Estimation Of Fault Location In Power IEEE 14 Bus System Based On the Value Of Voltage Sag And Phase Angle Using Matching Approach

Lilik Jamilatul Awalin[1], Muhammad Akbar Syahbani[2],Waldi Abdillah[3]

[1,2,3] Universitas Airlangga, Surabaya, 60115, Indonesia

lilik.j.a@ftmm.unair.ac.id

Abstract. The reliability of the electrical network system can be influenced by several factors, one of which is faults. Faults can interrupt the electrical network, leading to severe consequences, including blackouts. The location of the fault needs to be promptly identified to minimize the resulting losses. This research focuses on single-phase-to-ground faults and utilizes voltage sag and phase angle to determine the location of the faults. The method used is the Matching Approach, which identifies the location and distance of fault in the IEEE 14 Bus System. In brief, this method is based on the principle of locating faults through simulation and mathematical approaches. In this study, the data and the implementation of the method are carried out on the transmission network in the IEEE 14 bus power system. Single line-to-ground faults (SLGF) are applied to several nodes, occurring at the n-th second and lasting for half a cycle, causing voltage sag. The estimation of the fault location is simulated using PSCAD software. PSCAD is chosen because it can simulate faults and display real-time results. The research analyzes the fault location for line sections of various lengths: 10 Km, 50 Km, 75 Km, and 100 Km. The results indicate that the Matching Approach method is more accurate when applied to a line length of 10 Km, with an error rate of <1%. The Matching Approach method accurately identifies faulty sections for all line lengths. However, for line lengths of 50 Km, 75 Km, and 100 Km, there is a significant difference between the actual distance and the calculated distance using the Matching Approach method. Thus, estimating the fault location using the Matching Approach method can be implemented in the transmission network, and the maximum applicable section length is 10 Km.

Keywords: Matching Approach, Phase Angle, Transmission System, Voltage Sag

1 Introduction

In an electrical power system, faults are one of the critical factors that impact reliability [1]. Although faults are unavoidable, they can occur due to a range of causes, including malfunctions. [2], [3]. When a fault occurs in the power system, the fault location cannot be determined solely through visual observation[4], [5]. Therefore, a method is needed to determine the location of the fault. There are many methods to locate faults, including the travelling wave and impedance-based methods. These are

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first generation methods or classified as conventional methods. These methods identify faults and potential fault locations by comparing the relative distances of each "peak" of the high frequency current signal to a known reflection point in the distribution network [6]. On the other hand, the Impedance-Based method uses impedance values to determine fault location. This method utilizes voltage and current data for impedance calculation [7]. However, implementing these methods still has shortcomings, such as being influenced by system non-homogeneity, measurement errors inline parameters, inaccuracies in relay measurements, and fault resistance[8].

Based on the principle of locating faults in research, detecting fault locations requires a method that is both fast and low in error and economical to reduce operational costs. The Matching Approach method is one such economical method because it only requires measurements at the substation[9]. Thus, this study uses the Matching Approach to identify faults. Moreover, this method can enhance the conventional methods initially developed. It can be implemented in standard networks like the IEEE 14-bus power system analyzed in this study.

The Matching Approach method is applied to identify the location and distance of faults in the power system. Briefly, this method operates by locating faults through simulation and mathematical approaches[10], [11]. When a fault occurs in the power system, observable changes include voltage, current, and phase angle[12]–[14] By utilizing these easily observable variables, voltage, current, and phase angle data are collected through measurements taken at the substation[15]. These variables are compiled into a measurement database. The quick process, ease of use, and high accuracy make this method highly feasible for technicians. Fault location identification using the matching approach has been conducted in [16]–[18], which was applied to distribution networks. This study will be conducted on transmission networks. This contributes to the research by testing different feeder lengths 10 km, 50 km, 75 km, and 100 km.

