JSR Publications

Available Online

J. Sci. Res. **17** (1), 43-55 (2025)

JOURNAL OF SCIENTIFIC RESEARCH

www.banglajol.info/index.php/JSR

Advanced Digital Signal Processing, Interpolation and Extrapolation Based Symmetrical Fault Assessment in Transmission Line

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Received 12 April 2024, accepted in final revised form 17 October 2024

Abstract

This article describes a novel method for locating and detecting triple line to ground (LLL-G) faults in 110 km of 132 kV transmission lines. To find the transmission line fault, the three phase system currents were first recorded at the appropriate sampling frequency. Then, the total harmonic distortion (THD) and direct current (DC) components were computed using the Fast Fourier transform (FFT). When compared to normal conditions, high values of THD and DC components have been seen in fault situations; fault has been identified as a result. The fault distance in the transmission line has been measured using spline extrapolation or linear interpolation. With this method, very encouraging outcomes have been obtained for fault assessment in transmission line.

Keywords: FFT; THD; DC Component; Fault; Transmission line; Linear interpolation; Spline extrapolation.

doi: https://dx.doi.org/10.3329/jsr.v17i1.72628 J. Sci. Res. **17** (1), 43-55 (2025)

1. Introduction

A fault in any power system is defined as a failure that prevents electric current from flowing properly. This can include the short circuit fault as well as open circuit fault. In transmission line, short circuit faults are generally very high, approximately 6 to 10 times of full load current in that particular system. Typical faults in power systems are 'single line to ground fault', 'line to line to ground fault', 'line to line to line to ground fault', and a 'line to line fault' [1]. These types of problems are also known as short circuit faults and are common in transmission lines. The power transmission network must be secured from the flow of significant short-circuit currents, which might threaten personnel safety and cause permanent damage to key equipment, by disconnecting the problematic component of the system. The transmission line consists of resistance, inductance, capacitance and shunt or leakage conductance. These elements, in combination with the transmission lines and loads, define the power transmission system performance. The term "performance" refers to the sending end voltages, currents, power factor, power loss in the line. When a fault occurs in transmission lines, it impacts the power system availability and continuity of

