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Research Article

Determining Fault Location in Transmission Lines Using Differential Equation Algorithms

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***Abstract*—A transmission line, in the context of electrical engineering and power systems, is a high-voltage or high-tension line that is used to transmit electrical power over long distances from power generation sources (such as power plants) to substations, where the electricity is then distributed to homes, businesses, and industrial facilities. Transmission lines are the backbone of the electrical grid, serving as the highways for electricity delivery. Their efficient and reliable operation is essential for ensuring that electricity is generated, transmitted, and distributed effectively, meeting the needs of consumers while maintaining grid stability and resilience. Transmission line protection refers to a set of techniques and devices used in electrical power systems to detect and respond to faults or abnormal conditions that can occur in high-voltage transmission lines. These lines are a critical part of the electrical grid and are responsible for transporting electricity over long distances from power generation plants to distribution substations.**

This paper proposes a different differential equation algorithm to locate faulty section on transmission lines. As seen from performance curves, the proposed protection algorithm is able to distinguish normal and faulty conditions.

Index Terms— **Transmission Line, Protection, Differential Equations, Fault Location.**

I. Introduction

TRANSMISSION LINE, in the context of electrical engineering and power systems, is a specialized high-voltage power conductor used to transport electricity over long distances from power generation sources (such as power plants) to distribution substations, industrial facilities, and residential areas. Transmission lines are a crucial component of the electrical grid, and they serve several important purposes [1].

Long-Distance Power Transport: Transmission lines are designed to efficiently carry large quantities of electrical power over long distances, which is essential because power generation facilities are often located far away from where the electricity is needed. They bridge the gap between power generation and the distribution network.

Voltage Transformation: High-voltage transmission lines allow for the efficient transmission of electricity over long distances with minimal losses. However, before electricity is distributed to homes and businesses, it needs to be stepped down to lower voltages at substations. This voltage transformation reduces energy losses and makes it safer for distribution.

Grid Stability: Transmission lines help maintain the stability and reliability of the electrical grid by enabling the flow of electricity between different regions and balancing supply and demand. They allow for power to be rerouted in case of outages or unexpected changes in demand.

Grid Expansion and Reliability: As populations grow and energy demands increase, expanding and upgrading transmission infrastructure becomes crucial. Building new transmission lines or upgrading existing ones is essential to ensure a reliable and robust power supply.

Integration of Renewable Energy: Transmission lines play a significant role in integrating renewable energy sources, such as wind and solar farms, into the grid. These renewable energy sources are often located in remote areas, and transmission lines are needed to transport their electricity to urban centers.

Economic Benefits: A robust transmission infrastructure can support economic growth by enabling the development of industries and businesses that rely on a stable and abundant power supply. It also helps lower energy costs by facilitating access to diverse sources of electricity generation.

Redundancy and Reliability: Transmission lines are typically designed with redundancy to ensure reliability. If one line experiences a fault or needs maintenance, power can often be rerouted through alternate lines to minimize disruptions.

Power Quality: Transmission lines help maintain the quality of power delivered to end-users by regulating voltage levels and reducing electrical noise and disturbances during transmission.

Transmission lines are essential for the efficient, reliable, and safe delivery of electrical power over long distances. They form the backbone of the electrical grid, supporting the functioning of power systems and enabling economic growth and the integration of renewable energy sources. Maintaining and upgrading transmission infrastructure is critical to ensuring a stable and resilient power supply for communities and industries [2].

A. The Importance Of Line Protection

Transmission line protection refers to a set of techniques and devices used in electrical power systems to detect and respond to faults or abnormal conditions that can occur in high-voltage transmission lines. These lines are a critical part of the electrical grid and are responsible for transporting electricity

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over long distances from power generation plants to distribution substations. The primary goal of transmission line protection is to ensure the safety and reliability of the power system by quickly isolating faults or disturbances on the transmission lines while minimizing disruption to the rest of the grid. Here are some key aspects of transmission line protection [3].

Fault Detection: Transmission lines can experience various types of faults, such as short circuits, ground faults, and open circuits.

Fast Response: It is crucial to respond to faults swiftly to prevent damage to equipment and to minimize the extent of power outages.

