Fault Analysis of an Unbalanced Multiphase Distribution System with mutual coupling, using symmetrical components

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Abstract: **This paper presents the short circuit capacity evaluation at each bus, by performing fault analysis, of an unbalanced multiphase 34-bus distribution system consisting of mutually coupled lines, for LLLG (Symmetrical three phase to ground), LG (Single line to ground) and LLG (Double line to ground) faults, using existing software tools based on symmetrical components, by suitably modifying the network [1]. The 34-bus distribution system, shown in Fig.1 is the IEEE feeder network with a generator connected at node 890 [2]. The system contains two mutually coupled lines. The short circuit capacity at each bus, is evaluated by the symmetrical component method, and the results obtained are verified by the network phase model analysis [3, 4, 5]. The system is modeled and analyzed for fault studies, in terms of symmetrical components by taking certain assumptions and suitably modifying the network accordingly. The results, thus obtained are verified by analyzing the phase model of the network for fault studies. The results are recorded in Table 3. For the analysis, the software tool MATLAB is used, wherever required.**

Keywords: **Fault Analysis, Short circuit capacity, Symmetrical component model, multiphase distribution system with mutually coupled lines.**

1. INTRODUCTION

Whenever a fault occurs in a power system, high currents flow depending on nature and location of the fault. These currents are sensed through relays and the faulty sections of the system are isolated quickly by operation of circuit breakers, in a maximum of 5 cycles. Thus, time for operation of circuit breakers, after detection of fault, ranges from 10 ms to 100 ms. For interrupting the high currents, the circuit breakers must be able to withstand the interruption Fault MVA. At the planning and design stage, studies are carried out to estimate the values of short circuit currents throughout the network. The various types of faults occurring in a system in the order of frequency of occurrence are single line to ground, line to line, double line to ground, and three phase faults.

The short circuit fault analysis helps in determining the steady state currents for various types of faults at various locations in the system. In general, the fault current is maximum for the three phase to ground fault, excluding certain cases. The maximum short circuit capacity is thus evaluated by calculating the three phase to ground fault current. This short circuit information is used to select fuses, circuit breakers and switchgear of appropriate rating, in addition to setting the protective relays, considering into account the future expansion of the power system.

The fault analysis of any system can be performed either by using symmetrical components or by the phase coordinate method. In this paper, an IEEE 34-bus multiphase distribution system with mutually coupled lines, is considered and short circuit capacity of each bus is evaluated by performing fault analysis by symmetrical component method. The obtained results are verified by analyzing the phase model of the system.

The following sections of the paper describe the parameters of the sample system; formation of it's analytical model by the two stated methods; it's analysis, followed by the results and conclusion.

2. SYSTEM DESCRIPTION

The 34 node test feeder is referred from IEEE test feeders [2]. The single line diagram of the system is shown in Fig. 1. The three digit bus numbers indicated in Fig.1 are as per the IEEE feeder notation [2]. A generator is considered at bus 890 supplying power to the network through a transformer. The network consists of three phase and single phase distribution lines. In the figure, a single phase distribution line is represented by single hash on the respective line and rest are three phase lines. The assumed rating of the generator is 0.5 MVA, 24.9 kV. The rating of the transformer, the line lengths, line configurations and reactances are as per IEEE specifications [2]. The base MVA for the feeder is assumed to be 0.5. The base kV in generator circuit is 24.9, and base kV in the line circuit is 4.16, as per the IEEE reference.

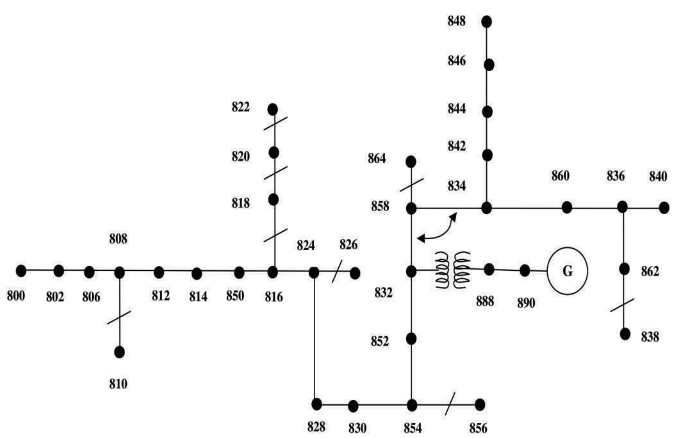

Fig. 1 Multiphase Distribution System (34 bus system)

The system contains 2 mutually coupled three phase lines namely 832-858 and 858-834. The mutual impedance between the three phases of the two lines (Phase Coordinate Model) is j0.04 p.u.