2. Method

2.1 System Flowchart

Figure 1 represents the overall steps carried out during the research work. The research was conducted on the IEEE 14-bus power system. The system was simulated using PSCAD software. Faults were then simulated at the sending and receiving buses. The simulation data were collected into a measurement database and analyzed mathematically. The next point in the flowchart shows the process of analyzing the faulty section. A section is considered faulty if it satisfies Equations (1) and (2). In this section, the analysis is focused on identifying the part with the highest probability of a fault from the various sections in the network. The research continues with the ranking process. Ranking is performed because more than one section may meet the criteria for a faulty section. The ranking process involves ordering the sections based on the smallest short distance (dk). Once the section with the highest fault probability is identified, the location and distance of the fault can be analyzed using Equation (5).

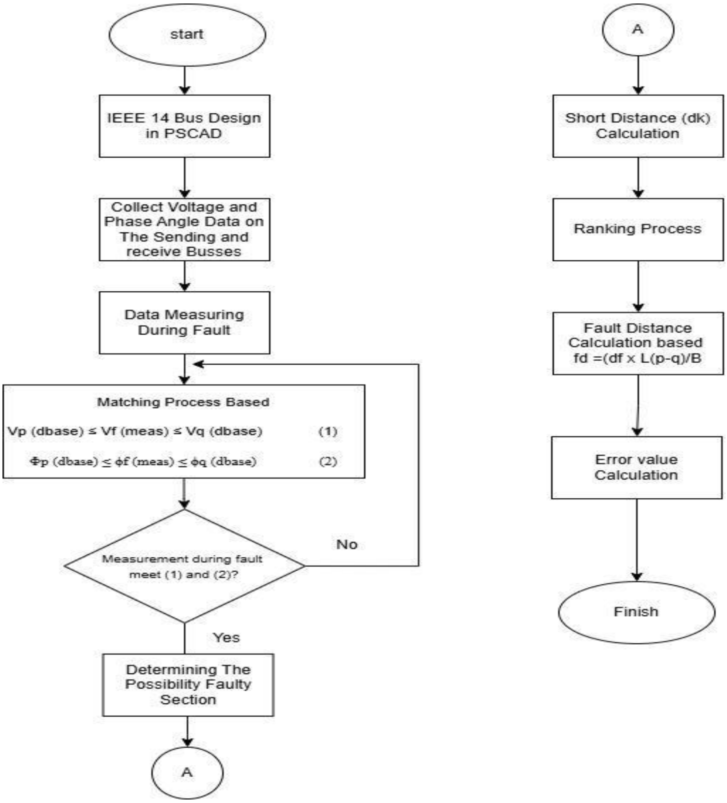

Figure 1. Flowchart of Fault Location

2.2 Testing Power System Network

This research uses data from simulations based on the IEEE 14-bus power system. This circuit model is one of the complex interconnection networks and serves as a standardized network used as a test case for power systems. The IEEE 14-bus system represents the American Electric Power System, consisting of 14 buses, 5 generators, and 11 loads.