Relay Protection: Protective relays are devices that monitor the electrical parameters of the transmission line and make decisions to trip circuit breakers or disconnect the faulty section in case of a fault.

Communication: In modern power systems, protection relays often use communication networks to exchange information with each other and with the central control system.

Zone Protection: Transmission lines are often divided into protection zones, and relays are set up to protect specific sections of the line.

Redundancy: Redundant protection systems are often employed to increase reliability.

Coordination: Protection schemes are coordinated with other elements of the power system, such as transformers, generators, and substations, to ensure that the correct section of the line is isolated and that other equipment is protected from damage.

This paper suggests a new differential equation algorithm to calculate R and L variables on transmission lines. Section 2 gives a brief explanation about proposed technique.

II. Material and Method

Transmission line protection methods are techniques and devices used to safeguard high-voltage electrical transmission lines from faults and abnormal conditions. These methods are critical for maintaining the reliability and stability of power systems. Here are some common transmission line protection methods related to our study [4].

Differential Protection: Differential relays compare the currents entering and leaving the transmission line. If there is a significant difference, indicating a fault within the protected zone, the relay will trip the circuit breaker.

Distance Protection: Distance relays measure the impedance of the transmission line and calculate the distance to the fault location. If a fault is detected within a predefined distance, the relay operates to isolate the faulted section.

Impedance-Based Protection: Impedance relays monitor the impedance of the transmission line. A change in impedance can indicate a fault, and the relay will operate to trip the circuit breaker.

Transformer and Capacitor Protection: Specialized protection schemes are used for transformers and capacitor banks connected to transmission lines to prevent damage to these assets in case of faults.

Ground Fault Protection: Ground fault protection methods detect when a transmission line has a connection to ground, indicating a fault. Ground fault relays can trip circuit breakers to isolate the fault. The proposed method serves differential, distance and impedance protection methods.

A. Differential Equation Technique

Because it gives a simple and rapid solution for locating faults in transmission lines, the differential equation approach is widely utilized in transmission lines. This approach is originally developed for the serial parameters of the transmission line at various sampling frequencies. Fig. 1 shows single phase transmission line with distributed parameters. Total resistance (R) is 8Ω and total inductance (L) is set to 32mH.

The proposed approach is based on Eq. (1) and requires voltage and current samples.

$$v(t) = Ri(t) + L\frac{di(t)}{dt} \tag{1}$$

In Eq. (1), R and L are the serial distributed transmission line parameters, $v(t)$ is the beginning line voltage, and $i(t)$ is the current flowing along the serial branch. Eq. (1) must be adjusted in light of the existence of the fault point resistance. The line's R and L parameters may be easily determined using the Eq. (1) expressed in different time intervals. Eq. (1) is traditionally rewritten using a trapezoidal integration method at various intervals (3 samples and 6 samples, respectively) and utilized as a defect location discovery technique. Using this approach, the serial R and L characteristics of a line may be determined sensitively, especially in short lines that are unaffected by parallel capacity. While Eq. (1) has two unknown parameters, the magnitudes ($v(t)$ and $i(t)$) are known. As a result, rewriting Eq. (1) in two distinct time periods yields Eqs. (2) and (3) [5,6].

The integral terms in Eqs. (2) and (3) are restructured using the trapezoidal method, yielding Eq. (4).

