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Fault Analysis in a Three-Phase System (1)

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Abstract -- Faults often occur in three-phase power systems. With the increasing demand for electrical power, one key challenge is the ability to identify and analyze these faults when they occur. In this paper, the performance of long transmission line in a balanced system has been discussed. This paper is the first in the series of four papers for fault analysis in a three-phase system. A three lines to ground (LLLG) fault occurred in the system, which automatically operated the circuit breakers and left them open. Simulink was used to view the waveforms of the current and voltage at both normal and fault conditions. The result showed that at the fault point, the sudden increase in current was accompanied by a drop in voltage. The system was also able to leave the breaker open all through the operation, suggesting the occurrence of a permanent fault.

Indexed Terms: faults, permanent, three-phase, transmission.

I. TRANSMISSION SYSTEM

A transmission line is a structure used to guide the flow of electromagnetic energy from one point to another. This line may be of any physical structure; that is, it may be made of two parallel wires or two parallel plates or coaxial conductors, or it may be of hollow conductor variety (waveguides). The general characteristics of electromagnetic wave propagation in these lines are the same. The preference depends only on the frequency of wave propagation and the use to which these lines are put. Conductors, be it in underground cables or overhead lines, are modelled by a π circuit, sufficiently accurate for short, middle, or long distances. For long conductors, chained π sections or distributed parameters can be their good approximation.

In general, if we examine a transmission line, we will find four parameters, *i.e.*, series resistance (R), series inductance (L), shunt capacitance (C) and shunt conductance (G), distributed along the whole length of the line. If R, L, C and G be these primary constants per unit length of the line, then the unit length of the line may be represented by an equivalent circuit of the type shown in Fig. 1. Naturally, a relatively long piece of line would contain several such identical sections.

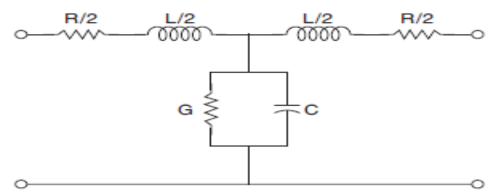

Fig 1: Equivalent circuit of a unit length of transmission line

i. Short transmission lines – length less than 80Km. Due to smaller, shunt capacitance effect is neglected, and performance depends on the resistance and inductance of the line. The parameters are also assumed to be lumped together.

ii. Medium transmission lines – length between 80Km and 200Km. Owing to appreciable length and voltage, the line charging current is appreciable and therefore shunt capacitance cannot be neglected. Lumped parameters are also assumed in this category.

iii. Long transmission lines – length above 200Km (with operating voltages greater than 100KV). Line parameters are not assumed to be lumped but considered to be uniformly distributed over the length of the line and therefore for their solutions, rigorous methods are employed.

1.1: Voltage Regulation

When a transmission line is carrying current, there is a voltage drop in the line due to resistance and inductance of the line. The result is that receiving end voltage (V_R) of the line is generally less than the sending voltage (V_s). This voltage drop (V_s – V_R) in the line is expressed as a percentage of receiving end voltage V_R and is called Voltage regulation.

$$\% \, voltage \; regulation = \frac{V_S - V_R}{V_R} \times 100 \qquad (1)$$

It is desirable that the voltage regulation index of a transmission line should be low i.e. the increase in load current should make very little difference in the receiving end voltage. The voltage regulation index determines the transmission efficiency, which is the power obtained at the receiving end of a transmission line which is usually less than the sending end power due to losses in the line reactance. The ratio of receiving end power to the sending end power of a transmission line is known as the transmission efficiency of the line. i.e.

$$\% \, transmission \; efficiency = \frac{Recieving \; end \; power}{sending \; end \; power} \times 100 \qquad (2)$$

1.2: Generalized circuit constants

In any passive, bilateral and linear network with two input and two output terminals, the input voltage and current can be expressed in terms of output voltage and current. Incidentally, a single-phase transmission line is a 4 – terminal network; two input terminals where the power enters the network and two output terminals where the power leaves the network. Such a circuit is passive as it does not contain any source of emf, linear as its impedance is independent of current flowing and bilateral as its impedance is independent of direction of current flowing. The input voltage and current per phase of a transmission line can be expressed as:

$$V_S = AV_R + BI_R \qquad (3)$$

$$I_S = CV_R + DI_R \qquad (4)$$

Where V_s is the sending end voltage per phase

I_s is the sending end Current

V_r is the receiving end voltage per phase

I_r is the receiving end current

A, B, C and D are constants called the generalized circuit constants of a transmission line. The values of these constants depend upon the particular method of solution employed. Once the values of these constants of a particular transmission line are known the performance of the line can be determined easily