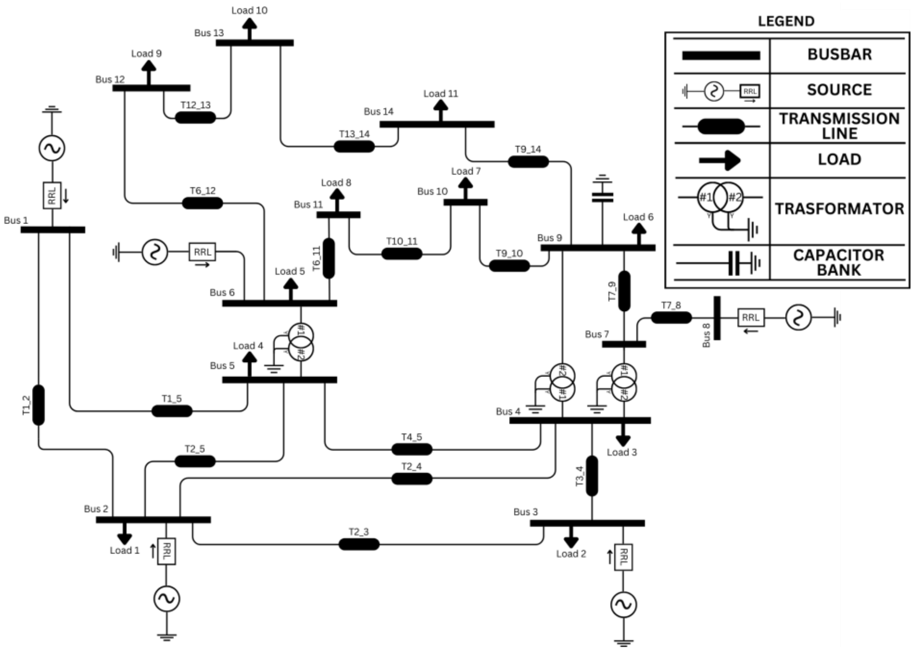

Fig 2. *IEEE 14 Bus System Network*

Figure 2 depicts the IEEE 14-bus power system created in the PSCAD software. A single phase to ground fault will be applied at one of the locations between adjacent feeders. In this network, the type and timing of the fault can be implemented in real time. From the fault simulation results, voltage sag, current, and phase angle will be obtained and stored in a database.

2.3 Faulty Section Identification

The faulty section is identified by comparing the magnitude of the actual voltage sags and phase angle due to the fault with the magnitude of the voltage sags and phase angle in the database. The section likely experiencing the fault is selected when the magnitude of the voltage sag and phase angle fall between the voltage sag magnitude and phase angle values of two adjacent nodes, as shown in Equations (1) and (2) below [15].

$$Vp\ (dbase) \leq Vf\ (meas) \leq Vq\ (dbase) \quad (1)$$

$$\Phi p\ (dbase) \leq \phi f\ (meas) \leq \phi q\ (dbase) \quad (2)$$

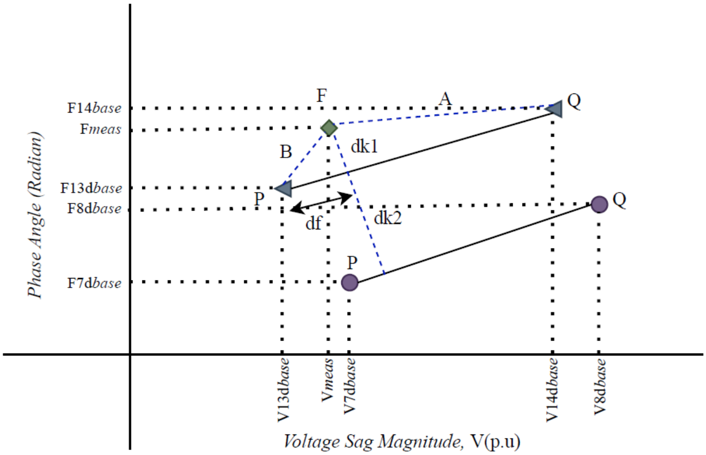

Fig 3. *Fault Location Analysis With Matching Approach*

Vp (dbase) and Vq (dbase) represent the voltage magnitudes obtained from the measurements at the sending and receiving buses, respectively. Meanwhile, φp (dbase) and φq (dbase) represent the phase angles from the simulation in the database, resulting from the fault measured at the sending and receiving buses. The sending and receiving buses are sequentially adjacent buses.

2.3 Ranking Process

For each fault simulation conducted on every bus, multiple sections may satisfy Equations (1) and (2), meaning that more than one section could meet these criteria[19]. This could occur due to the similarity of voltage and phase angle values within the voltage and phase angle range of a particular section's sending and receiving buses. A ranking process is applied to address this issue. The ranking is based on dk to determine the section with the highest probability of being the faulty section. The ranking order is determined by sorting the sections in ascending order of dk, with the smallest (dk) indicating the most likely faulty section. Using trigonometric equations, the short distance dk is calculated through Equation (3)[6].