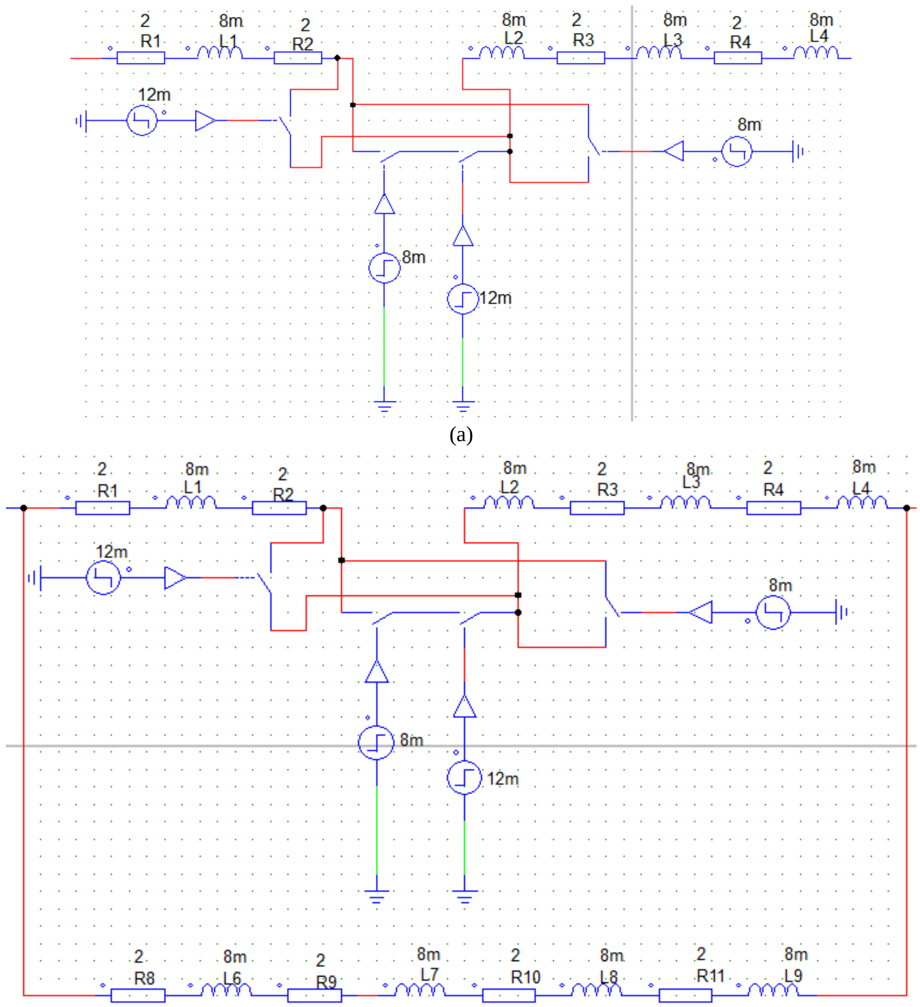
$$\int_{t0}^{t1} v(t)dt = R\int_{t0}^{t1} i(t)dt + L[i(t_1) - i(t_0)] \tag{2}$$

$$\int_{t1}^{t2} v(t)dt = R\int_{t1}^{t2} i(t)dt + L[i(t_2) - i(t_1)] \tag{3}$$

The integral terms in Eqs. (2) and (3) are restructured using the trapezoidal method, yielding Eq. (4).

$$\int_{t0}^{t1} v(t)dt = \frac{\Delta t}{2}[v(t_1) + v(t_0)] = \frac{\Delta t}{2}[v_1 + v_2] \tag{4}$$

The above method is also very well-known as trapezoidal integration rule (TIR). In this paper, other integration numerical methods are also tried and the parameter estimation results are compared.



(a)

(b)

Fig. 1 Transmission line under investigation, (a) series and (b) parallel

1) Short Window

The TIR technique is commonly stated as Eq. (5), and it employs two voltage and three current samples to estimate the parameters.

$$\begin{bmatrix} \frac{\Delta t}{2}(i_{k+1}+i_k) & (i_{k+1}-i_k) \\ \frac{\Delta t}{2}(i_{k+2}+i_{k+1}) & (i_{k+2}-i_{k+1}) \end{bmatrix} \begin{bmatrix} R \\ L \end{bmatrix} = \begin{bmatrix} \frac{\Delta t}{2}(v_{k+1}+v_k) \\ \frac{\Delta t}{2}(v_{k+2}+v_{k+1}) \end{bmatrix} \tag{5}$$

2) Long Window

Especially Eq. (6) is concerned, singular value decomposition method must be used to solve the line parameters system matrices because there are few known parameters despite the unknown parameters. Eq. (5) and Eq. (6) are still used as a conventional DEA techniques and a numerical distance protection relay algorithm in transmission lines.