The results obtained by symmetrical component model & phase model, are presented in Table 3. The bus at which short circuit capacity is evaluated for the specific fault, is indicated in column 2, in the table. The evaluated short circuit capacities of the model, by the above stated both methods, for the three types of faults namely LG, LLG and LLLG faults, are recorded. The short circuit capacity at each bus, is evaluated by omitting loads, and assuming each bus voltage to be 1 p.u.

The percentage error is recorded with respect to the results obtained by phase model.

The length and configuration of each line of the IEEE 34 Node Feeder circuit is recorded in Table-1. The voltage ratio and impedance of transformer connected in the single line diagram (Fig.1) are recorded in Table-2.

The impedance of each line is classified according to it's material and configuration (column 5, Table-1). The impedance matrices configuration-wise are :

Configuration 300:

Z =(R +jX) in ohms per mile

$$Z = \begin{bmatrix} 1.3368 + j1.3343 & 0.2101 + j0.5779 & 0.2130 + j0.5015 \\ 0.2101 + j0.5779 & 1.3238 + j1.3569 & 0.2066 + j0.4591 \\ 0.2130 + j0.5015 & 0.2066 + j0.4591 & 1.3294 + j1.3471 \end{bmatrix}$$

Configuration 301:

Z =(R +jX) in ohms per mile

$$Z = \begin{bmatrix} 1.9300 + j1.4115 & 0.2327 + j0.6442 & 0.2359 + j0.5691 \\ 0.2327 + j0.6442 & 1.9157 + j1.4281 & 0.2288 + j0.5238 \\ 0.2359 + j0.5691 & 0.2288 + j0.5238 & 1.9219 + j1.4209 \end{bmatrix}$$

Configuration 302:

Z =(R +jX) in ohms per mile

$$Z = \begin{bmatrix} 2.7995 + j1.4855 & 0 + j0 & 0 + j0 \\ 0 + j0 & 0 + j0 & 0 + j0 \\ 0 + j0 & 0 + j0 & 0 + j0 \end{bmatrix}$$

Configuration 303:

Z =(R +jX) in ohms per mile

$$Z = \begin{bmatrix} 0 + j0 & 0 + j0 & 0 + j0 \\ 0 + j0 & 2.7995 + j1.4855 & 0 + j0 \\ 0 + j0 & 0 + j0 & 0 + j0 \end{bmatrix}$$

Configuration 304:

Z= (R +jX) in ohms per mile

$$Z = \begin{bmatrix} 0 + j0 & 0 + j0 & 0 + j0 \\ 0 + j0 & 1.9217 + j1.4212 & 0 + j0 \\ 0 + j0 & 0 + j0 & 0 + j0 \end{bmatrix}$$

Table 1:Length and Configuration of each line (IEEE 34 Node Feeder)

S.No.	Node A	Node B	Length (ft.)	Configuration
1	800	802	2580	300
2	802	806	1730	300
3	806	808	32230	300
4	808	810	5804	303
5	808	812	37500	300
6	812	814	29730	300
7	814	850	10	301
8	816	818	1710	302
9	816	824	10210	301
10	818	820	48150	302
11	820	822	13740	302
12	824	826	3030	303
13	824	828	840	301
14	828	830	20440	301
15	830	854	520	301
16	832	858	4900	301
17	832	888	0	Transformer
18	834	860	2020	301
19	834	842	280	301
20	836	840	860	301
21	836	862	280	301
22	842	844	1350	301
23	844	846	3640	301
24	846	848	530	301
25	850	816	310	301
26	852	832	10	301
27	854	856	23330	303
28	854	852	36830	301
29	858	864	1620	302
30	858	834	5830	301
31	860	836	2680	301

Table 2: Voltage ratio and Impedance of Transformer (IEEE 34 Node Feeder)

	kVA	kV- high	kV- low	R (%)	X(%)
Substation	2500	69 - D	24.9 – Gr.W	1	8
Transformer	500	24.9 – Gr.W	4.16 – Gr.W	1.9	4.08

3. ANALYTICAL MODEL FORMATION OF SAMPLE SYSTEM

The system shown in Fig. 1 is analyzed for three faults namely LLLG (Symmetrical three phase to ground), LG (Single line to ground) and LLG (Double line to ground) faults. The network is analyzed by symmetrical components and the results are verified by the phase coordinate model.