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operation. This happens due to fault occur that are not resolved promptly, they generate power outages, which can result in service disruption. Furthermore, when a problem is experienced, it compromises the lives of individuals and equipment [2]. Mirzaei *et al*. [3] stated in a study of the fault location technique of distribution power that there are already a number of basic methods for identifying transmission line problems. The impedance-based technique is one of them. This kind of approach uses an impedance-based technique to estimate the fault's distance from the principal distribution bus to the problem location. In this kind of application, the received voltage and current readings are utilized to solve mathematical equations in order to determine the location of the problem. One or both ends of this kind of approach can yield the voltage and current numbers. This is referred to as the single-ended and double-ended methods, respectively, in this instance. The impedance-based approach is the simplest of all the strategies, but this shows that there are certain drawbacks, such as multi-estimation, which claims that although this method is exact, it is not accurate since estimations are made across a potential sequence of failures. Although the travelling wave method uses a certain principle from the impedance-based approaches, it is a far more accurate and precise fault detection technique. Power systems that provide energy to three major structures essential to daily operations are susceptible to faults. Goh *et al*. [4] analyzed fault finding approaches in the electrical power system and state that human, equipment, and natural causes can all contribute to problems in these systems. Because of this, fault location is important to guarantee that the system is operational constantly to decrease the revenue losses and reduce the risks to the environment and the equipment. It claims that a traveling-based approach is more beneficial for locating faults in the transmission lines since it is not impacted by factors such as high grounding resistance, series capacitor bank, or load fluctuation. The gadgets required for this strategy may make it considerably more expensive even if it is a far more efficient solution. The ability to create an effective model for a three-phase power system is a crucial component of the study. In this study, no method will be considered effective if it does not have a functional simulated environment. The three-phase Power System Network Simulation Model in MATLAB conducted by Tharani *et al*. [5] demonstrates the reliability and convenience of using MATLAB software for the investigation and modelling of three-phase faults in transmission lines. A unique system of analysis and detection of transmission line faults was evaluated using MATLAB Simulation with Simulink and the Sim Power toolkit. The LG fault, LL-G fault, and LLL-G fault were tested. The study efficient use of MATLAB software is demonstrated by Karekar, Thakur, and Manju [6]. The system used in this study includes distributed parameter lines, three-phase simulators, and 33kV generators. In this model, the distributed parameter lines represent the transmission line faults, and the three-phase simulators function is to simulate faults at the midpoint. In literature [7], Fast Fourier Transform (FFT) based phasor measurement unit has been implemented to identify the fault in double circuit transmission line. In this analysis, second (2nd) harmonic to third (3rd) harmonic ratio has been used to classify the faults in the transmission line. Now a days Wavelet Transform (WT) is widely used for different purposes, such as to extract frequency information, nonlinear equation solution, denoising of signal etc., but selection of a suitable mother wavelet is very difficult, and this is absolutely problem-specific [8,9]. In literature [10], discrete Wavelet transform (DWT) based skewness and kurtosis has been used to detect line-to-ground, line-to-line faults in IEEE standard 9 (Nine) bus system. Clarke' transform and DWT used elsewhere [11], to detect fault type, phase and position of the fault in 115 kV transmission system. In this analysis, on three phase current signals Clarke's transform has done to extract positive sequence, zero sequence and alpha sequence current and DWT was done thereafter to assess the faults. N. Ahmed et al. proposed DWT based fault analysis in 500kV transmission system. In this analysis MATLAB is applied to simulate and identify different transmission line faults [12]. Stationary Wavelet Transform (SWT) and Continuous Wavelet Transform (CWT) fault assessment in transmission line was discussed [13], where SWT was used to detect the faults and CWT was used to extract faulty area. In literature [14], multi-learner based single phase-earth fault detection models are proposed. Originally, a denoising model based on the WT optimized by the suggested threshold improvement technique is proposed to remove disturb noise in fault recording profiles. In order to identify the most efficient combination of fault feature set, two essential feature transforming methods- 'principal component analysis (PCA)' and 'random forest (RF)'- are separately applied after feature engineering reflecting the local and/or global evolutionary process of fault evolving features is modeled. The feature subset in high priority is then input into six learners of logistical regression (LR), K-neighbor (KN), support vector machine (SVM), XGBoost, RF, and LightGBM based fault identification models, each of which is completely custom-designed. Datta *et al*. proposed ANN and Stockwell transform (ST) based Statistical analysis to detect different faults in IEEE 14 bus microgrid [15,16]. Mukherjee *et al*. suggested DWT and Stockwell Transform (ST) based statistical analysis for assessment of faults in grid connected wind system [17].

None of the aforementioned works, 'line-to-line-to-ground fault' has been assessed by THD, DC component, interpolation and extrapolation techniques. This has been motivated the authors to do the work in this way. So, the objective of this work is quick identification of symmetrical (most severe) faults in transmission lines based on FFT-based DC components and THD analysis, followed by finding out the distance location of faults by spline extrapolation and linear interpolation on fault data.

The rest portion of this work is structured as follows: section-2 describes simulated network of transmission line, section-3 narrates analytical methods for fault analysis, flow chart of proposed methods is described in section-4, section-5 describes results and discussions, and ultimately section 6 describes conclusions of this work.

2. Transmission Line Simulated Network

132 kV double ends fed 110 km single circuit transmission line has been considered for three lines to ground (LLL-G) fault analysis and single line diagram of this is depicted in Fig. 1, where circuit has been simulated in MATLAB Simulink platform. Here double end fed, 220 kV voltage source and 50 Hz system frequency have been considered. Within 110 km transmission line, LLL-G faults are created at different distances. In normal and fault

conditions the three phase outgoing currents of bus 1 is captured for analysis. Distributed line parameters have been considered for the analysis where positive sequence and zero sequence resistance, inductance and capacitance values per kilometer (km) are considered as 0.01273 Ω, 0.3864 Ω, 0.9337e-3 H, 4.1264e-3 H, 12.74e-9 F and 7.751e-9 F. Total simulation time is considered as 0.5 second (sec).

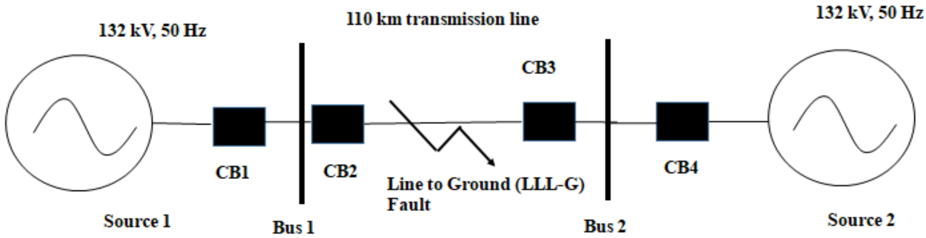

Fig. 1. 132 kV, 110 km Double End Fed Transmission Line.