$$\begin{bmatrix} \frac{\Delta t}{2}(i_{k+1}+i_k) & (i_{k+1}-i_k) \\ \frac{\Delta t}{2}(i_{k+2}+i_{k+1}) & (i_{k+2}-i_{k+1}) \\ \frac{\Delta t}{2}(i_{k+3}+i_{k+2}) & (i_{k+3}-i_{k+2}) \\ \frac{\Delta t}{2}(i_{k+4}+i_{k+3}) & (i_{k+4}-i_{k+3}) \\ \frac{\Delta t}{2}(i_{k+5}+i_{k+4}) & (i_{k+5}-i_{k+4}) \end{bmatrix} \begin{bmatrix} R \\ L \end{bmatrix} = \begin{bmatrix} \frac{\Delta t}{2}(v_{k+1}+v_k) \\ \frac{\Delta t}{2}(v_{k+2}+v_{k+1}) \\ \frac{\Delta t}{2}(v_{k+3}+v_{k+2}) \\ \frac{\Delta t}{2}(v_{k+4}+v_{k+3}) \\ \frac{\Delta t}{2}(v_{k+5}+v_{k+4}) \end{bmatrix} \tag{6}$$

3) Very Long Window

Similarly, Eq. (7) must be used to solve the line parameters system matrices because there are few known parameters despite the unknown parameters.

$$\begin{bmatrix} \frac{\Delta t}{2}(i_{k+1}+i_k) & (i_{k+1}-i_k) \\ \frac{\Delta t}{2}(i_{k+2}+i_{k+1}) & (i_{k+2}-i_{k+1}) \\ \frac{\Delta t}{2}(i_{k+3}+i_{k+2}) & (i_{k+3}-i_{k+2}) \\ \frac{\Delta t}{2}(i_{k+4}+i_{k+3}) & (i_{k+4}-i_{k+3}) \\ \frac{\Delta t}{2}(i_{k+5}+i_{k+4}) & (i_{k+5}-i_{k+4}) \\ \frac{\Delta t}{2}(i_{k+6}+i_{k+5}) & (i_{k+6}-i_{k+5}) \\ \frac{\Delta t}{2}(i_{k+7}+i_{k+6}) & (i_{k+7}-i_{k+6}) \\ \frac{\Delta t}{2}(i_{k+8}+i_{k+7}) & (i_{k+8}-i_{k+7}) \end{bmatrix} \begin{bmatrix} R \\ L \end{bmatrix} = \begin{bmatrix} \frac{\Delta t}{2}(v_{k+1}+v_k) \\ \frac{\Delta t}{2}(v_{k+2}+v_{k+1}) \\ \frac{\Delta t}{2}(v_{k+3}+v_{k+2}) \\ \frac{\Delta t}{2}(v_{k+4}+v_{k+3}) \\ \frac{\Delta t}{2}(v_{k+5}+v_{k+4}) \\ \frac{\Delta t}{2}(v_{k+6}+v_{k+5}) \\ \frac{\Delta t}{2}(v_{k+7}+v_{k+6}) \\ \frac{\Delta t}{2}(v_{k+8}+v_{k+7}) \end{bmatrix} \quad (7)$$

Eqs. (6) and (7) are assumed ill-conditions matrixes. While ill-conditioned matrices don't have a specific visual form, they exhibit certain characteristics that make them numerically unstable and challenging to work with. A hermitian matrix is a square matrix that is equal to the transpose of its conjugate matrix. The diagonal elements of a hermitian matrix are all real numbers, and the element of the (i, j) position is equal to the conjugate of the element in the (j, i) position.

Here's a breakdown of key concepts:

a) ill-Conditioning

It arises when a matrix is close to being singular (non-invertible), which means its determinant is nearly zero.

Small changes in the matrix's entries can lead to disproportionately large variations in its inverse or in solutions to linear systems involving it.

b) Condition Number

A numerical measure of how sensitive a matrix is to changes in its entries.

Mathematically, it's defined as the ratio of the largest singular value of the matrix to its smallest singular value.

Larger condition numbers indicate greater ill-conditioning.

Furthermore, an ill-conditioned matrix is a matrix that is nearly singular or singular, meaning that its condition number is very large. The condition number of a matrix measures how sensitive the solution of a linear system is to changes in the input data. A large condition number indicates that the matrix is ill-conditioned, and small changes in the input data can result in large changes in the output.