The values of A, B, C and D can be determined as follows;

If receiving end of transmission line is open circuited, then

Receiving end current I_r is zero, from equations 3 and 4 above;

$$A = \frac{V_S}{V_R} \qquad (5)$$

and $C = \frac{I_S}{V_R}$ (6)

With receiving end short circuited

Receiving end voltage V_r is zero, from equation 3 and 4;

$$B = \frac{V_S}{I_R} \qquad (7)$$

and $D = \frac{I_S}{I_R}$ (8)

From the above expressions, A, B, C and D can be defined as follows

A can be defined as the ratio of the sending end voltage V_s to receiving end voltage V_R when the line is open circuited at the receiving end. A is dimensionless

B is defined as the ratio of sending end voltage Vs to receiving end current Ir when the line is short-circuited on receiving end. B is in ohm

C is defined as the ratio of sending end current Is to receiving end voltage V_R when the line is open circuited on the receiving end. C is in Siemen

D is defined as the ratio of sending end current I_s to receiving end current I_R when the line is short circuited on the receiving end. D is dimensionless

By circuit analysis, for short transmission lines, A=1, B =Z, C=0 and D=1

For a nominal T – network, $A = D = 1 + \frac{YZ}{2}$; $B = Z\left(1 + \frac{YZ}{2}\right)$ and C=Y

For a nominal π – network, $A = D = 1 + \frac{YZ}{2}$; B=Z and $C = Y\left(1 + \frac{YZ}{4}\right)$

Where Z is the impedance and Y is the admittance.

II. FAULTS

In an electric power system, a fault is any abnormal occurrence on the system. Fault current is any abnormal electric current flowing through non-required current. For example, a short circuit is a fault in which current bypasses the normal load. An open-circuit fault occurs if a circuit is interrupted by some failure. In three-phase systems, a fault may involve one or more phases and ground, or may occur only between phases. In a ground fault or earth fault, current flows into the earth. The prospective short-circuit current of a predictable fault can be calculated for most situations. In power systems, protective devices can detect fault conditions and operate circuit breakers and other devices to limit the loss of service due to a failure.

In a polyphase system, a fault may affect all phases equally which is a symmetrical fault. If only some phases are affected, the resulting asymmetrical fault becomes more complicated to analyses. The analysis of these types of faults is often simplified by using methods such as symmetrical components. The design of systems to detect and interrupt power system faults is the main objective of power-system protection.

2.1: Transient fault

A transient fault is a fault that is no longer present if power is disconnected for a short time and then restored; or an insulation fault which only temporarily affects a device's dielectric properties which are restored after a short time. Many faults in overhead power lines are transient in nature. When a fault occurs, equipment used for power system protection operates to isolate the area of the fault. A transient fault will then clear and the power-line can be returned to service. Typical examples of transient faults include: momentary tree contact, bird or other animal contact, lightning strike, conductor clashing

Transmission and distribution systems use an automatic re-close function which is commonly used on overhead lines to attempt to restore power in the event of a transient fault. This functionality is not as common on underground systems as faults there are typically of a persistent nature. Transient faults may still cause damage both at the site of the original fault or elsewhere in the network as fault current is generated.

2.2: Permanent fault

One extreme is where the fault has zero impedance, giving the maximum prospective short-circuit current. Notionally, all the conductors are considered connected to ground as if by a metallic conductor; this is called a "bolted fault". It would be unusual in a well-designed power system to have a metallic short circuit to ground but such faults can occur by mischance. Typical examples of permanent faults include: conductors breaking from the insulators and resting on a firm earth or on another phase, two or more conductors twisting due to a high-speed wind, etc.

For a system with an auto-reclose function, this kind of fault usually initiates permanent trip to the circuit breaker leaving it de-energized until the bolted fault is cleared.

2.3: Symmetric fault

A symmetric or balanced fault affects each of the three phases equally. In transmission line faults, roughly 5% are symmetric. This is in contrast to an asymmetrical fault, where the three phases are not affected equally.