3. Analytical Methods

Fast Fourier Transform (FFT), interpolation and extrapolation have been used to detect of the symmetrical fault and, locate that fault in the transmission line.

3.1. *Fast Fourier Transform (FFT)*

FFT is used in different fields. To extract frequency information from a stationery signal FFT is used. Using this mathematical tool time domain data is converted to frequency domain [7]. In FFT, analysed signal is broken down in the form of series of sinusoids. FFT is faster than discrete Fourier transform (DFT). In continuous time domain and discrete time domain Fourier Transform (FT) can be done. FT of a function y(t) is Y(ω), where, [18,19]

$$Y(\omega) = \int_{-\infty}^{\infty} y(t) e^{-j\omega t} dt \tag{1}$$

Inverse FT of Y (ω) is y (t) which is expressed as,

$$y(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} Y(\omega) e^{j\omega t} d\omega \tag{2}$$

Where, Y(ω) is the signal’s spectrum. Cooley and Tukey proposed the Fast Fourier Transform (FFT) in 1965. which reduces the computation time and complexity of DFT. Using two algorithms FFT can be calculated. One is Decimation in Time (DIT) another is Decimation in Frequency (DIF). To compute ‘N’ point DFT, total number of N2 complex multiplications are required where as to calculate FFT, N/2 log2N complex multiplication are required. This is the advantage of FFT over DFT.

4. Flow Chart of Proposed Method

Fig. 2 depicts a flow diagram for the suggested approach.

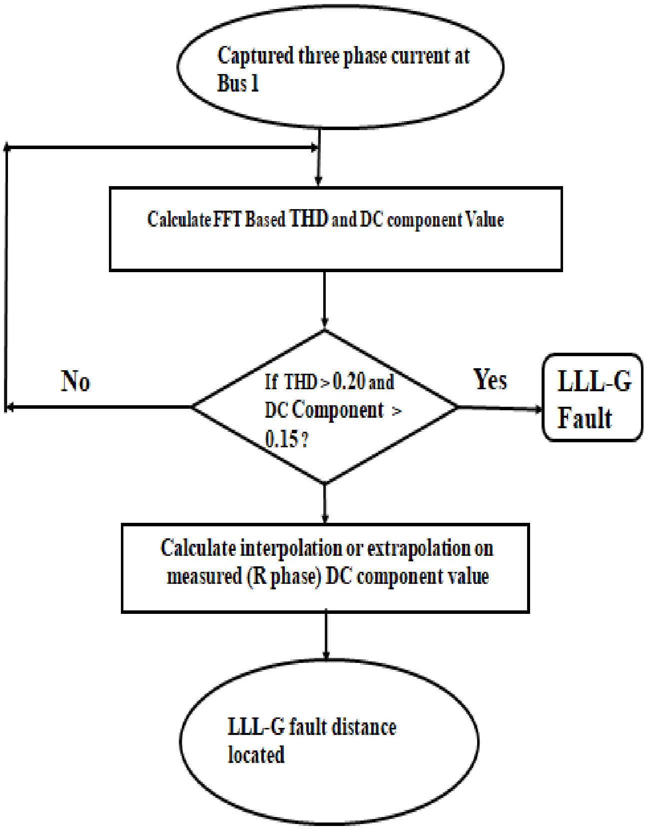

Fig. 2. Flow diagram for the proposed technique.

5. Results and Discussion

5.1. *FFT based THD analysis*

In normal condition, three phase outgoing currents of Bus1 have been captured and FFT has been done. Fig. 3a depicts the three phase currents at normal condition. Fig. 3b to Fig. 3d limns the FFT results of ‘R, Y, and B’ phase current at this condition. Total harmonic distortion (THD) of ‘R, Y, B’ phase currents have been observed as 0.01 %, 0.15 % and 0.17 %.