$$d_k = |sin\theta_{BC}| \quad (3)$$

Where

$$\theta_{BC} = Cos^{-1}[(B^2 + C^2 - A^2)/(2\ x\ B\ x\ C)] \quad (4)$$

$$A = \sqrt{(\emptyset_P^{(dbase)} - \emptyset_F^{(meas)})^2 + (V_F^{(meas)} - V_P^{(dbase)})^2}$$

$$B = \sqrt{(\emptyset_P^{(dbase)} - \emptyset_q^{(dbase)})^2 + (V_q^{(dbase)} - V_P^{(dbase)})^2}$$

$$C = \sqrt{(\emptyset_F^{(meas)} - \emptyset_q^{(dbase)})^2 + (V_q^{(dbase)} - V_F^{(meas)})^2}$$

2.4 Fault Distance Analysis

Fault distance is the fault location analysis calculated within the faulty section. In the results of this research, the fault distance will be presented in kilometers. The identified distance is measured from the sending bus. In this fault distance calculation, a mathematical approach is used, as shown in the following equation[18].

$$Fd = \left|\frac{df}{l(p-q)}\right| x\ length\ section \tag{5}$$

$$df = \sqrt{(Vf - Vp)^2 + (\varphi F - \varphi S)^2} \tag{6}$$

$$l(p-q) = \sqrt{(Vq - Vp)^2 + (\varphi P - \varphi S)^2} \tag{7}$$

This equation obtains the fault distance using Equation (5), where *df* represents the assumed distance from the sending bus to the fault point. Meanwhile, *Lp-q* is the actual length of the cable. This equation is based on trigonometric principles. The voltage and phase angle at the sending and receiving buses form coordinates. A linear line is drawn between the coordinates of the sending and receiving buses. The distance between the voltage and phase angle coordinates during the fault simulation is drawn perpendicular to this linear line, allowing Equation (5) to be applied. An illustration of the voltage and phase angle coordinates can be observed in Figure 3.

3. Result

3.1 Fault Distance on Section 10 Km

Based on the analysis of the fault location using Equation (5), the fault distance results obtained using the Matching Approach method are shown in Table 1. This table contains information on the test fault locations in the PSCAD simulation along with the fault distance analysis results using the Matching Approach method. The length of the section used in the test is 10 km. In this 10 km network, the fault is placed in the middle of the network (5 Km). Thus, the accuracy of the Matching Approach method can be assessed. The estimated fault location for the 10 km section shows that the difference between the test fault location in PSCAD and the results from the Matching Approach method is minimal. Therefore, implementing this method for a 10 km IEEE 14-bus transmission network is considered adequate. Table 1 also shows the possible faulty sections and their rankings. This allows the inspection team to repair the network promptly and accurately regarding the fault location.

Table 1. Fault Distance Analysis Section Length 10 Km

Section length	*Test Section*	*Location Test*	*Fault distance*	*Possibility Faulty Section*	*dk*	*Ranking*
10 Km	(9-14)	5 km	5,10 km	(9-14)	0,0148	1
				(9-10)	0,0231	2
				(7-8)	0,05	3
	(2-3)	5 km	4,97 km	(2-3)	0,0342	2
				(3-4)	0,0065	1
	(7-8)	5 km	5,20 km	(7-8)	0,0092	1
	(4-5)	5 km	4,98 km	(4-5)	0,0324	2
				(2-5)	0,0103	1

3.2 Fault Distance on Section 50 Km

The fault location estimation for a section, as shown in Table 2, is analyzed for a 50 km section length. The results indicate that the Matching Approach method can provide accurate fault section results. However, for a 50 km section length, the fault distance estimation using the Matching Approach shows a significant deviation. Additionally, there are several sections ranked 2 and 3. This requires the inspection team to prioritize inspections of the section ranked 1 first, potentially increasing the time needed to repair the network.

Table 2. Fault Distance Analysis Section Length 50 Km

Panjang *Section*	*Test Section*	*Location Test*	*Fault distance*	*Possibility fault section*	dk	*Ranking*
50 km	(13-14)	25 km	36 km	(13-14)	0,0225	2
				(9-10)	0,006	1
	(10-11)	25 km	36,16 km	(9-10)	0,0194	1
				(10-11)	0,0355	2
				(12-13)	0,0331	3
	(9-10)	25 km	35 km	(9-10)	0,016	1
	(12-13)	25 km	30,62 km	(12-13)	0,0615	1

3.3 Fault Distance on Section 75 Km

The fault location was subsequently estimated by setting the Pi Section component line length in PSCAD to 75 km. The fault was applied in the middle of the line, at 35 km. The deviation from the actual distance at 75 km is quite large. Despite the significant deviation, the faulty section was successfully identified, and the entire system ranked 1. This can be seen in Table 3.

