

FAULT ANALYSIS OF FIVE PHASE TRANSMISSION SYSTEM

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Abstract: Transmission infrastructure is congested due to a combination of increasing load demands, declining investment, and aging facilities. It is anticipated that significant investments will be required for new construction and upgrades in order to serve load demands. High Phase order transmission system is being well thought-out a possible alternative for increasing the power transmission capacity of overhead electric power transmission. High phase order system will experienced quickly with external or internal faults. When fault current magnitudes are important, it can cause smash up to equipment. It is important to design the power system such as the fault is out-of-the-way quickly to minimize the equipment damage and improve own safety. Fault analysis is the stage to determine the magnitude of the current flowing throughout the power system at assorted time intervals after a fault. In this paper, the different types of fault analysis techniques used to analyze the level of fault in Five Phase Transmission System. This Analysis is used to identify the Level of Protection. MATLAB Simulation results give the wave shape of the fault current.

Keywords: Fault analysis, Symmetrical Components, Sequence impedance of Transmission line.

1. Introduction

In INDIA, some states and regions have high demand load growth, due to the growth of the economy and the population. The high load demand growth requires more power transfer capability of the existing transmission infrastructure. Considering the lengthy process of transmission line construction, investment on transmission grid should be made for the long term. Additionally, the areas with high level load demands are suffering critical transmission grid congestion, because of the limited capacity of transmission infrastructure. The congestion areas also demand additional transmission capability to deliver more power from neighboring areas. Meanwhile, most of the existing transmission infrastructures, which were constructed in 1950's, are aging. According to the data from Department of Energy (DoE), 70% of transmission lines and transformers are more-than 25 years old and 60% of circuit breakers are more than 30 years old[1]. To meet the challenges on the transmission grid and improve power transfer capability, billions of dollars will be spent on new transmission infrastructure construction and upgrades.

The most common approach to increase power transfer capability is increasing system voltage. System voltage has been steadily increased from 115kV to 1000kV for AC transmission lines and ± 400 kV to ± 800 kV DC lines have been either built or under construction worldwide [2]. However, in the INDIA, constructing or upgrading a transmission line today is more complicated, compared to decades ago. Some factors responsible for this are listed below:

- a. *Social concerns about the impact of transmission lines:* Much more attention is paid to constructing and upgrading transmission lines today [3]. Electric and Magnetic Fields (EMF) and impacts of transmission lines on daily life have provoked intense criticism [4].
- b. *Laws and standards issued by governments and organization:* In many states, the maximum values of transmission line electric and magnetic fields are regulated. Organizations in power industry, such as Institute of Electrical and Electronics Engineers (IEEE), and Electric Power Research Institute (EPRI), also published standards to define acceptable transmission electric and magnetic fields criteria. The difficulty of constructing or upgrading higher voltage level transmission lines with limited Right of Way (RoW) increases because of those criteria.
- c. *Charge of the transmission line corridor:* The cost of obtaining the transmission line corridor is expensive in those metropolitan areas and regions. Some residential communities have been built around existing transmission lines and difficult to extend the Right of Way (RoW)[3].

Line compaction, Higher Phase Order (HPO) systems, and High Temperature Low Sag (HTLS) conductors, can be used to boost the power convey capability of transmission lines with limited Right of Way (RoW). Additional phases increases the number of possible faults highly and consequently complicate. For instance, the no.of faults in a five phase system be 61 where as it is only 11 in a three phase system. Fault occur one time in a while due to lighting, flashover due to contaminated insulation, diminishing of tree branches on the overhead system, animal invasion and flawed operations. When the fault current magnitudes are momentous, it can cause harm to equipment and

detonation if the fault is not cleared for protracted time. Also, electrical fire hazards to people are probable in a faulted power system. Therefore, it is significant to design the power system such as the fault is out-of-the-way quickly to minimize the equipment harm and advance personal safety. Fault analysis is performed to conclude the magnitude of the current flowing all the way through the power system at an assortment of time intervals after a fault. The magnitude of the current all the way through the power system after a fault varies with time awaiting it reaches a steady state situation. During the fault, the power system is called on to sense, suspend and cut off these faults. The duty frightened on the equipment is dependent on the magnitude of the current, which is a job of the time of fault instigation. The calculated fault currents are used to pick fuses, circuit breakers and surge protective relays. The balanced component model and phase coordinate method is used in the analysis of the asymmetrical faults.

Applying Five Phase alternative in Transmission planning is the design of an ample protective scheme. This requires an in depth and practical fault analysis which is the main argument of this paper. General definition for fault is "Any failure that interferes with the normal flow of current". The fault current that occurs in power system is regularly huge and precarious. Faults can occur because of short circuit or partial short circuit, open circuit, unequal conditions or any other reasons. Short circuit faults are the majority and most harmful, as the excessive current can source thermal and mechanical damage to the plant shipping it.

The complexity of fault examination in a five-phase system is bigger than in a three-phase system. Five-phase faults are the least common while single-line to ground faults is the most common. In addition, faults involving two and three phases with several dissimilar possibilities could be more frequent in five-phase systems compared to three-phase system.

2. Faults on Five – Phase Power System

The faults in Five Phase System are of Symmetrical or Unsymmetrical types, which may consist of short circuits, faults through impedances or open conductors. The fault investigation in Five Phase System is more convoluted than in the usual three phase systems. This is due to the fact that there are five phases, each subjected to a different voltage, and the existence of a neutral makes the number of fault types much larger.