2.4: Asymmetric fault

An asymmetric or unbalanced fault does not affect each of the three phases equally. Common types of asymmetric faults and their causes include:

i. line-to-line: a short circuit between lines, caused by ionization of air, or when lines come into physical contact, for example due to a broken insulator. In transmission line faults, roughly 5% - 10% are asymmetric line-to-line faults.

ii. line-to-ground: a short circuit between one line and ground, very often caused by physical contact, for example due to lightning or other storm damage. In transmission line faults, roughly 65% - 70% are asymmetric line-to-ground faults.

iii. double line-to-ground: two lines come into contact with the ground (and each other), also commonly due to storm damage. In transmission line faults, roughly 15% - 20% are asymmetric double line-to-ground.

2.5: Arcing fault

Where the system voltage is high enough, an electric arc may form between power system conductors and ground. Such an arc can have relatively high impedance (compared to the normal operating levels of the system) and can be difficult to detect by simple overcurrent protection. For example, an arc of several hundred amperes on a circuit normally carrying a thousand amperes may not trip overcurrent circuit breakers but can do enormous damage to bus bars or cables before it becomes a complete short circuit. Utility, industrial, and commercial power systems have additional protection devices to detect relatively small but undesired currents escaping to ground. In residential wiring, electrical regulations may now require Arc-fault circuit interrupters on building wiring circuits, to detect small arcs before they cause damage or a fire.

III. POWER SOURCE

The power source is the input to the system and could be a generator output stepped up to E_1KV or a supply from a EKV feeder. There are two types of system available in electric circuit, single phase and three phase systems. In the perfectly balanced case all three lines share equivalent loads. Examining the circuits, the derived relationships between line voltage and current can be obtained as well as the load voltage and current for wye and delta connected loads.

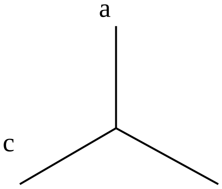

Fig. 2: 3-Phase balanced system

In a balanced system of fig. 2, each line will produce equal voltage magnitudes at phase angles equally spaced from each other. With V_a as our reference and V_c lagging V_b lagging V_a, using angle notation, and V_{ph} the voltage between the line and the neutral gives:

$$V_a = V_{ph}\angle 0° \quad (9)$$

$$V_b = V_{ph}\angle -120° \quad (10)$$

$$V_c = V_{ph}\angle +120° \quad (11)$$

These voltages feed into either a wye or delta connected load.

3.1: Star or Wye (Y) Connection

To derive the relations between line and phase currents and voltages of a star connected system, we have first to draw a balanced star connected system. Suppose due to load impedance the current lags the applied voltage in each phase of the system by an angle ϕ. As we have considered that the system is perfectly balanced, the magnitude of current and voltage of each phase is the same. Let us say, the magnitude of the voltage across the red phase i.e. magnitude of the voltage between neutral point (N) and red phase terminal (R) is V_R. Similarly, the magnitude of the voltage across yellow phase is V_Y and the magnitude of the voltage across blue phase is V_B. In the balanced star system, magnitude of phase voltage in each phase is V_{ph}.

$$\therefore V_R = V_Y = V_B = V_{ph} \quad (12)$$

The star connection is shown below-

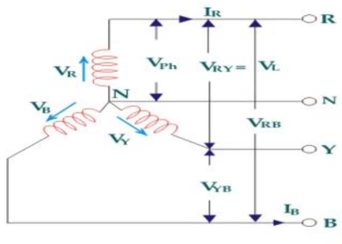

Fig 3: Star connection

From fig 3 above for a star connection, the line currents are equal to the phase currents as there are no nodes between them, hence for star connected systems:

$$I_L = I_{ph} \tag{13}$$

The vector diagram for a star connected system is shown in figure 3 below

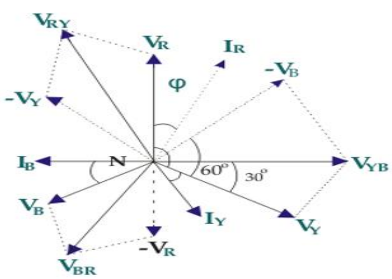

Fig 4: A phasor diagram for a wye configuration.