Table 3. Fault Distance Analysis Section Length 75 Km

Panjang	*Test Section*	*Location Test*	*Fault Distance*	*Possibility Faulty Section*	dk	*Ranking*

Section						
75 km	(6-13)	35 km	59 km	(6-13)	0,0476	1
				(6-12)	0,0482	2
	(6-12)	35 km	52,05 km	(6-12)	0,0591	1
				(6-13)	0,0597	2
	(2-5)	35 km	63,6 km	(2-5)	0,0508	1
	(6-11)	35 km	50.11 km	(6-12)	0,1326	1

3.4 Fault Distance on Section 100 Km

The fault location estimation using the Matching Approach method was conducted for a section of 100 km. There was a substantial discrepancy between the estimated result and the actual fault location. The most significant deviation occurred at Node 2-4, with the fault positioned at the section's midpoint (50 km). Although the deviation was considerable, the method successfully identified the faulty section at this distance. The process can indicate where the fault happened for a 100 km section, though the fault distance varies significantly from the actual location.

Table 4. Fault Distance Analysis Section Length 100 Km

Panjang *Section*	***Test Section***	***Test* Lokasi**	***Fault Distance***	***Possibility Faulty Section***	**dk**	***Ranking***
100 km	(1-2)	50 km	35,88 km	(1-2)	0,216	2
				(2-4)	0,0045	1
	(1-5)	50 km	79,148 km	(2-4)	0,0169	2
				(1-5)	0,081	1
				(1-2)	0,2177	3
	(2-4)	50 km	88,9 km	(1-2)	0,1784	1
				(2-4)	0,2326	2
	(3-4)	50 km	85,78 km	(1-2)	0,1831	1
				(3-4)	0,1907	2

3.5 Error Analysis on Section Length 10 km

Figure 4 illustrates the error values for fault testing with a section length of 10 km. The simulation results showed minimal fault distance discrepancy compared to the fault location analysis using the Matching Approach method. The total network length in this simulation is 160 km. The fault simulation test at this distance had an error of less than 1%. The Matching Approach method method remains applicable based on the 10 km section test results.

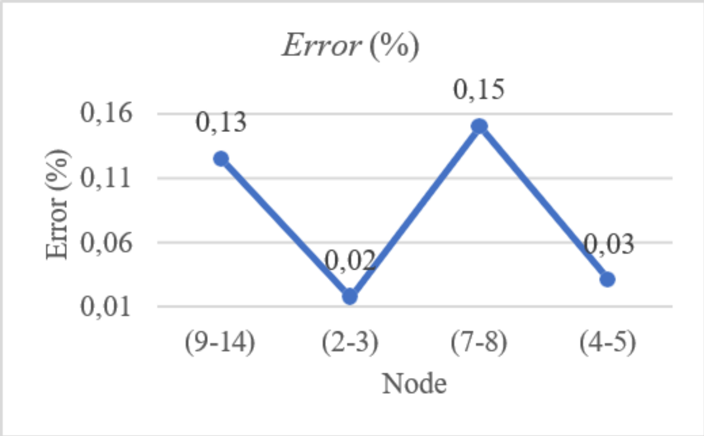

Figure 4. Error Measurement on 10 Km Feeder Length

3.6 Error Analysis on Section Length 50 km

Figure 5 presents a graph that shows the error values during fault testing across different sections. The fault test distance was randomly placed for each section. The results from the Matching Approach method displayed a considerable difference compared to the test distances in PSCAD. Although the Matching Approach successfully pinpointed the section where the fault occurred, the discrepancy between the estimated and actual distances was still quite large. The section length, in this case, was 200 km. For a section length of 50 km, the Matching Approach method yielded an error within a 5% range. Even though there was a significant distance deviation, the error remained within 5%, indicating that the Matching Approach can still be used for a 50 km section, though it is not advisable.