TABLE I

Faults types and combinations of Five Phase System

Fault Type	No. of Combinations	Significant Combinations	Example
5 Phase	1	1	a-b-c-d-e
5 Phase to Neutral	1	1	a-b-c-d-e-n

4 Phase	5	1	a-b-c-d
4 Phase to Neutral	5	1	a-b-c-d-n
3 Phase	12	2	a-b-c, a-c-e
3 Phase to Neutral	12	2	a-b-c-n, a-c-e-n
2 Phase	10	2	a-b, b-d
2 Phase to Neutral	10	2	a-b-n, b-d-n
Single Phase to Neutral	5	1	d-n
Total	61	13	

The number of likely significant faults in three phase and five phase systems is 5 and 13 respectively. The 15 two phase fault combinations are reducing to two major combinations are: Fault between phases 72° apart (e.g.: phase a to phase b), Fault between phases 144° apart (e.g.: phase a to phase c). In a similar manner, analysis for all faults can be restricted to 13 significant combinations as mentioned.

3. Sequence Impedance of Transmission Line

In classify to analyze uneven conditions on transmission lines, need to concern the method of symmetrical components. To do so, first need to convey the impedance of a transmission line as positive-, negative- and zero-sequence mechanism. Fig. 1 shows the circuit of a fully transposed line carrying unbalanced currents. The return path for I_n is sufficiently away for the mutual effect to be ignored. Let Z_s = Each Line Self Impedance, Z_m = Pair of lines Mutual Impedance.

The following KVL equations can be written from Fig. 1.

$$\begin{aligned} V_a - V_{a1} &= Z_s I_a + Z_m I_b + Z_m I_c + Z_m I_d + Z_m I_e \\ V_b - V_{b1} &= Z_m I_a + Z_s I_b + Z_m I_c + Z_m I_d + Z_m I_e \\ V_c - V_{c1} &= Z_m I_a + Z_m I_b + Z_s I_c + Z_m I_d + Z_m I_e \\ V_d - V_{d1} &= Z_m I_a + Z_m I_b + Z_m I_c + Z_s I_d + Z_m I_e \\ V_e - V_{e1} &= Z_m I_a + Z_m I_b + Z_m I_c + Z_m I_d + Z_s I_e \end{aligned} \quad (1)$$

In matrix form:

$$\begin{bmatrix} V_a - V_{a1} \\ V_b - V_{b1} \\ V_c - V_{c1} \\ V_d - V_{d1} \\ V_e - V_{e1} \end{bmatrix} = \begin{bmatrix} Z_s & Z_m & Z_m & Z_m & Z_m \\ Z_m & Z_s & Z_m & Z_m & Z_m \\ Z_m & Z_m & Z_s & Z_m & Z_m \\ Z_m & Z_m & Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_m & Z_m & Z_s \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \\ I_d \\ I_e \end{bmatrix} \quad (2)$$

The above equation can be written as:

$$\Delta V_s = A_5^{-1} Z A_5 I_s \quad (3)$$

$$\text{Where, } A_5 = \text{Transformation Matrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & a^4 & a^3 & a^2 & a \\ 1 & a^3 & a & a^4 & a^2 \\ 1 & a^2 & a^4 & a & a^3 \\ 1 & a & a^2 & a^3 & a^4 \end{bmatrix}$$

$$Z = \begin{bmatrix} Z_s & Z_m & Z_m & Z_m & Z_m \\ Z_m & Z_s & Z_m & Z_m & Z_m \\ Z_m & Z_m & Z_s & Z_m & Z_m \\ Z_m & Z_m & Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_m & Z_m & Z_s \end{bmatrix} \& A_5^{-1} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & a & a^2 & a^3 & a^4 \\ 1 & a^2 & a^4 & a & a^3 \\ 1 & a^3 & a & a^4 & a^2 \\ 1 & a^4 & a^3 & a^2 & a \end{bmatrix}$$

$$A_5^{-1} Z A_5 = \begin{bmatrix} Z_s + 4Z_m & 0 & 0 & 0 & 0 \\ 0 & Z_s - Z_m & 0 & 0 & 0 \\ 0 & 0 & Z_s - Z_m & 0 & 0 \\ 0 & 0 & 0 & Z_s - Z_m & 0 \\ 0 & 0 & 0 & 0 & Z_s - Z_m \end{bmatrix}$$

Therefore,

$$\begin{bmatrix} 0 - V_a^1 \\ e_{a1} - V_b^1 \\ 0 - V_c^1 \\ 0 - V_d^1 \\ 0 - V_e^1 \end{bmatrix} = \begin{bmatrix} Z_s + 4Z_m & 0 & 0 & 0 & 0 \\ 0 & Z_s - Z_m & 0 & 0 & 0 \\ 0 & 0 & Z_s - Z_m & 0 & 0 \\ 0 & 0 & 0 & Z_s - Z_m & 0 \\ 0 & 0 & 0 & 0 & Z_s - Z_m \end{bmatrix} \begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \\ I_{a3} \\ I_{a4} \end{bmatrix} \quad (4)$$

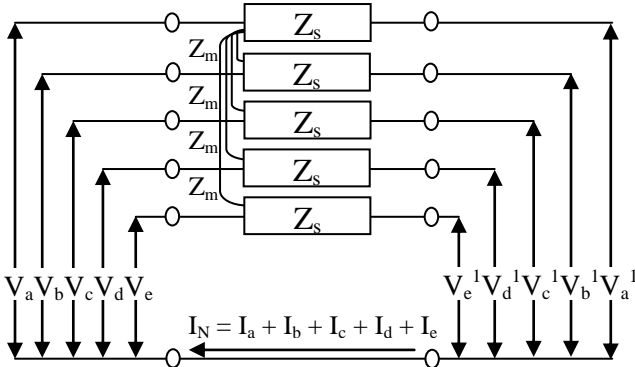


Fig. 1. Circuit of Fully Transposed Line.