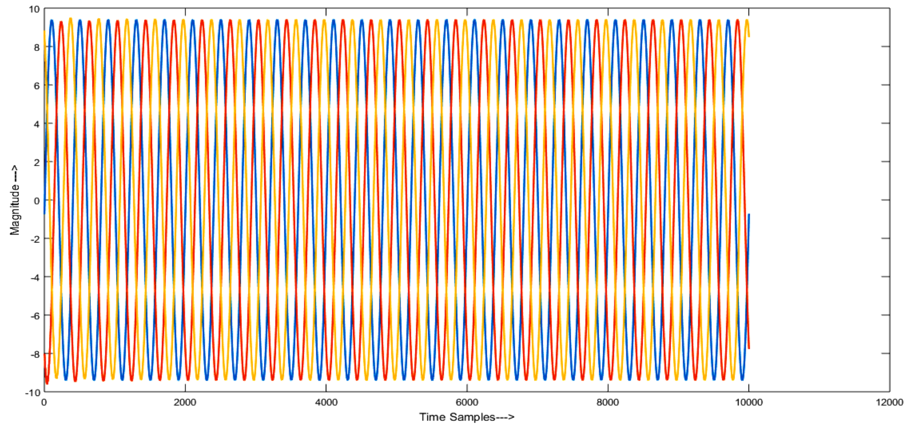

Fig. 3(a). Three phase system current at normal condition.

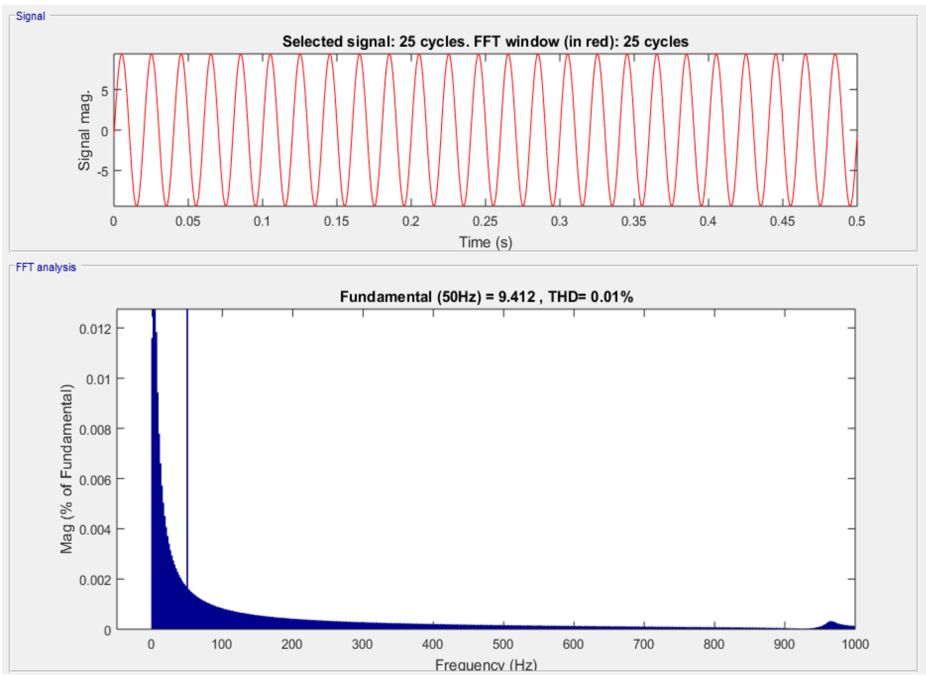

Fig. 3(b). FFT of ‘R’ Phase current signal.