We know in the star connection; line current is same as phase current. The magnitude of this current is same in all three phases and says it is I_L.

$$\therefore I_R = I_Y = I_B = I_L \tag{14}$$

Where, I_R is line current of R phase, I_Y is line current of Y phase and I_B is line current of B phase. Again, phase current, I_{ph} of each phase is same as line current I_L in star connected system.

$$\therefore I_R = I_Y = I_B = I_L = I_{ph}$$

Now, let us say, the voltage across R and Y terminal of the star connected circuit is V_{RY}.

The voltage across Y and B terminal of the star connected circuit is V_{YB}. The voltage across B and R terminal of the star connected circuit is V_{BR}.

From the fig. 4, it is found that

$$V_{RY} = V_R + (-V_Y) \tag{15}$$

Similarly, $V_{YB} = V_Y + (-V_B)$ (16)

And, $V_{BR} = V_B + (-V_R)$ (17)

Now, as angle between V_R and V_Y is 120° (electrical), the angle between V_R and $-V_Y$ is $(180° - 120°) = 60°$(electrical).

Resolving,

$$V_L = |V_{RY}| = \sqrt{{V_R}^2 + {V_Y}^2 + 2V_R V_Y \cos 60°}$$

But $V_R=V_Y=V_B=V_{ph}$ for a balanced circuit

$$= \sqrt{{V_{ph}}^2 + {V_{ph}}^2 + (2V_{ph}V_{ph} \times \tfrac{1}{2})}$$

$$= \sqrt{3{V_{ph}}^2} = \sqrt{3}V_{ph}$$

Hence, $V_L = \sqrt{3}V_{ph}$ (18)

Thus, for the star-connected system, line voltage = √3 × phase voltage.

Line current = Phase current

As, the angle between voltage and current per phase is φ, the electric power per phase is

$$V_{ph}I_{ph}\cos\varphi = \frac{V_L}{\sqrt{3}} I_L \cos\varphi$$

So, the total power of three phase system is

$$3 \times \frac{V_L}{\sqrt{3}} I_L \cos\varphi = \sqrt{3}V_L I_L \cos\varphi \tag{19a}$$

By applying Kirchhoff's current law (KCL) to the neutral node, the three phase currents sum to the total current in the neutral line. In the balanced case:

$$I_1 + I_2 + I_3 = I_N = 0$$

3.3: Delta Connection (Δ)

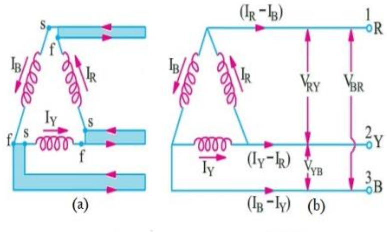

Fig 5: Delta Connected System

i. Line Voltages and Phase Voltages in Delta Connection

It is seen from fig 4 that there is only one phase winding between two terminals (i.e. there is one phase winding between two wires). Therefore, in Delta Connection, the voltage between (any pair of) two lines is equal to the phase voltage of the phase winding which is connected between two lines.

i.e. for delta systems, $V_L = V_{ph}$ (19b)

Since the phase sequence is R → Y → B, therefore, the direction of voltage from R phase towards Y phase is positive (+), and the voltage of R phase is leading by 120° from Y phase voltage. Likewise, the voltage of Y phase is leading by 120° from the phase voltage of B and its direction is positive from Y towards B.

If the line voltage between Line 1 and Line 2 = V_{RY}, Line 2 and Line 3 = V_{YB}, Line 3 and Line 1 = V_{BR}

Then, we see that VRY leads VYB by 120° and VYB leads VBR by 120°.

Let's suppose,

$V_{RY} = V_{YB} = V_{BR} = V_L$ …… (Line Voltage) (20)

I.e. in Delta connection, the Line Voltage is equal to the Phase Voltage.

ii. Line Currents and Phase Currents in Delta Connection

It will be noted from fig. 6 that the total current of each Line is equal to the vector difference between two phase currents flowing through that line. i.e.;

- Current in Line 1, $I_1 = I_R - I_B$ (21)
- Current in Line 2, $I_2 = I_Y - I_R$ (22)
- Current in Line 3, $I_3 = I_B - I_Y$ (23)

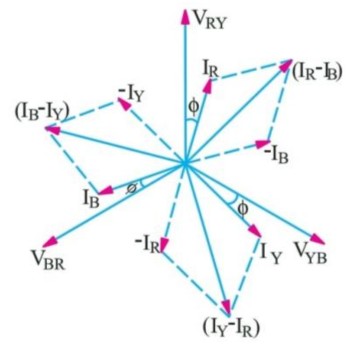

Fig 6: Phasor diagram for delta connection.