Where,

- $Z_0 = Z_s + 4Z_m$ = Impedance of Zero sequence
- $Z_1 = Z_s - Z_m$ = Impedance of First (or +ve) sequence
- $Z_2 = Z_s - Z_m$ = Impedance of Second sequence
- $Z_3 = Z_s - Z_m$ = Impedance of Third sequence
- $Z_4 = Z_s - Z_m$ = Fourth (or -ve) sequence impedance

4. Symmetrical Components

The method of symmetrical mechanism is the most authoritative tool for dealing with unbalanced poly phase systems. In 1918, C. L. Fortescue projected a system whereby a set of n – unbalanced phasors may be resolved into $(n-1)$ balanced, n – phase systems of dissimilar phase sequence and one zero phase sequence system. According to Fortescue's theorem, five unbalance (voltage or current) phasors of a five – phase system be able to be resolved into five balanced systems of phasors (see Fig. 2).

The balanced sets of components are:

- 1st (or +ve) sequence components
- 2nd sequence components
- 3rd sequence components
- 4th (or -ve) sequence components
- Zero sequence components

Each of the i th sequence components ($i = 0, 1, 2, 3, 4$) consists of five phasors like in magnitude and displaced with other by $(72^\circ \cdot i)^0$ in phase except the zero sequence component, which is co-phasal (i.e. all in the same phase). Let the five phases of original system be a, b, c, d and e with phase sequence “abcde”. For 2nd sequence the phase

sequence is “adbce”, for 3rd sequence the phase sequence is “acebd”, for 4th sequence the phase sequence is “aedcb”. A Five Phase system of unbalanced voltage phasors can be uttered in terms of their balanced components by the equations shown below:

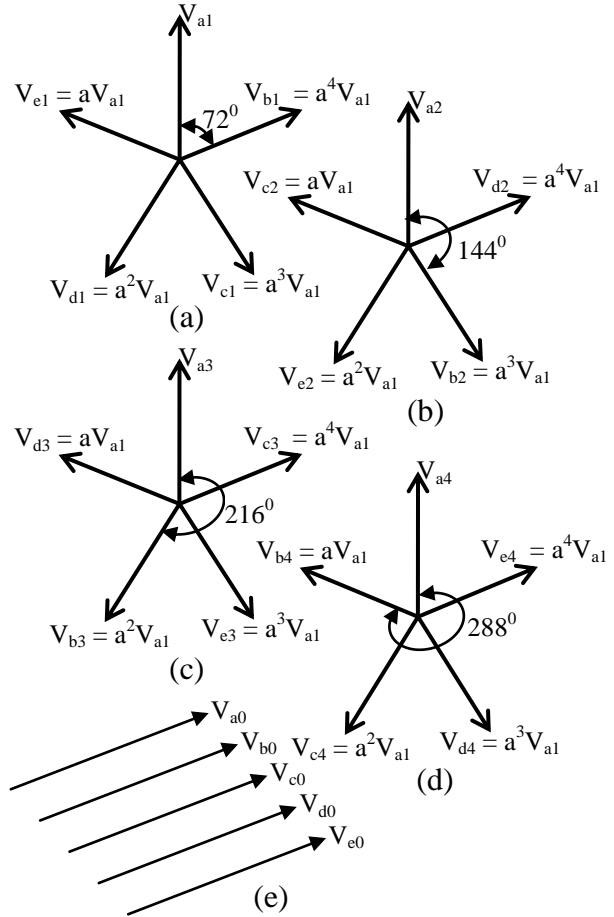


Fig. 2. Five – Phase Symmetrical Components (a) 1st (or +ve) sequence, (b) 2nd sequence, (c) 3rd sequence, (d) 4th (or –ve) sequence, (e) Zero sequence components.

$$\begin{aligned} V_a &= V_{a1} + V_{a2} + V_{a3} + V_{a4} + V_{a0} \\ V_b &= a^4 V_{a1} + a^3 V_{a2} + a^2 V_{a3} + a V_{a4} + V_{a0} \\ V_c &= a^3 V_{a1} + a V_{a2} + a^4 V_{a3} + a^2 V_{a4} + V_{a0} \\ V_d &= a^2 V_{a1} + a^4 V_{a2} + a V_{a3} + a^3 V_{a4} + V_{a0} \\ V_e &= a V_{a1} + a^2 V_{a2} + a^3 V_{a3} + a^4 V_{a4} + V_{a0} \end{aligned} \quad (5)$$

in matrix form:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \\ V_e \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & a^4 & a^3 & a^2 & a \\ 1 & a^3 & a & a^4 & a^2 \\ 1 & a^2 & a^4 & a & a^3 \\ 1 & a & a^2 & a^3 & a^4 \end{bmatrix} \begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \\ V_{a3} \\ V_{a4} \end{bmatrix} \quad (6)$$

also be written as:

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \\ V_{a3} \\ V_{a4} \end{bmatrix} = \frac{1}{5} \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & a & a^2 & a^3 & a^4 \\ 1 & a^2 & a^4 & a & a^3 \\ 1 & a^3 & a & a^4 & a^2 \\ 1 & a^4 & a^3 & a^2 & a \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \\ V_e \end{bmatrix} \quad (7)$$

The five phase operator, $a = 1\angle 72^\circ = 0.309 + j0.951$

$$\begin{aligned} a^2 &= 1\angle 144^\circ \\ a^3 &= 1\angle -144^\circ \\ a^4 &= 1\angle -72^\circ \\ 1 + a + a^2 + a^3 + a^4 &= 0 \end{aligned}$$

5. Fault Analysis

I. Using Symmetrical Components method:

a. Single Line to Ground Fault (SLG) (a-n)