For example, consider a system of linear equations Ax=b. If A is ill-conditioned, small changes in b can result in large changes in x, making the solution sensitive to input perturbations [7-9].

B. Simulation Studies

Energy transmission lines can be divided into three according to their length. Lines from 0 to 100 km are called short lines. Lines between 100-250 km are called medium-length lines. Lines of 250 km and longer are called long transmission lines and necessary calculation methods and line parameters are found. If we examine transmission lines from an electrical perspective, line parameters and lengths are in question. Since our investigations are generally transmission lines using alternating current, all quantities used in alternating current will be in question here. Transmission lines have an ohmic resistance (R). This resistance is approximately 1.5 times higher than that in direct current due to the skin phenomenon. On the other hand, due to the fluxes surrounded by the currents flowing in neighboring conductors, self and mutual inductances of the phase conductors occur [10-12].

Since we work with sinusoidal currents, the term inductive reactance, which is a function of the network frequency, is used instead of inductance. The ohmic resistance and inductive reactance of the line are considered to be connected in series to each other, and the series sum of these two quantities, impedance, is used to characterize the line.

In this study, short lines are used for parameters using DEA algorithms. The theorical background is as follow. A two-gate circuit representation of a power transmission line is given in Fig. 2.

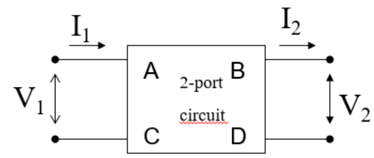


Fig.2. Two-door circuit representation with ABCD parameters

The relations between the inputs and outputs shown in the Figure 2 are given as below.

$$V_1=A\cdot V_2+B\cdot I_2 \text{ and } I_1=C\cdot V_2+D\cdot I_2 \quad (8)$$

It is in the form. If we write the expressions as a matrix

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \cdot \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \quad (9)$$

If the four-terminal circuit is symmetrical, A and D are equal and unitless. The units of B and C are Ω (ohm) and S (Siemens = 1/Ω), respectively. Provided that this symmetry is achieved AD - BC = 1 and the system is balanced.

In this study, two-busbar serial and one-bar parallel transmission lines were used. Line impedances for both transmission lines are selected as 8+j10.5 ohms.

1) Series Connection of Two Four-Term Circuits

In case two short lines with line constants A_1, B_1, C_1, D_1 and A_2, B_2, C_2, D_2 are connected in series, common ABCD coefficients will be calculated by DEA.

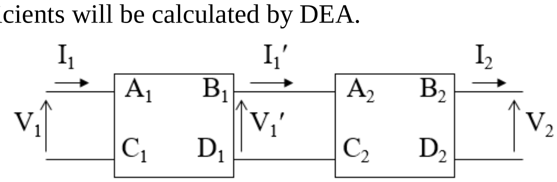


Fig.3. Series connection of two four-pin circuits

Here, the ABCD coefficients are $A=A_1A_2+B_1C_2$, $B=A_1B_2+B_1D_2$, $C=C_1A_2+D_1C_2$ and $D=C_1B_2+D_1D_2$, respectively.