The current of Line 1 can be found by determining the vector difference between I_R and I_B and we can do that by increasing the I_B Vector in reverse, so that, I_R and I_B makes a parallelogram. The diagonal of that parallelogram shows the vector difference of I_R and I_B which is equal to Current in Line 1= I_1. Moreover, by reversing the vector of I_B, it may indicate as ($-I_B$), therefore, the angle between I_R and $-I_B$ (I_B, when reversed = $-I_B$) is 60°. If,

$I_R = I_Y = I_B = I_{PH}$ …. The phase currents

Then;

The current flowing in Line 1 would be;

$$I_1 = 2 \times I_{ph} \times \cos\frac{60°}{2}$$

$$= 2 \times I_{ph} \times \cos 30° = 2 \times I_{ph} \times \frac{\sqrt{3}}{2}$$

$$since \ \cos 30° = \frac{\sqrt{3}}{2}$$

$$I_1 = I_L = \sqrt{3} I_{ph} \quad (24)$$

i.e. In Delta Connection, The Line current is √3 times of Phase Current

Similarly, we can find the remaining two line-currents as same as above. i.e.,

$I_2 = I_Y - I_R$ … Vector Difference = √3 I_{PH}

$I_3 = I_B - I_Y$ … Vector difference = √3 I_{PH}

As, all the Line current are equal in magnitude i.e.

$I_1 = I_2 = I_3 = I_L$

Hence

$I_L = \sqrt{3} I_{ph}$

It is seen from the fig. 6 above that;

- The Line Currents are 120° apart from each other
- Line currents are lagging by 30° from their corresponding Phase Currents
- The angle Φ between line currents and respective line voltages is (30°+Φ), i.e. each line current is lagging by (30°+Φ) from the corresponding line voltage.

iii. Power in Delta Connection

We know that the power of each phase

Power per Phase = $V_{ph} \times I_{ph} \times \cos\theta$

And the total power of three phases;

$$Total\ power = P = 3 \times V_{ph} \times I_{ph} \times \cos\theta \quad (25)$$

We know that the values of Phase Current and Phase Voltage in Delta Connection are;

$I_{ph} = \frac{I_L}{\sqrt{3}}$ from (24)

And $V_{PH} = V_L$ from (19b)

Putting (24) and (19b) in power equation of (25)

$$P = 3 \times V_L \times \left(\frac{I_L}{\sqrt{3}}\right) \times \cos\theta$$
$$P = \sqrt{3} \times \sqrt{3} \times V_L \times \left(\frac{I_L}{\sqrt{3}}\right) \times \cos\theta$$
$$P = \sqrt{3} \times V_L \times I_L \times \cos\theta$$

Hence Power in Delta Connection,

$P = 3 \times V_{ph} \times I_{ph} \times \cos\theta$ ……or

$$P = \sqrt{3} \times V_L \times I_L \times \cos\theta \quad (26)$$

This can be seen to be the same as the power for star connection found in equation 19a, hence

Power in star = power in delta.

3.4: Performance and Analysis of Long Transmission lines

The equivalent circuit of a long transmission line is shown schematically in fig. 7 below

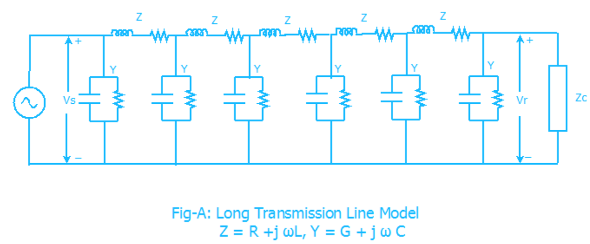

Fig 7: Equivalent circuit of long transmission lines

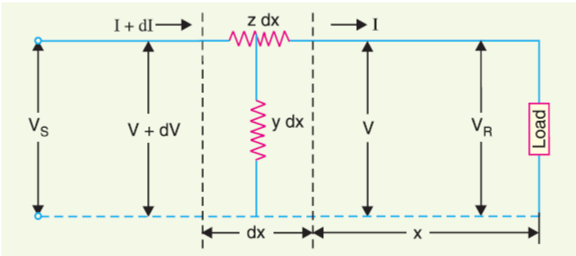

Fig 8 – sectional view of a long transmission line

Consider an infinitely small length dx of the line at a distance x from the receiving end as seen in fig. 8.