Boundary conditions: $V_a = 0$ and $I_a = I_b = I_c = I_d = I_e = 0$.
Substituting above equations in below equation:

$$\begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \\ I_{a3} \\ I_{a4} \end{bmatrix} = \frac{1}{5} \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & a & a^2 & a^3 & a^4 \\ 1 & a^2 & a^4 & a & a^3 \\ 1 & a^3 & a & a^4 & a^2 \\ 1 & a^4 & a^3 & a^2 & a \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \\ I_d \\ I_e \end{bmatrix} \quad (8)$$

So, $I_{a0} = I_{a1} = I_{a2} = I_{a3} = I_{a4} = I_a/5$

From equation (4)

$$\begin{bmatrix} v_{a0} \\ v_{a1} \\ v_{a2} \\ v_{a3} \\ v_{a4} \end{bmatrix} = \begin{bmatrix} 0 \\ E_{a1} \\ 0 \\ 0 \\ 0 \end{bmatrix} - \begin{bmatrix} z_a & 0 & 0 & 0 & 0 \\ 0 & z_1 & 0 & 0 & 0 \\ 0 & 0 & z_2 & 0 & 0 \\ 0 & 0 & 0 & z_3 & 0 \\ 0 & 0 & 0 & 0 & z_4 \end{bmatrix} \begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \\ I_{a3} \\ I_{a4} \end{bmatrix} \quad (9)$$

From boundary conditions:

$$v_a = v_{a0} + v_{a1} + v_{a2} + v_{a3} + v_{a4} = 0 \quad (10)$$

Solving above equation:

$$I_{a1} = E_{a1}/(Z_0 + Z_1 + Z_2 + Z_3 + Z_4) \quad (11)$$

$$\text{Fault Current, } I_f = I_a = 5I_{a1} \quad (12)$$

$$I_f = 5*(E/Z_0 + Z_1 + Z_2 + Z_3 + Z_4) \quad (13)$$

b. Four Line to Ground Fault (4LG) (b-c-d-e-n)

Boundary conditions: $V_b = V_c = V_d = V_e = 0$ (14)

and $I_a = I_{a0} = I_{a1} = I_{a2} = I_{a3} = I_{a4} = 0$

$$I_{a0} = -(I_{a1} + I_{a2} + I_{a3} + I_{a4}) \quad (15)$$

$$I_f = 5I_{a0} \quad (16)$$

$$\begin{bmatrix} v_{a0} \\ v_{a1} \\ v_{a2} \\ v_{a3} \\ v_{a4} \end{bmatrix} = \frac{1}{5} \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & a & a^2 & a^3 & a^4 \\ 1 & a^2 & a^4 & a & a^3 \\ 1 & a^3 & a & a^4 & a^2 \\ 1 & a^4 & a^3 & a^2 & a \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \\ v_d \\ v_e \end{bmatrix} \quad (17)$$

By substituting periphery conditions in above equation we get: $v_{a0} = v_a/5$;

$$v_{a1} = v_{a2} = v_{a3} = v_{a4} = 1/5(v_a + av_b + a^2v_b + a^3v_b + a^4v_b) = v_a/5. \quad (18)$$

From equation (1) we get:

$$\begin{bmatrix} Z_0 & 0 & 0 & 0 & 0 \\ 0 & Z_1 & 0 & 0 & 0 \\ 0 & 0 & Z_2 & 0 & 0 \\ 0 & 0 & 0 & Z_3 & 0 \\ 0 & 0 & 0 & 0 & Z_4 \end{bmatrix} \begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \\ I_{a3} \\ I_{a4} \end{bmatrix} = \begin{bmatrix} 0 \\ E_a \\ 0 \\ 0 \\ 0 \end{bmatrix} - \begin{bmatrix} E_a - I_{a1}Z_1 \\ E_a - I_{a1}Z_1 \\ E_a - I_{a1}Z_1 \\ E_a - I_{a1}Z_1 \\ E_a - I_{a1}Z_1 \end{bmatrix} \quad (19)$$

Now,

$$\begin{aligned} I_{a0} + I_{a1} + I_{a2} + I_{a3} + I_{a4} &= -(E_a/Z_0) + (I_{a1}Z_1/Z_0) + I_{a1} - \\ & (E_a/Z_2) + (I_{a1}Z_1/Z_2) - (E_a/Z_3) + (I_{a1}Z_1/Z_3) - (E_a/Z_4) + \\ & (I_{a1}Z_1/Z_4) \end{aligned} \quad (20)$$

From boundary conditions:

$$\begin{aligned} I_{a1} \left[1 + Z_1 \left[\frac{1}{Z_0} + \frac{1}{Z_2} + \frac{1}{Z_3} + \frac{1}{Z_4} \right] \right] &= E_a \left[\frac{1}{Z_0} + \frac{1}{Z_2} + \frac{1}{Z_3} + \frac{1}{Z_4} \right] \\ I_{a1} \left[\frac{Z_0 Z_2 Z_3 Z_4}{Z_2 Z_3 Z_4 + Z_0 Z_3 Z_4 + Z_0 Z_2 Z_4 + Z_0 Z_2 Z_3} + Z_1 \right] &= E_a \\ I_{a1} &= \frac{E_a}{Z_1 + \frac{Z_0 Z_2 Z_3 Z_4}{Z_2 Z_3 Z_4 + Z_0 Z_3 Z_4 + Z_0 Z_2 Z_4 + Z_0 Z_2 Z_3}} \quad (21) \end{aligned}$$

Now by using equation (16) we can find fault current for 4LG fault. Although the six phase symmetrical component method seems to be a accurate technique for calculating faults in a six phase system, it has many drawbacks, first this method has been for just some simple faults in isolated five phase system and all important faults that could take place on five phase line are not willing to symmetrical component analysis. Second, the fault resistance has been ignored, which with existence of fault resistance the calculation become more complicated and the third and main drawback of this method is that in case of simultaneous faults on the system symmetrical component becomes rather complicated to use.