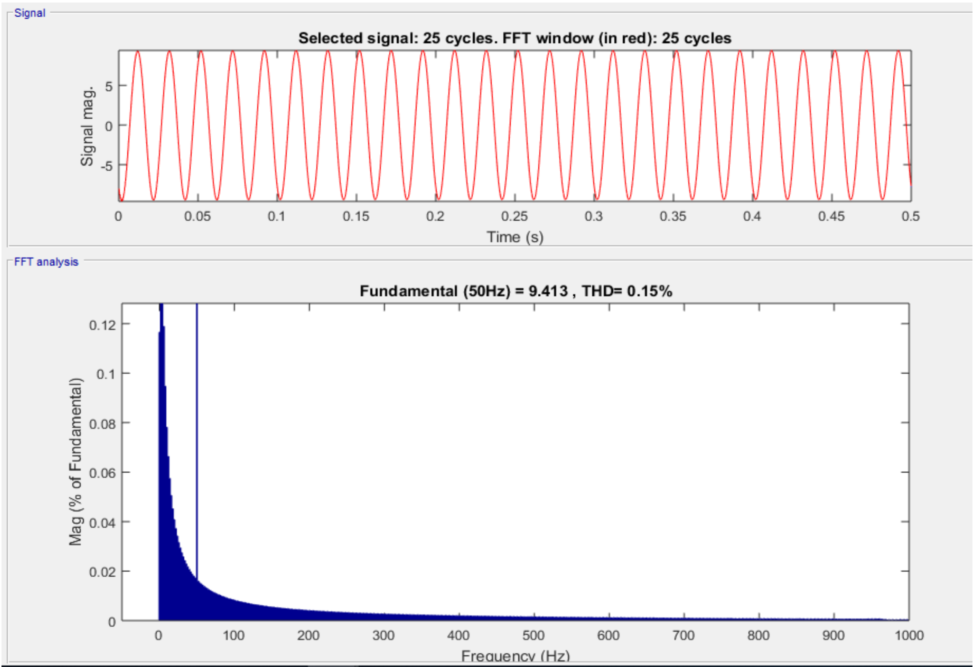

Fig. 3(c). FFT of 'Y' Phase current signal.

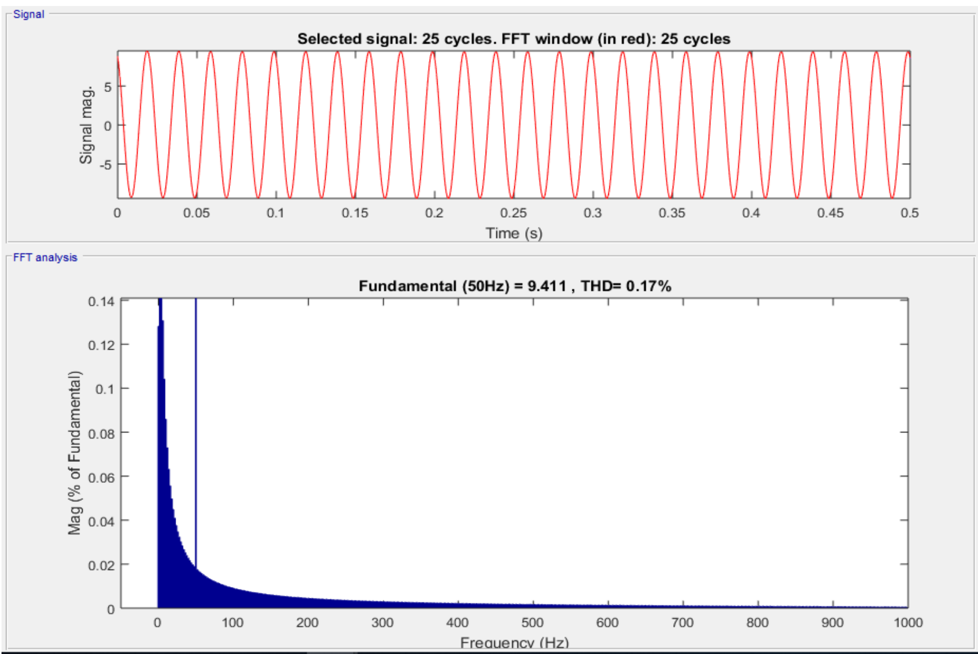

Fig. 3(d). 'B' Phase current signal and its FFT.

Three phase symmetrical fault (LLL-G) has been created at 50 km apart from Bus1 for the duration 0.3 to 0.4 sec. At this condition, three phase system currents and its FFT results have been depicted in Fig. 4.

