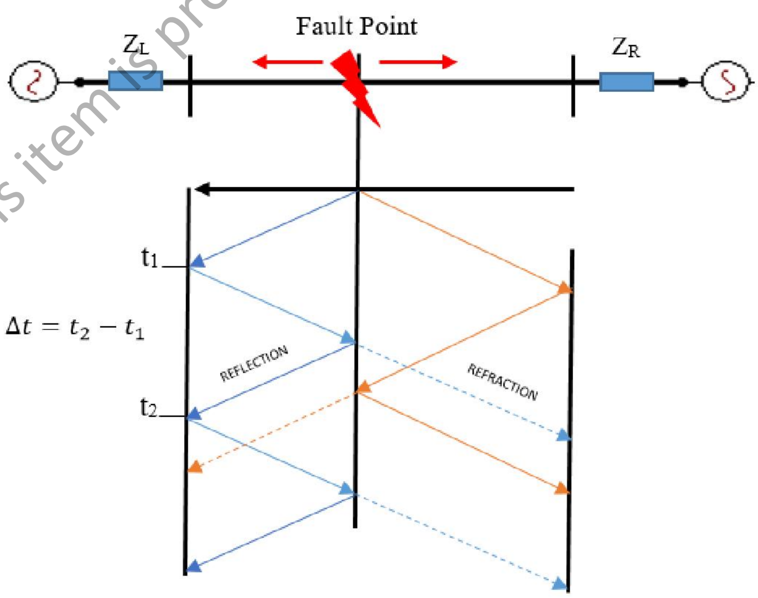


Figure 2.4: Operation principal of Passive single-ended method.

$$D_{fault} = \frac{L}{2} + \frac{v_p \times \Delta t}{2} \tag{2.4}$$

Active single-ended method is a method where an impulse is injected into the line when fault is detected. Differences in time between arrival of the injection impulses and its reflection will be used to calculate the distance of the fault occurred. Another name for this method is Time Domain Reflectometery (TDM) (Reuters, 2015).

Other than that, there is a fault location type that needs very high time tagging at all line terminals and telecommunication between different travelling wave device and central unit. A time synchronized clock was installed at each terminal and time was stamped for every wave arrived and sent to central processing unit. The distance to fault was then calculated using the time stamped. The information sent then triggered by a surge detector resulting in data sampling of the fault location (Reuters, 2015).



Lastly, single-ended mode is a method that uses the transients created by the line that is re-energized when a circuit breaker at one line terminal is closed. The method is equivalent to the impulse current method of fault location which is widely used on underground cables. This method can be used to locate permanent faults, and additionally, can be used to measure the electrical length of healthy lines (Reuters, 2015).

Moreover, travelling wave method is also used to detect fault locations in High Voltage Direct Current (HVDC) transmission lines. A different approach had been developed which is using S transform to analyse the travelling wave in order to present the characteristics and variations in time frequency domain. S transform is a mathematical time frequency analysis method which uses integration value of frequency spectrum in detecting the fault positions accurately (Yuntao et al., 2016).

Travelling wave fault location method has a disadvantage whereby its performance is limited as it can be performed at a frequency band less than 100 kHz of traditional current transformer (CT). Thus, a new transducer, Rogowski coil based electronic current transformer (R-ECT) has been proposed. R-ECT can widen the bandwidth of the frequency up to 1MHz. It has differential output characteristic. It comes with Hilbert-Huang transform (HHT) analysis which is specifically for irregular signal where it can accurately identify the mutation points of differential travelling wave (D. Wang, Gao, Luo, & Zou, 2016).

Besides that, some researches proved that travelling wave method performs very well on branchless network. Unfortunately when fault occurred on branch networks, it fails to work efficiently. Because of that, (Jiang, Wang, Liu, & Ning, 2016) proposed an algorithm that can locate fault on branch networks. The researchers applied an improved transient detection technique based on Park's transformation (TDQ) whereby it can simply retrieve initial travelling wave at every branch terminal. Unlike wavelet transform method which needed several previous travelling wave sample for travelling wave monitoring, based on TDQ characteristics, this technique does not require any sample storage, thus simpler to implement. This method can also be called as multi-terminal algorithm. The moment when initial travelling waves arrived at each branches, the time difference of arrival (TDOA) was analysed and recorded. With the aid of synchronized transient detection module (STDM) positioned at each branch, the fault location can be detected precisely.

Multi-terminal high voltage direct current (MTHVDC) is important for transporting power supplies from large offshore renewable power stations. The needs of an intelligent and high speed system to locate faulty area in the system are for maintaining the stability of the system and continuity of supply. Hossam-Eldin, Lotfy, Elgamal and Ebeed (2016) proposed a fault locating method called Hybrid travelling wave fuzzy logic based wavelet decomposition. This is a combination of two methods which are travelling wave and fuzzy logic. Fuzzy logic is used to analyse non-stationary current travelling waves formed at fault location. The captured wave is further decomposed by wavelet analyser. Lastly, the data collected is transferred to a travelling wave based algorithm to identify the exact fault locations.



### 2.2.2 **Impedance Based Technique**

Commonly, the easiest way in determining fault location is by calculating impedance of the faulted line using the voltages and currents at terminals which resembles the distance to the faults' position. This technique is called impedance based fault location algorithm. Based on the input signal from fault locator, this technique can be classified into several cases which are two terminal and single-circuit line, double circuit lines, also application to three terminal lines and multi-terminal and tapped lines (Saha et al., 2009).

Referring to the two terminal and single-circuit line case, the measurement can be utilised by using the following method which are three-phase current and voltage measured at one line end, three-phase current and voltage measured at two line ends and lastly, incomplete three-phase voltage and current measured at two line ends (Saha et al., 2009). Among all of them, the one line end method is simpler and economical compared to two line end methods and those based on the travelling wave and high frequency component techniques. Therefore, this technique is still quite popular among electric power utilities.

Figure 2.5 illustrates the one end impedance based fault location method which estimates the location by analysing from only one end of a transmission line. With the aid of intelligent electronic device (IED), fault can be determined by installing it at one end of a line by determining the apparent impedance between the device and fault locations. Besides, this method is easy to be implemented as they don't need any remote data or communication channels (Das, Santoso, Gaikwad, & Patel, 2014).

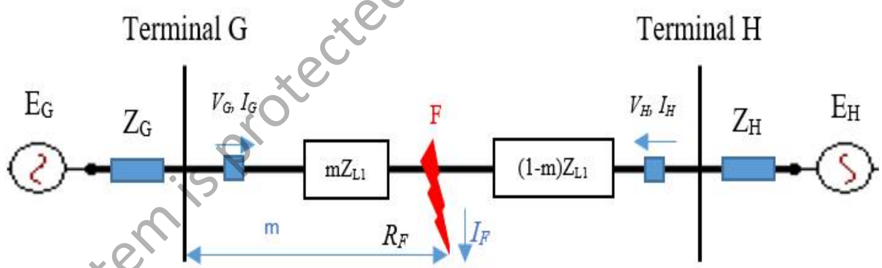


Figure 2.5: Single line diagram of a two terminal transmission network.



Based on figure 2.5, the law of one-ended method can be illustrated. Considering the two terminals G and H, the transmission line have a total impedance represented as $Z_{L1}$. $Z_G$ and $Z_H$ is the respective of thevenin impedance equivalents. $R_F$ represents the resistance of fault occurred at a distance of $m$ from terminal G. This results in total current fault of $I_F$. With the aid of IED, voltage and current phasors are recorded at terminal G and labelled as $V_G$ and $I_G$ respectively. The same applies at terminal H, where the recorded