II. Fault Analysis using Phase Coordinates method:

The phase coordinate method is usually used in three phase for analyzing faults in an unbalanced system like distribution and also it is a useful tool for analyzing simultaneous faults, because in these situations the symmetrical component does not provide any advantages to ease the problem at hand. Equation (2) is used to conduct fault analysis in this method.

a. Single Line to Ground Fault (SLG) (a-n)

Boundary conditions: $V_a = 0$ and $I_a = I_b = I_c = I_d = I_e = 0$, by substituting these conditions in equation (2) we get:

$$\begin{bmatrix} v_a - 0 \\ \alpha^4 v_a - v_b^1 \\ \alpha^3 v_a - v_c^1 \\ \alpha^2 v_a - v_d^1 \\ \alpha v_a - v_e^1 \end{bmatrix} = \begin{bmatrix} Z_s & Z_m & Z_m & Z_m & Z_m \\ Z_m & Z_s & Z_m & Z_m & Z_m \\ Z_m & Z_m & Z_s & Z_m & Z_m \\ Z_m & Z_m & Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_m & Z_m & Z_s \end{bmatrix} \begin{bmatrix} I_a \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (22)$$

From above equation we get: $I_a = v_a/Z_s$

b. Double Line to Ground Fault (LLG) (a-b-n)

Boundary conditions: $V_a = V_b = 0$ and $I_c = I_d = I_e = 0$, by substituting these conditions in equation (4) we get:

$$\begin{bmatrix} v_a - v_b^1 \\ \alpha^4 v_a - 0 \\ \alpha^3 v_a - 0 \\ \alpha^2 v_a - v_d^1 \\ \alpha v_a - v_e^1 \end{bmatrix} = \begin{bmatrix} Z_s & Z_m & Z_m & Z_m & Z_m \\ Z_m & Z_s & Z_m & Z_m & Z_m \\ Z_m & Z_m & Z_s & Z_m & Z_m \\ Z_m & Z_m & Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_m & Z_m & Z_s \end{bmatrix} \begin{bmatrix} 0 \\ I_b \\ I_c \\ 0 \\ 0 \end{bmatrix} \quad (23)$$

By solving above equation we get:

$$a^4 v_a = Z_s I_b + Z_m I_c \quad (24)$$

$$I_b = (a^4 v_a - Z_m I_c)/Z_s \quad (25)$$

$$a^3 v_a = Z_m I_b + Z_m I_c$$

By substituting equation (24) in equation (25) we get:

$$I_c = (E_a(a^3 Z_s - a^4 Z_m))/(Z_s + Z_m)(Z_s - Z_m) \quad (26)$$

c. Triple Line to Ground Fault (3LG) (a-b-c-n)

Boundary conditions: $V_a = V_b = V_c = 0$ and $I_d = I_e = 0$, by substituting these conditions in equation (2) we get:

$$\begin{bmatrix} v_a - 0 \\ \alpha^4 v_a - 0 \\ \alpha^3 v_a - 0 \\ \alpha^2 v_a - v_d^1 \\ \alpha v_a - v_e^1 \end{bmatrix} = \begin{bmatrix} Z_s & Z_m & Z_m & Z_m & Z_m \\ Z_m & Z_s & Z_m & Z_m & Z_m \\ Z_m & Z_m & Z_s & Z_m & Z_m \\ Z_m & Z_m & Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_m & Z_m & Z_s \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \\ 0 \\ 0 \end{bmatrix} \quad (27)$$

From the above equation:

$$V_a = Z_s I_a + Z_m I_b + Z_m I_c \quad (28)$$

$$\alpha^4 v_a = Z_m I_c + Z_s I_b + Z_m I_c \quad (29)$$

$$\alpha^3 v_a = Z_m I_a + Z_m I_b + Z_s I_c \quad (30)$$

by solving above three equations we can solve fault current for 3LG fault.

d. Four Line to Ground Fault (4LG) (a-b-c-d-n)

Boundary conditions: $V_a = V_b = V_c = V_d = 0$ and $I_e = 0$, by substituting these conditions in equation (2) we get:

$$\begin{bmatrix} v_a - 0 \\ \alpha^4 v_a - 0 \\ \alpha^3 v_a - 0 \\ \alpha^2 v_a - 0 \\ \alpha v_a - v_e^1 \end{bmatrix} = \begin{bmatrix} Z_s & Z_m & Z_m & Z_m & Z_m \\ Z_m & Z_s & Z_m & Z_m & Z_m \\ Z_m & Z_m & Z_s & Z_m & Z_m \\ Z_m & Z_m & Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_m & Z_m & Z_s \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \\ I_d \\ 0 \end{bmatrix} \quad (31)$$

From the above equation:

$$V_a = Z_s I_a + Z_m I_b + Z_m I_c + Z_m I_d$$

$$\alpha^4 v_a = Z_m I_a + Z_s I_b + Z_m I_c + Z_m I_d$$

$$\alpha^3 v_a = Z_m I_a + Z_m I_b + Z_s I_c + Z_m I_d$$

$$\alpha^2 v_a = Z_m I_a + Z_m I_b + Z_m I_c + Z_s I_d \quad (32)$$

by solving above four equations we can solve fault current for 4LG fault.

e. Five Line to Ground Fault (5LG) (a-b-c-d-e-n)