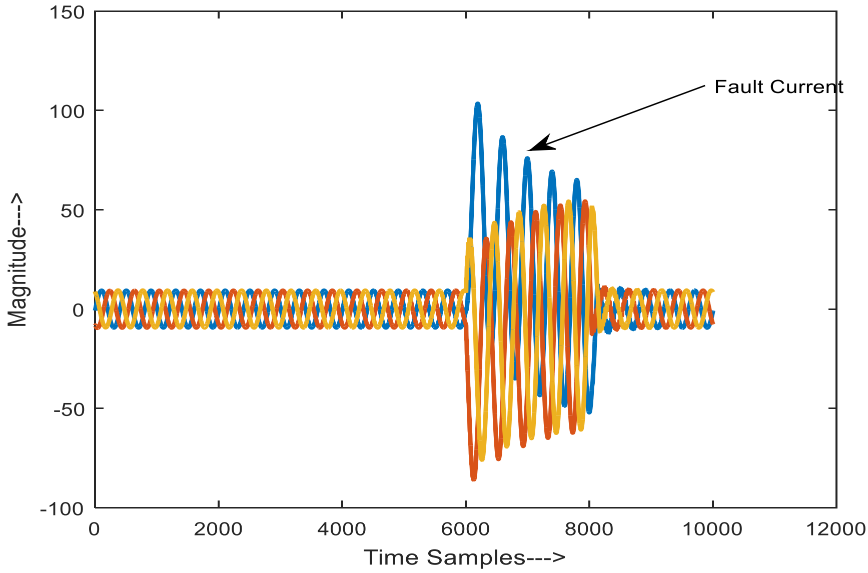

Fig. 4(a). System current (Three phase) at LLL-G fault condition.

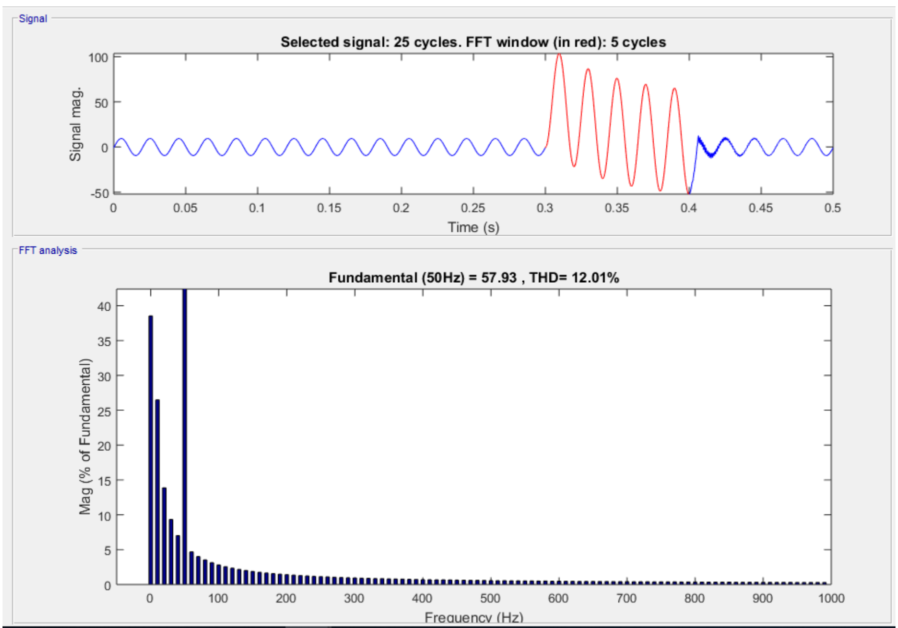

Fig. 4(b). 'R' Phase current and its FFT.