Let r = Resistance per unit length

x= Reactance per unit length

b = Susceptance per unit length

g = conductance per unit length

$z = \sqrt{r^2 + x^2}$

$y = \sqrt{g^2 + b^2}$

V = Voltage per phase at the end of the element towards sending end

V + dV = Voltage per phase at the end of the element towards sending end

V_R = Voltage per phase at receiving end

V_s = Voltage per phase at sending end

I_R = Current per phase at receiving end

I_s = Current per phase at sending end

I + dI = Current entering the element dx

And I = Current leaving the element dx

Now the series impedance of element dx of the line = zdx

The shunt admittance of element dx of the line = ydx

The rise in voltage over the element length in the direction of increasing x,

$dv = Izdx$ Or $\frac{dv}{dx} = zI$ (27)

Similarly, the difference of current entering the element and that leaving the element, $dI = Vydx$ Or $\frac{dI}{dx} = Vy$ (28)

Differentiating (27) W.r.t x, and substituting in (28), we get

$\frac{d^2V}{dx^2} = z\frac{dI}{dx} = zVy$ (29)

The solution of the above differential equation is

$V = A1e^{\sqrt{yzx}} + A2e^{-\sqrt{yzx}}$ (30)

where A1 and A2 are unknown constants.

Differentiating (30) above w.r.t x, we get

$\frac{dV}{dx} = \sqrt{yz}\left[A1e^{\sqrt{yzx}} - A2e^{-\sqrt{yzx}}\right]$ (31)

But from (27) we have $= \frac{1}{z}\frac{dV}{dx}$. substituting this in (31) above gives

$I = \frac{1}{z}\sqrt{yz}\left[A1e^{\sqrt{yzx}} - A2e^{-\sqrt{yzx}}\right]$

$I = \sqrt{\frac{y}{z}}\left[A1e^{\sqrt{yzx}} - A2e^{-\sqrt{yzx}}\right]$ (32)

Equations (30) and (32) thus give the expressions for V and I in the form of unknown constants A1 and A2. The values of A1 and A2 can be determined by applying receiving end conditions as under:

At receiving end x=0, $V=V_R$, $I=I_R$

Substituting these values in equations (30) and (32) we get

$V_R = A_1 + A_2$ (33)

$I_R = \sqrt{\frac{y}{z}}(A_1 - A_2)$ (34)

For transmission line, $\sqrt{\frac{z}{y}}$ is a constant called the characteristic constant, Z_c and $\sqrt{yz}$ is another constant called the propagation constant γ, both are complex quantities.

From (33) and (34) above, solving simultaneously we have

$A_1 = \frac{1}{2}V_R + \frac{1}{2}\sqrt{\frac{z}{y}}I_R = \frac{1}{2}(V_R + I_R Z_c)$

$A_2 = \frac{1}{2}V_R - \frac{1}{2}\sqrt{\frac{z}{y}}I_R = \frac{1}{2}(V_R - I_R Z_c)$

Thus, the expressions for V and I become

$V = \frac{1}{2}[V_R + I_R Z_c]e^{\gamma x} + \frac{1}{2}[V_R - I_R Z_c]e^{-\gamma x}$ (35)

And $I = \frac{1}{Z_c}\left[\frac{1}{2}[V_R + I_R Z_c]e^{\gamma x} - \frac{1}{2}[V_R - I_R Z_c]e^{-\gamma x}\right]$

Or $I = \frac{1}{2}\left[\left(\frac{V_R}{Z_c} + I_R\right)\right]e^{\gamma x} - \frac{1}{2}\left[\left(\frac{V_R}{Z_c} - I_R\right)\right]e^{-\gamma x}$ (36)

Expanding and rearranging (35) and (36) above we get

$$V = V_R \cosh \gamma x + I_R Z_c \sinh \gamma x \qquad (37)$$

And $I = I_R \cosh \gamma x + \frac{V_R}{Z_C} \sinh \gamma x \qquad (38)$

The sending end voltage, Vs and sending end current Is can be obtained by substituting x= L in the above equations

$$V_s = V_R \cosh \gamma l + I_R Z_c \sinh \gamma l \qquad (39)$$

And $I_s = I_R \cosh \gamma l + \frac{V_R}{Z_C} \sinh \gamma l \qquad (40)$

Now $\gamma l = \sqrt{yz} \times l = \sqrt{yl \times zl} = \sqrt{YZ} \qquad (41)$

Where Z is the total impedance of the line and Y is the total admittance of the line.