Boundary conditions: $V_a = V_b = V_c = V_d = V_e = 0$, by substituting these conditions in equation (2) we get:

$$\begin{bmatrix} v_a \\ \alpha^4 v_a \\ \alpha^3 v_a \\ \alpha^2 v_a \\ \alpha v_a \end{bmatrix} = \begin{bmatrix} Z_s & Z_m & Z_m & Z_m & Z_m \\ Z_m & Z_s & Z_m & Z_m & Z_m \\ Z_m & Z_m & Z_s & Z_m & Z_m \\ Z_m & Z_m & Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_m & Z_m & Z_s \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \\ I_d \\ I_e \end{bmatrix} \quad (33)$$

From above equation:

$$V_a = Z_s I_a + Z_m I_b + Z_m I_c + Z_m I_d + Z_m I_e$$

$$\alpha^4 v_a = Z_m I_a + Z_s I_b + Z_m I_c + Z_m I_d + Z_m I_e$$

$$\alpha^3 v_a = Z_m I_a + Z_s I_b + Z_m I_c + Z_m I_d + Z_m I_e$$

$$\alpha^2 v_a = Z_m I_a + Z_s I_b + Z_m I_c + Z_m I_d + Z_m I_e$$

$$\alpha v_a = Z_m I_a + Z_s I_b + Z_m I_c + Z_m I_d + Z_m I_e \quad (34)$$

by solving above five equations we can solve fault current for 5LG fault.

6. Fault Analysis using MATLAB Simulink

Conventional three phase supply is converted into five phase supply by using specially connected transformer connection. Later the five phase power is transmitted by using PI section lines as shown in Fig. 3. The input parameters used in simulation are shown in Table II.

TABLE II Input Parameters for Fault Analysis	
Parameters	Values
Input Voltage to Transmission Line	132kV
Transmission Line Resistance	0.25 ohms per km
Transmission Line Inductance	1.3492 mH per km
Transmission Line Capacitance	0.003725 μ F per km
Load Resistance and Inductance	R = 290 ohms & L = 100 mH
Line Length	120 km

From the waveforms, the sending end voltage is 131.05kV, the receiving end voltage is 116.1kV and the current is 398A. The loss of voltage in transmission line is 14.95kV. So, the transmission line efficiency is 88.5%. Fault analysis is conducted on all ground faults (i.e., 7 significant ground faults).

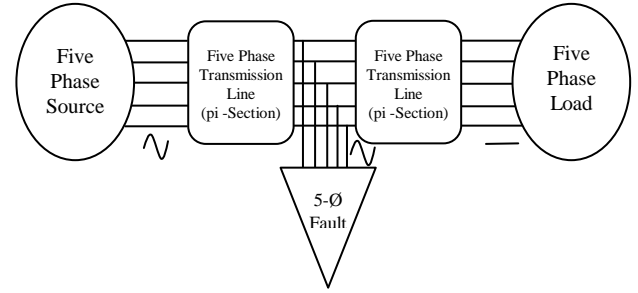


Fig. 3. Five Phase Transmission System Schematic Diagram

Five Phase fault is created in MATLAB Simulink by using five single phase breakers and the switching time is set to 0.05 to 0.15 sec. The fault is created at the middle of the transmission line. In this analysis, consider the currents at sending end side at the fault condition. The values of these currents are used to design the protection scheme.

For the healthy system, introducing Single Line to Ground (SLG) Fault applied at 0.05sec to 0.15sec by operating switch in MATLAB Simulation to Phase-D (d-n).