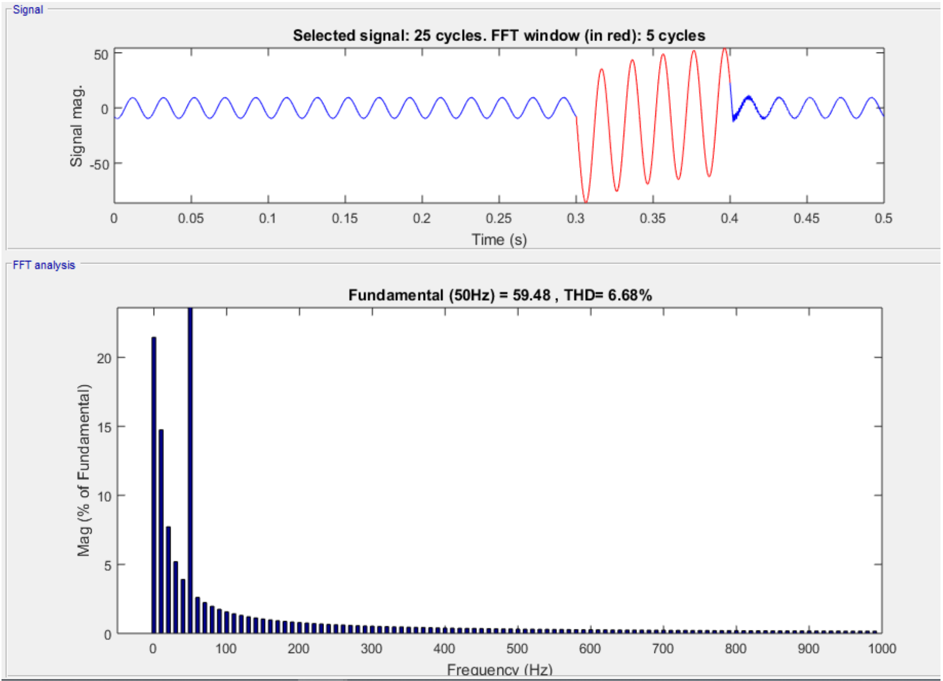

Fig. 4(c). 'Y' Phase current and its FFT.

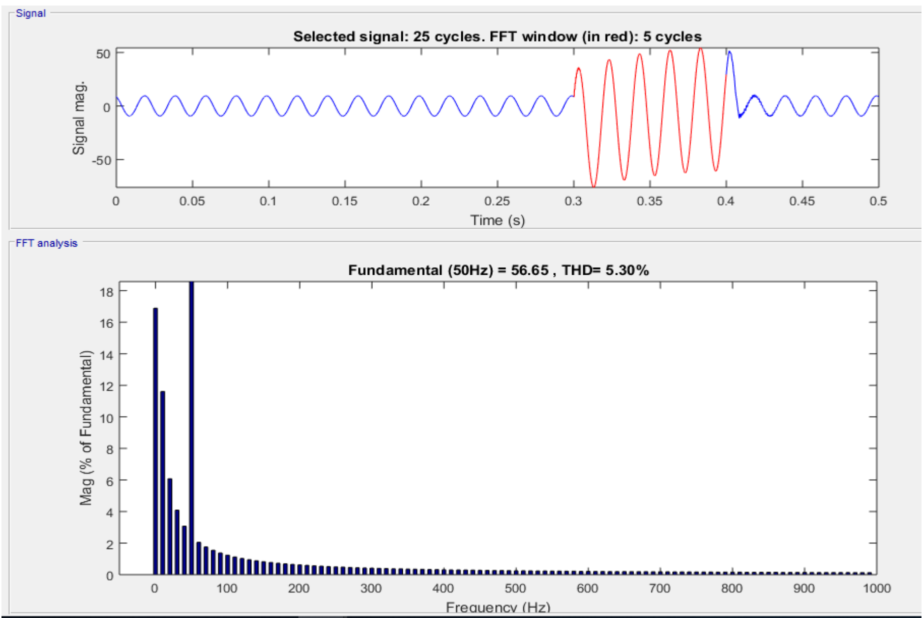

Fig. 4(d). 'B' Phase current signal and its FFT.

During the fault, the system current is very high which is clear in Fig. 4(a). During this time, FFT of R, Y and B phase are depicted in Fig. 4(b) to Fig. 4(d). THD of R, Y and B phase current has been recorded as 12.01 %, 6.68 % and 5.30 %. From these FFT based THD analysis, LLL-G fault can be detected easily.

5.2. *THD, DC component analysis*

THD value and DC component value in percentage (%) of three phase currents in normal and fault conditions (at different distances) have been calculated which is given in Table 1. Maximum THD and DC component value have been observed for 'R' phase current at fault condition.

Table 1. THD and DC component value (%) of three phase system currents.

Different conditions	THD value (%)			DC component value (%)		
	R Phase	Y Phase	B Phase	R Phase	Y Phase	B Phase
Normal Condition	0.01	0.15	0.17	0.01	0.12	0.13
LLL-G at 15 km	12.84	5.98	6.91	29.62	13.80	15.95
LLL-G at 20 km	12.70	6.11	6.62	31.49	15.16	16.42
LLL-G at 30 km	12.44	6.33	6.12	34.49	17.54	16.93
LLL-G at 40 km	12.21	6.51	5.68	36.76	19.61	17.05
LLL-G at 50 km	12.01	6.68	5.30	38.53	21.45	16.89
LLL-G at 60 km	11.83	6.87	5.02	39.95	23.12	16.53
LLL-G at 70 km	11.76	7.05	4.76	41.09	24.67	16.03
LLL-G at 80 km	11.53	7.21	4.48	42.03	26.13	15.42
LLL-G at 90 km	11.42	7.44	4.49	42.82	27.51	14.73

Table 2. DC component value of three phase system currents.