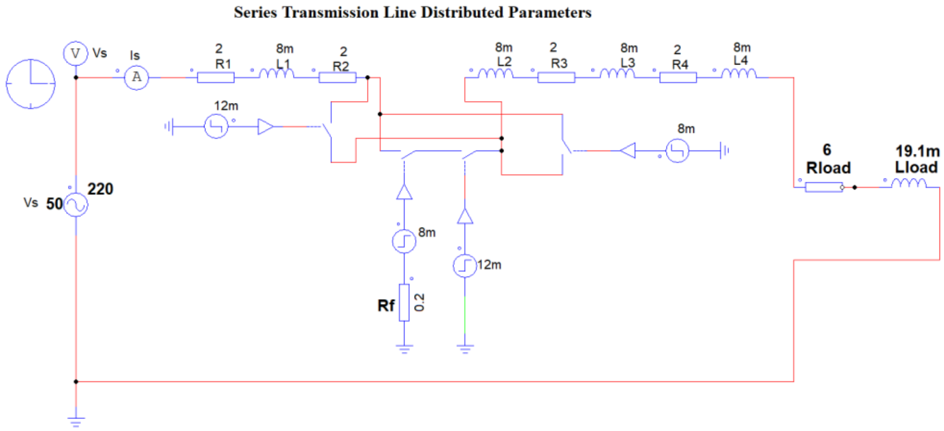


Fig.4. Serial transmission line distributed parameters

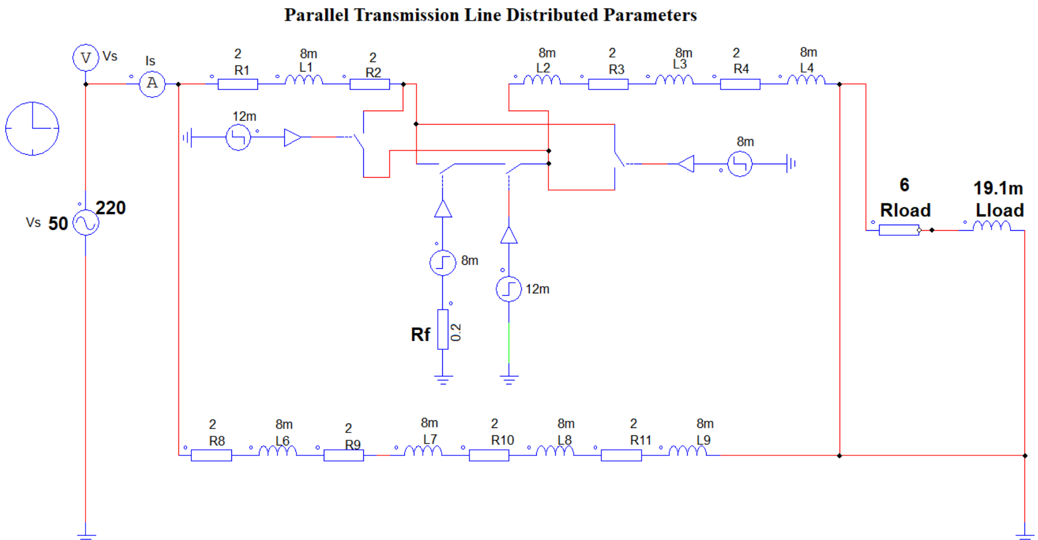


Fig.5. Parallel transmission line distributed parameters

2) Parallel Connection of Two Four-Pin Circuits

Figure 5 shows parallel connection of two four-pin.

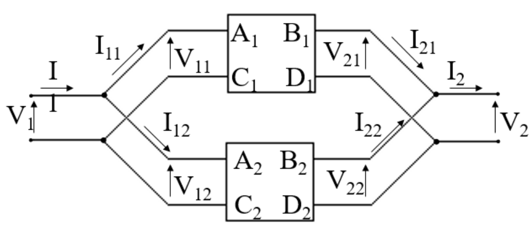


Fig.6. Parallel connection of two four-pin circuits

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} \dfrac{A_1B_2+A_2B_1}{B_1+B_2} & \dfrac{B_1B_2}{B_1+B_2} \\ C_1+C_2\dfrac{(A_1-A_2)(D_2-D_1)}{B_1+B_2} & \dfrac{D_1B_2+D_2B_1}{B_1+B_2} \end{bmatrix} \cdot \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \quad (10)$$

Here, the ABCD coefficients are as follow.

Simulation studies cover sampling frequency (Fs) and median filtering to choose best option. Figure 7 shows series distributed line parameters of R3, R6, R3m, R6m and L3, L6, L3m, L6m without filtering and with filtering. Figure 7 shows parallel distributed line parameters of R3, R6, R3m, R6m and L3, L6, L3m, L6m without filtering and with filtering. Tables 1-4 show the effects of Fs and median filter degrees. As seen Tables 1-4 the technique is robust and does not require the higher Fs values.

Eq. 7 shows 9 point transmission line parameter. Eq. 7 does not required since 6-point method accurate estimating parameters of R and L.