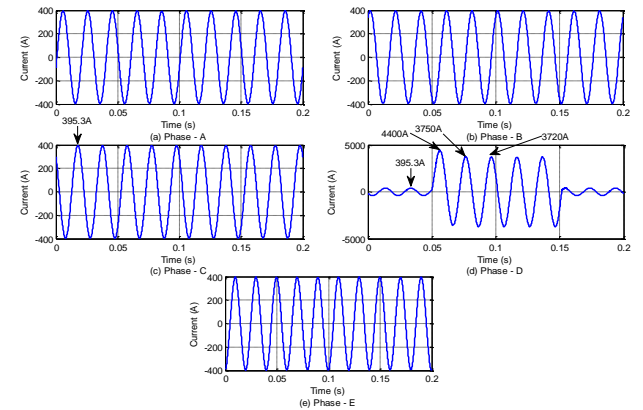


Fig. 4. SLG (d-n) Fault Currents

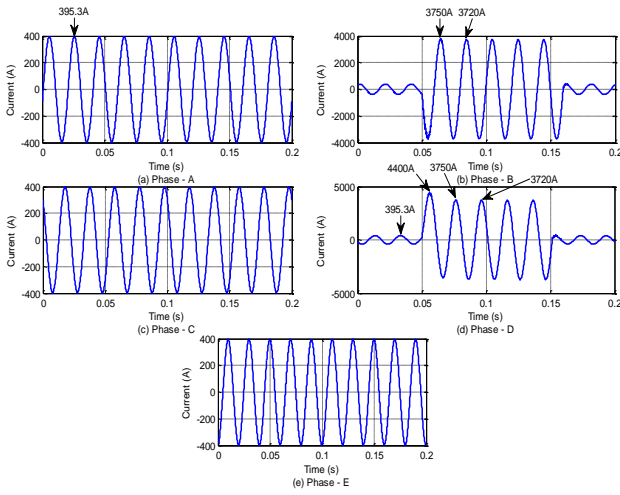


Fig. 5. DLG (b – d – n) Fault Currents

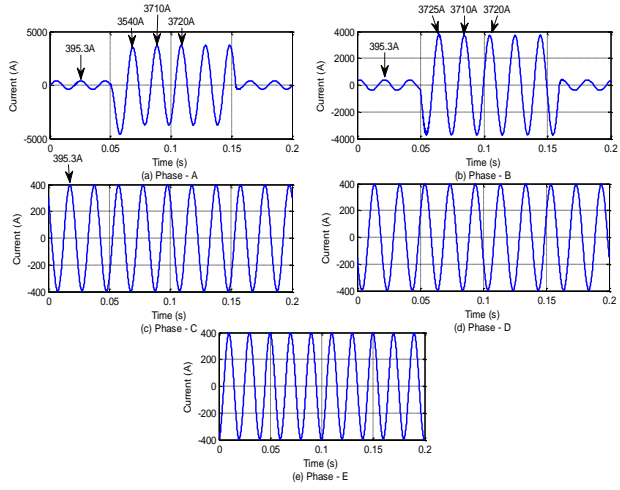


Fig. 6. DLG (a – b – n) Fault Currents

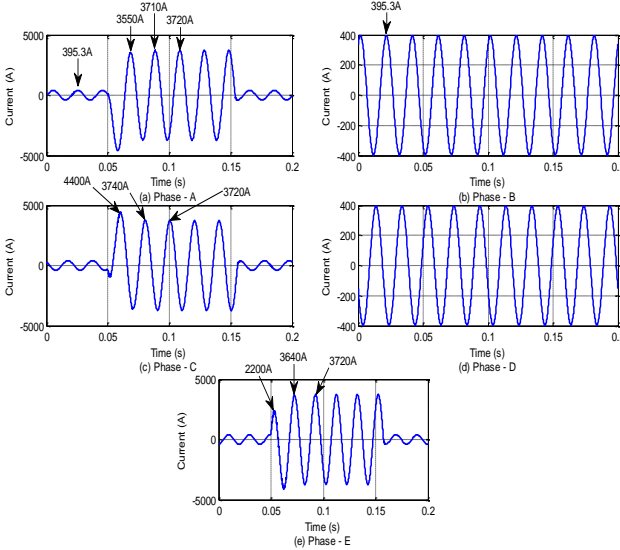


Fig. 7. TLG (a – c – e – n) Fault Currents

For the healthy system, introducing Double Line to Ground (DLG) Fault applied at 0.05sec to 0.15sec by operating switch in MATLAB Simulation to Phase – B & Phase – D (b-d-n) as shown in Fig. 5 and Phase – A & Phase – B (a-b-n) as shown in Fig. 6, observe the abnormal raise the current at both the phases.

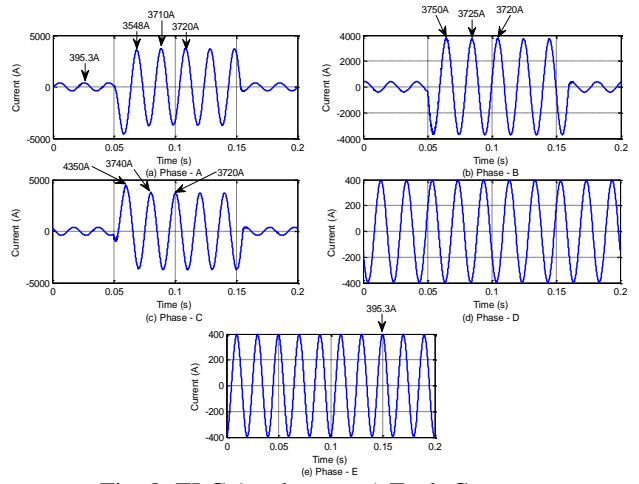


Fig. 8. TLG (a – b – c – n) Fault Currents

For the healthy system, introducing Triple Line to Ground (TLG) Fault applied at 0.05sec to 0.15sec by operating switch in MATLAB Simulation to Phase – A, Phase – C & Phase – E (a-c-e-n) as shown in Fig. 7 and Phase – A, Phase – B & Phase – C (a-b-c-n) as shown in Fig. 8, observe the abnormal raise the current in three phases.

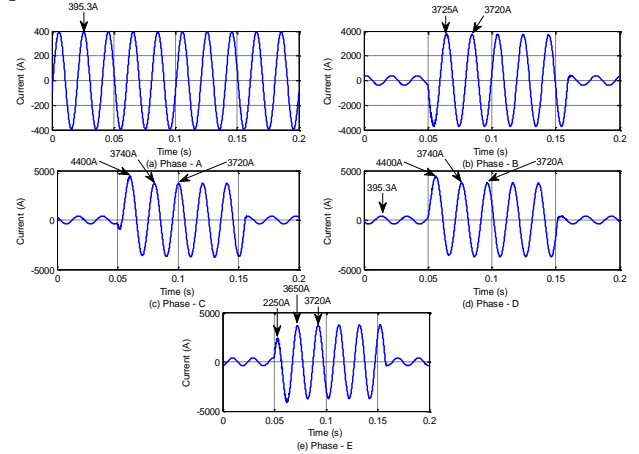


Fig. 9. QLG (b – c – d – e – n) Fault Currents

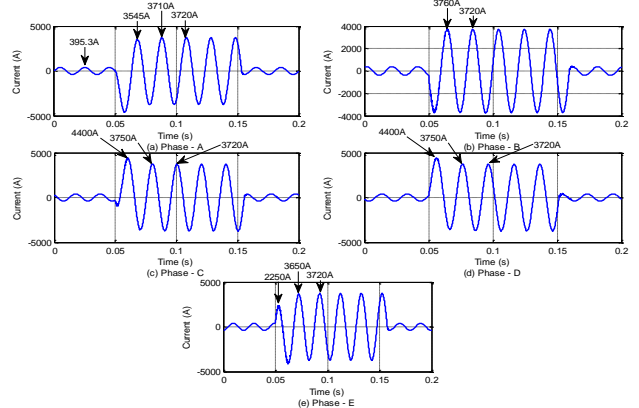


Fig. 10. PLG (a-b-c-d-e-n) Fault Currents

For the healthy system, introducing Quadric Line to Ground (QLG) Fault applied at 0.05sec to 0.15sec by operating switch in MATLAB Simulation to Phase – B, Phase – C, Phase – D & Phase – E (b-c-d-e-n). From the Fig. 9, observe the abnormal raise the current in four phases.