The expression for sending end voltage and sending end currents are now gotten by substituting (41) into (40) and (39). Hence,

$$V_s = V_R \cosh \sqrt{YZ} + I_R Z_c \sinh \sqrt{YZ}$$

And $I_s = I_R \cosh \sqrt{YZ} + \frac{V_R}{Z_C} \sinh \sqrt{YZ}$

Comparing the above equations with the general voltage and current equations of the line (equations 30 and 32), we have

$$A = D = \cosh \sqrt{YZ}$$

$$B = Z_C \sinh \sqrt{YZ}$$

And $C = \frac{1}{Z_C} \sinh \sqrt{YZ}$

IV. ANALYSIS AND DISCUSSION OF FAULT ON A THREE-PHASE SYSTEM

A L-L-L-G fault was made to appear on the line after 1.5 seconds. The CB trip/control signal trips the system at the fault point.

The Simulink simulation waveforms for current and voltage during normal & fault conditions are shown in figures 9 and 10 respectively. The system load, transmission line parameters and other parameter were assumed to be kept in their normal conditions.

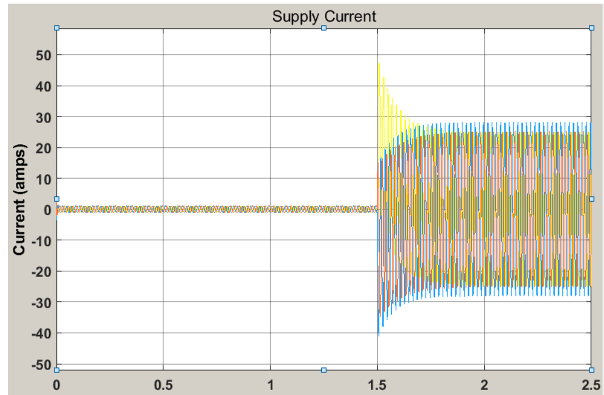

Fig. 9: Current waveform operating normally before fault occured.

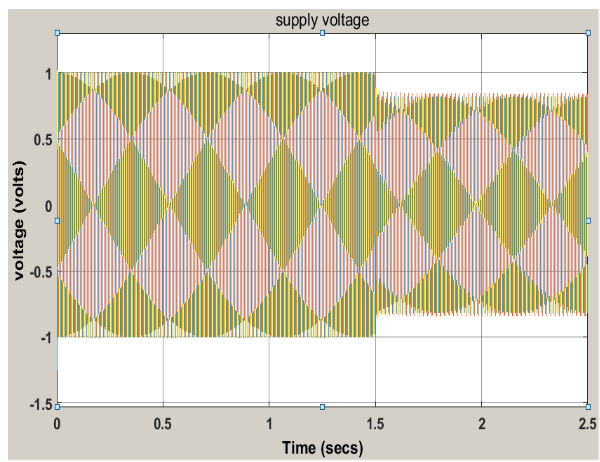

Fig. 10: Voltage waveform operating normally before fault occurred.

V. CONCLUSION

The three-phase power system was in a balanced state and operated normally until a fault was introduced through the trip signal. When the fault occurred, there was a sudden rise in the operating current as shown in fig. 9. Conversely, there was a voltage drop on the system as shown in fig. 10. For a transient fault, an overcurrent relay would send a signal for the CB to reclose. However, the results showed that the trip signal immediately came into action detecting the fault and sending the trip pulse to the circuit breaker to open. If the fault was still on the line after some time delay, then the line would attempt to reclose and bring the system back to normal operation. These attempts will be unsuccessful if the fault is a permanent one. The line would remain open due to the fault till it is manually cleared, suggesting a permanent fault.

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