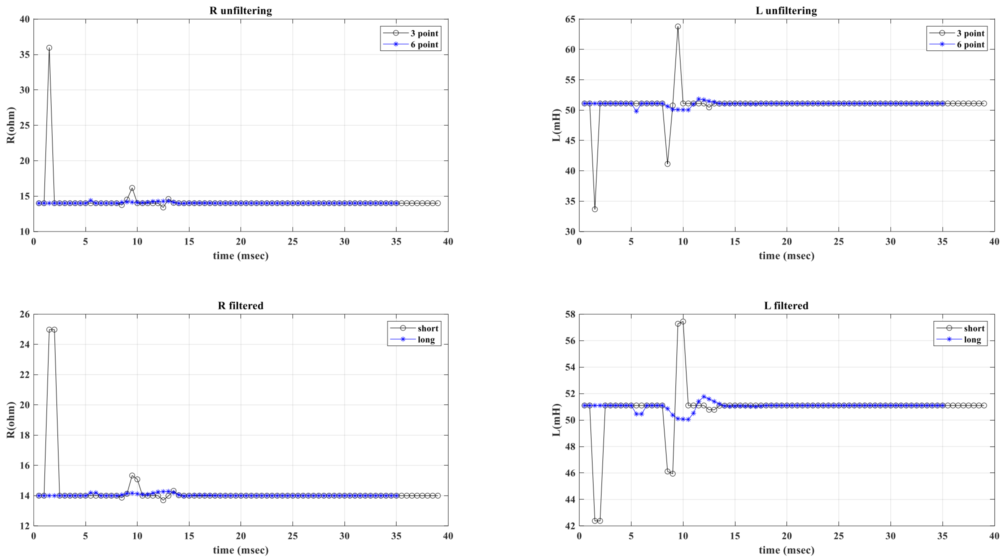


Fig.7. Parallel distributed *R* and *L* parameters (Fs=2kHz, filter degree of 3)

TABLE I
THE EFFECTS FS WITH RESPECT OF CORRELATION COEFFICIENTS VALUES FOR SERIES LINE (FILTER DEGREE OF 3)

Fs (Hz)	R3 and R3m	L3 and L3m	R6 and R6m	L6 and L6m
2000	**0.0666**	0.2990	**0.8265**	0.8726
2500	0.0399	0.2868	0.6540	**0.8812**
3333	0.0031	**0.3141**	0.3471	0.8439
5000	0.0087	0.2702	0.2195	0.8929
10000	0.0027	0.2609	0.0816	0.8969

TABLE II
THE EFFECTS Fs WITH RESPECT OF CORRELATION COEFFICIENTS VALUES FOR SERIES LINE (FILTER DEGREE OF 6)

Fs (Hz)	R3 and R3m	L3 and L3m	R6 and R6m	L6 and L6m
2000	-0.0057	**-0.0086**	**0.7785**	0.8042
2500	**-0.0124**	-0.0063	0.6233	**0.8288**
3333	-0.0097	-0.0045	0.3284	0.7968
5000	-0.0072	-0.0027	0.2085	0.8495
10000	-0.0030	-0.0013	0.0776	0.8553

TABLE III
THE EFFECTS Fs WITH RESPECT OF CORRELATION COEFFICIENTS VALUES FOR PARALLEL LINE (FILTER DEGREE OF 3)

Fs (Hz)	R3 and R3m	L3 and L3m	R6 and R6m	L6 and L6m
2000	0.0685	0.3004	**0.8310**	**0.8712**
2500	**0.0431**	**0.2879**	0.6587	0.8794
3333	0.0034	0.3144	0.3488	0.8421
5000	0.0086	0.2708	0.2214	0.8914
10000	0.0028	0.2614	0.0817	0.8957

TABLE IV
THE EFFECTS FS WITH RESPECT OF CORRELATION COEFFICIENTS VALUES FOR PARALLEL LINE (FILTER DEGREE OF 6)

Fs (Hz)	R3 and R3m	L3 and L3m	R6 and R6m	L6 and L6m
2000	**-0.0131**	**-0.0086**	**0.7851**	0.8043
2500	-0.0126	-0.0064	0.6279	**0.8271**
3333	-0.0398	-0.0050	0.3269	0.7949
5000	-0.2893	-0.0027	0.2102	0.8481
10000	0.0454	-0.0013	0.0778	0.8542

Keep in mind that this approach is for simple linear differential equations representing lines. More complex scenarios may involve higher-order differential equations or nonlinear relationships, requiring different techniques for solution.