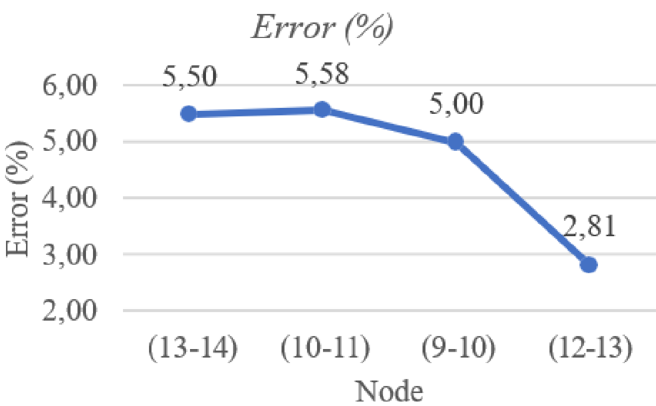

Figure 5. Error Measurement on 50 Km Feeder Length

3.7 Error Analysis on Section Length 75 km

Figure 6 shows a graph illustrating the percentage error in fault location estimation. The total network length is 225 km. In the 75 km section test, faults were tested at random distances, as shown in Figure 6. The results revealed a significant distance discrepancy, with error percentages exceeding 5%. This indicates that the Matching Approach method is not recommended for fault location analysis at this distance.

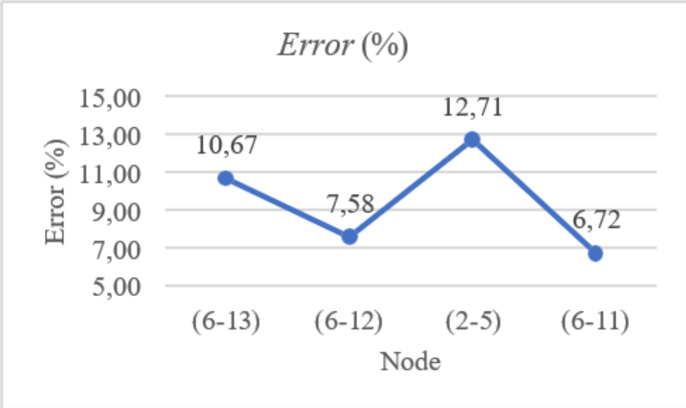

Figure 6.Error Measurement on 75 Km Feeder Length

3.8 Error Analysis on Section Length 100 km

In the fault testing for a 100 km section, there was a significant discrepancy between the actual fault location and the results from the Matching Approach method, as shown in Figure 7. This testing was conducted on a network with a total line length of 250 km. The Matching Approach method produced a distance error with a percentage greater than 5%. Therefore, applying the Matching Approach method for this distance in the IEEE 14-bus transmission system is not recommended.

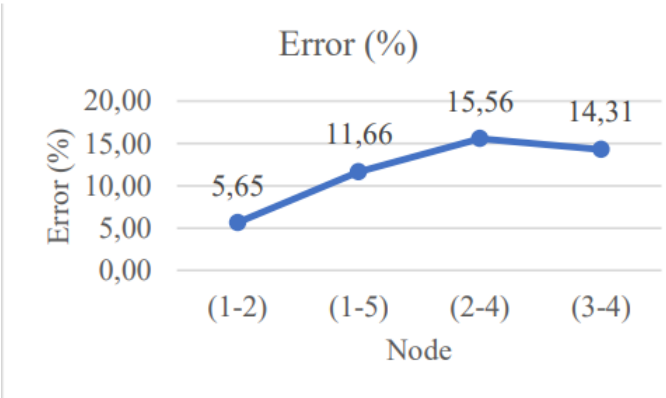

Figure 7.Error Measurement on 100 Km Feeder Length

4. Discussion

4.1 Analysis of The Innacurracy of The Matching Approach Method

In the fault location analysis using the Matching Approach method, faults were assessed on sections of 10 km, 50 km, 75 km, and 100 km. The variations in section length were tested to determine which section length could accurately analyze fault locations using the Matching Approach. The research results indicated that fault location estimation for sections of 50 km, 75 km, and 100 km was inaccurate due to significant discrepancies between the actual and measured distances.