Different conditions	DC component value (%)		
	R Phase	Y Phase	B Phase
Normal Condition	0.01	0.12	0.13
LLL-G at 15 km	29.62	13.80	15.95
LLL-G at 20 km	31.49	15.16	16.42
LLL-G at 30 km	34.49	17.54	16.93
LLL-G at 40 km	36.76	19.61	17.05
LLL-G at 50 km	38.53	21.45	16.89
LLL-G at 60 km	39.95	23.12	16.53
LLL-G at 70 km	41.09	24.67	16.03
LLL-G at 80 km	42.03	26.13	15.42
LLL-G at 90 km	42.82	27.51	14.73

Table 2 depicts the presence of DC component value (%) in three phase currents in normal condition and LLL-G fault conditions at different distances. Minimum DC component value has been recorded for R phase current in normal condition and maximum value has been recorded for R phase current at LLL-G fault condition. From these THD and DC component analysis, LLL-G fault conditions can be detected very easily.

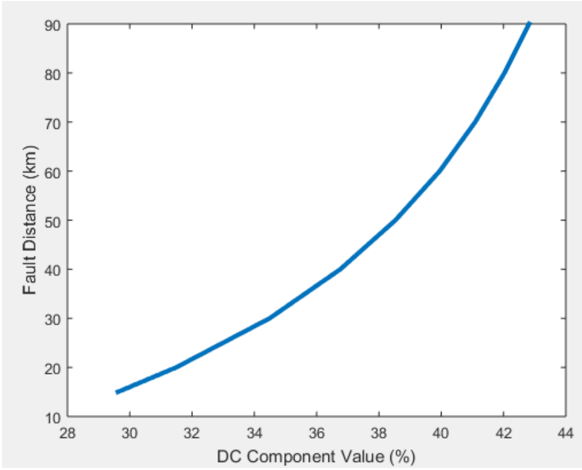

Fig. 5. DC component value (%) versus fault distances (km) of R phase current.

From the Table 2, DC component value for different fault distances has been plotted in Fig. 5. Using this figure, applying linear interpolation and spline extrapolation, fault distances for unknown cases have been calculated which is presented in Table 3. Minimum error has been recorded in calculation of fault distances. 50 unknown cases have been tested and most of the cases error is less than 1%; though 7 cases have been shown here. This established the accuracy level of this approach for calculating fault location in transmission line. This technique is very simple to implement in real time scenario. To calculate the error (%) the following formula has been used.

$$\text{Percentage (\%) Error} = \{(\text{Calculated value} - \text{Actual value}) / \text{Actual value}\} \times 100 \quad (3)$$

Table 3. Fault distance calculations.

Unknown cases	DC component value (%) of R phase current	Actual fault distance (km)	Calculated fault distance (km)	Absolute value (or modulus) of % Error
1	30.41	17	17.11	0.64 %
2	33.10	25	25.36	1.44 %
3	35.69	35	35.28	0.8 %
4	39.69	58	58.16	0.27 %
5	41.86	78	78.19	0.24 %
6	42.96	92	91.95	0.05 %
7	43.15	95	94.69	0.32

In a nutshell, findings of this work have been summarized as follows:

i) In ideal condition, maximum THD and DC component value of three phase current have been observed as 0.17 % and 0.13 % respectively.

ii) In fault condition, maximum and minimum THD values have been observed as 12.84 % and 4.49 % respectively.

iii) In fault condition maximum and minimum DC component values have recorded as 42.82 % and 13.80 % respectively.
iv) Using linier interpolation or spline extrapolation, fault distances have been calculated where maximum and minimum errors have come out 1.44 % and 0.05 % respectively.

6. Conclusion

The 110 km, 132 kV transmission line's LLL-G fault has been evaluated in this investigation. Three phase system currents under various conditions have been computed using FFT-based THD and DC component, and faults have been detected as a result. In normal condition maximum THD and DC component values have been observed as 0.17 % and 0.13 % where as in fault condition minimum THD and DC component values were observed as 4.49 % and 13.80 %, which clearly indicates the difference of the measurand. Following fault detection, the fault distances where the error has been determined to be the lowest have been estimated using linear interpolation and spline extrapolation. For finding out fault distance location, highest error was observed as 1.44 % and most of the cases it was less than 0.3 % which proves the perfection of this technique. This method can also be used to evaluate other transmission line issues due to its fastness and high accuracy.

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