The following codes give the implementation of R3, L3, R6, and L6 in Matlab™, respectively.

```
R3(k)=((g(k+1)+g(k))*(a(k+2)-a(k+1))-
((g(k+2)+g(k+1))*(a(k+1)-a(k))))/...
      ((a(k+1)+a(k))*(a(k+2)-a(k+1))-
(a(k+2)+a(k+1))*(a(k+1)-a(k)));
dt=(t(n)-t(n-1));
```
(11)

```
L3(k)=(dt/2)*((a(k+1)+a(k))*(g(k+2)+g(k+1))-
((a(k+2)+a(k+1))*(g(k+1)+g(k))))/...
((a(k+1)+a(k))*(a(k+2)-a(k+1))-(a(k+2)+a(k+1))
*(a(k+1)-a(k)));
```

```
R6(k)=((g(k)+2*g(k+1)+2*g(k+2)+2*g(k+3)+2*g(k+4
)+g(k+5))*(a(k+10)-a(k+5))-(g(k+5)+2*g(k+6)
+2*g(k+7) +2*g(k+8)+2*g(k+9) +g(k+10))*(a(k+ 5)-
a(k)))/((a(k)+2*a(k+1)+2*a(k+2)+ 2*a(k+3)
+2*a(k+4)+ a(k+5))* (a(k+10)-a(k+5))-(a(k+5)+
2*a(k+6)+2*a(k+7) +2*a(k+8)+ 2*a(k+9)+a(k+10))
*(a(k+5)-a(k)));
dt=(t(n)-t(n-1));
```
(12)

```
L6(k)=(dt/2)*((a(k)+2*a(k+1)+2*a(k+2)+2*a(k+3)+2*
a(k+4)+a(k+5))*(g(k+5)+2*g(k+6)+2*g(k+7)+2*g(k+
8)+2*g(k+9)+g(k+10))-
(a(k+5)+2*a(k+6)+2*a(k+7)+2*a(k+8)+2*a(k+9)+a(k
+10))*(g(k)+2*g(k+1)+2*g(k+2)
+2*g(k+3)+2*g(k+4)+g(k+5)))/((a(k)+2*a(k+1)+2*a(
k+2)+2*a(k+3)+2*a(k+4)+a(k+5))*(a(k+10)-a(k+5))-
(a(k+5)+2*a(k+6)+2*a(k+7)+2*a(k+8)+2*a(k+9)+a(k
+10))*(a(k+5)-a(k)));
```

III. CONCLUSION

The protection of transmission lines is essential due to their vulnerability to a myriad of risks, including natural disasters, equipment failures, and malicious activities. Disruptions to these lines can have far-reaching consequences, leading to widespread power outages, economic losses, and societal disruptions. Therefore, implementing robust protection measures is imperative to ensure the reliability and availability of electrical power.

The protection of transmission lines is a multifaceted endeavor that requires a holistic approach, combining engineering ingenuity, advanced technologies, and comprehensive planning. As our dependence on electrical power continues to grow, ensuring the resilience of transmission lines becomes increasingly vital. By embracing innovative solutions, prioritizing regular maintenance, and integrating robust cybersecurity measures, we can build a power infrastructure that is not only reliable but also resilient in the face of evolving challenges. In doing so, we fortify the backbone of our power grid, securing a stable and uninterrupted supply of electricity for the benefit of society as a whole.

Calculating parameters and characteristics of transmission lines involves several key factors such as impedance, propagation velocity, and attenuation. The calculations can vary depending on the type of transmission line. In this study, single representation of 3-phase line (1-125km) is used for calculating R and L parameters using DEA. As seen from Table1-4 the methods predict R and L parameters even at low Fs.

In future study, fault detection and location in power systems with a high density of inverter based generation, to overcome the issues of reverse power flow using DEA.

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