As proposed by Awalin et al. 2019, the Matching Approach method was initially designed for distribution networks, typically characterized by shorter line lengths. In contrast, this study applied the Matching Approach to long-distance transmission networks. Voltage measurements taken from substations show that the sag voltage at the receiving bus is lower than the sending voltage due to resistance effects. As a result, more extended networks tend to have higher measurement errors. In the IEEE 14-bus transmission system, there are instances where the mistake in longer sections can be more minor compared to shorter distances from the sending bus, influenced by the presence of other power flows.

The entire power flow shifts to the fault point when a fault occurs, as illustrated in Figure 8.

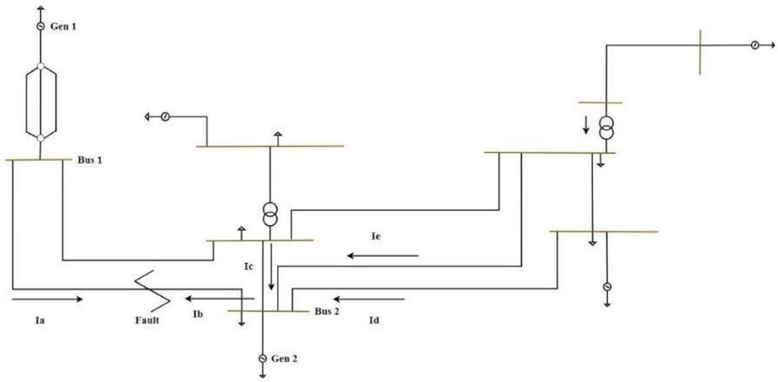

Figure 8 illustrates the condition of buses 1-2. During the fault simulation test for this section, faults were tested at distances of 2 km, 3 km, 4 km, and 7 km within a section length of 10 km and a total network length of 160 km. The error for the 2 km distance was 0.43%, which increased to 0.725% at 3 km and rose to 0.944% at 4 km. However, the error decreased to 0.3% at 7 km. According to Hazlie Mokhlis & Li, 2011, the error at 7 km should have been more significant. Still, in this testing scenario, as shown in Table 5, the error at 7 km is relatively small due to the influence of power flow. Voltage analysis due to contributions from other power sources was calculated as follows.

$$V_a = I_a \text{ x } Z_{line\ 7km} + Z_{line\ 3km} \text{ x (Ib+Ic+Id+Ie)} + R_f \text{ (Ia+Ib+Ic+Id+Ie)} \quad (8)$$

Where Ia, Ib, Ic, Id, Ie are the currents from the generator shown in Figure 8. Furthermore, Rf is the fault resistance and the Z line is the impedance of the distance to the fault point. The fault occurred 7 km from the first generator, near the second generator. This proximity allows the second generator to contribute to the power flow during the voltage drop, minimizing the error, as shown in Table 5.

Table 5. Error Fault Distance Analysis

Voltage Sag	***Fault Test Distance***	***Fault Distance Calculation***	***Error***
15, 881	2 Km	1,35 Km	0,47 %
16,347	3 Km	1,85 Km	0,70 %
16,916	4 Km	2,5 Km	0,94%
17, 934	7 Km	6,52 Km	0,3 %

5. Conclusion

Based on the fault location and distance estimation study findings, the following points were observed.

a. The Matching Approach method is effective in transmission networks with a maximum viable length of 10 km.

b. The method can be applied to transmission networks up to 10 km long.

c. The fault distance estimation using the Matching Approach method has an error margin of less than 1% for a test section of 10 km.

d. For sections of 50 km, the error rate increases to approximately 5%. While the Matching Approach method can still be applied at this distance, it is not advisable due to the significant deviation.

e. For section lengths of 75 km and 100 km, the estimation errors become substantial, exceeding 5%, rendering the Matching Approach method impractical for these distances.

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