For the healthy system, introducing Pentad Line to

Ground (PLG) Fault applied at 0.05sec to 0.15sec by operating switch in MATLAB Simulation to Phase – A, Phase – B, Phase – C, Phase - D & Phase – E (a-b-c-d-e-n). Form all the waveforms, observe the abnormal raise the current in the respective phases. The steady state current value is 3720A at fault condition.

TABLE III

Current values at fault condition from MATLAB Simulink

7 significant ground faults	Sub-Transient current	Transient current	Steady State Current
SLG (d-n)	4400A	3720A	395A
DLG (b-d-n)	b – 3750A d – 4400A	3720A	395A
DLG (a-b-n)	a – 3540A b – 3725A	3720A	395A
TLG (a-c-e-n)	a – 3550A c – 4400A e – 2200A	3720A	395A
TLG (a-b-c-n)	a – 3548A b – 3750A c – 4350A	3720A	395A
QLG (b-c-d-e-n)	b – 3725A c – 4400A d – 4400A e – 2250A	3720A	395A
PLG (a-b-c-d-e-n)	a – 3545A b – 3760A c – 4400A d – 4400A e – 2250A	3720A	395A

Similarly, same result obtained from NI Multisim based simulation for all the seven significant faults. NI Multisim simulation diagram shown in fig. 11. Some slight differences in current values from MATLAB Simulation to NI Multisim based Simulation. Because, NI Multisim based simulation is somewhat near to the real world.

TABLE IV

Current values at fault condition from NI Multisim

7-Significant ground faults	Transient current	Steady State Current
SLG (d-n)	3.681kA	394.829A
DLG (b-d-n)	b – 3.681kA d – 3.681kA	394.829A
DLG (a-b-n)	a – 3.681kA b – 3.681kA	394.829A
TLG (a-c-e-n)	a – 3.681kA c – 3.681kA e – 3.681kA	394.829A
TLG (a-b-c-n)	a – 3.681kA b – 3.681kA c – 3.681kA	394.829A
QLG (b-c-d-e-n)	b – 3.681kA c – 3.681kA d – 3.681kA e – 3.681kA	394.829A
PLG (a-b-c-d-e-n)	a – 3.681kA b – 3.681kA c – 3.681kA d – 3.681kA e – 3.681kA	394.829A

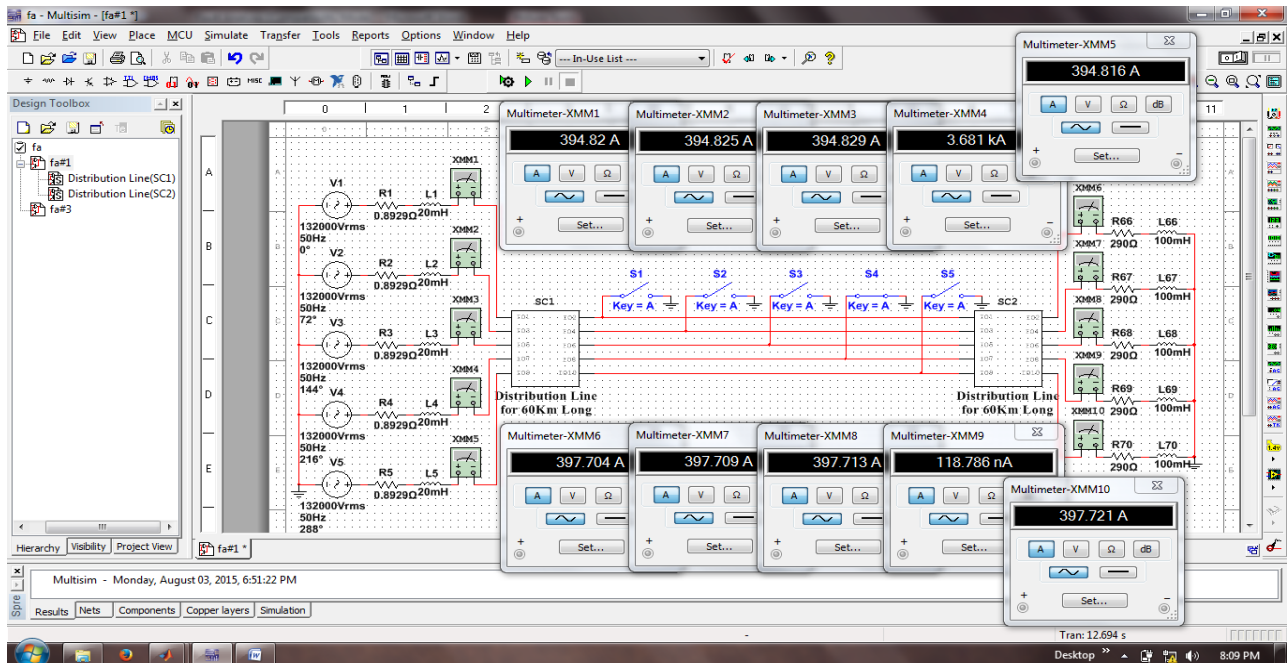


Fig. 11: NI Multisim based Simulation results for SLG (d-n) fault.

Conclusion

Fault analysis is performed to conclude the magnitude of the current elegant throughout the power system at a range of time intervals after a fault. The symmetrical component method and phase coordinate methods are very useful techniques to analysis the fault in a power system. MATLAB Simulation results and NI Multisim based simulation results are obtained and presented in this paper for different fault conditions.

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