The formation of both models is explained in the following sub-sections.

A. Phase Coordinate Model

The distribution line, generator and transformer impedance model individually between buses 'i', 'j', is represented in terms of phase impedance matrices, given by equation (1).

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$$Z_{ij}^{abc} = \begin{bmatrix} Z^{aa} & Z^{ab} & Z^{ac} \\ Z^{ba} & Z^{bb} & Z^{bc} \\ Z^{ca} & Z^{cb} & Z^{cc} \end{bmatrix} \quad (1)$$

The phase model is represented by the overall bus impedance matrix, Z_{BUS} of the network formed by the impedance matrix building algorithm, where the individual models of generator, transformer & distribution lines are formed and represented in the form of an impedance matrix as given by equation (1). For a generator and transformer, the elements of impedance matrix are evaluated as per their connections [3,4,5,6,7]. The order of bus impedance matrix is (3n x 3n), where 'n' is the number of nodes/buses in the network.

B. Symmetrical Component Model

For representing the system model in terms of symmetrical components, every distribution line is converted into it's three phase equivalent line [1], as per the following assumptions :

i. For any 2-phase line, the non-existent phase is represented by a dummy impedance whose phase impedance is taken equal to the average of the phase impedances of the two existent phases (though, since current through this phase is zero it can be assumed any value). For example, for a line with existent phases (a, b), say if phase impedances for phases 'a', 'b' are Z^a, Z^b, the impedance for the non-existent phase 'c' is assumed to be $(Z^a + Z^b) / 2$

ii. For any 1-phase line, the non-existent phases are represented by dummy impedances whose phase impedances are taken equal to that of the existent phase. For example, for a line with Z^a as the phase impedance of existent phase 'a', the phase impedances of non-existent phases 'b', 'c' are assumed to be $Z^a = Z^b = Z^c$

iii. The shunt elements (charging admittances) are omitted in calculations.

The network impedance matrix is formed by singular transformation method as explained in the following part of the section.

After converting every distribution line into it's equivalent three phase model according to the directions specified in the above section, the symmetrical component matrix i.e. Z_{ij}^{012} for every distribution line between nodes/buses 'i', 'j', is evaluated by eq.

$$Z_{ij}^{012} = A^{-1}\left[Z_{ij}^{abc}\right]A \quad (2).$$

where,

$$A = \text{Transformation matrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \quad (3.1)$$

$$A^{-1} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \quad (3.2)$$

$\alpha = -0.5 + j\,0.866$, $\alpha^2 = -0.5 - j\,0.866$

The diagonal elements of the symmetrical component impedance matrix are extracted, and the off diagonal elements are neglected, as specified in eq. (4.1).

$$Z_{ij}^{012} = \begin{bmatrix} Z_{ij}^0 & 0 & 0 \\ 0 & Z_{ij}^1 & 0 \\ 0 & 0 & Z_{ij}^2 \end{bmatrix} \quad (4.1)$$

After evaluating Z_{ij}^{012} of each distribution line, the primitive impedance matrices Z_{prim}^0 , Z_{prim}^1 , Z_{prim}^2 (for zero, positive and negative sequence networks respectively) are evaluated taking the impedance of the mutually coupled lines into account. The primitive admittance matrices likewise are evaluated by eq. (4.2) to (4.4)

$$y_{prim}^0 = z_{prim}^0 \quad (4.2)$$

$$y_{prim}^1 = z_{prim}^1 \quad (4.3)$$

$$y_{prim}^2 = z_{prim}^2 \quad (4.4)$$

The overall bus admittance matrix is formed using singular transformation technique by eq. (5.1) to (5.3).

$$Y_{bus}^0 = IM^T\left[y_{prim}^0\right]IM \quad (5.1)$$

$$Y_{bus}^1 = IM^T\left[y_{prim}^1\right]IM \quad (5.2)$$

$$Y_{bus}^2 = IM^T\left[y_{prim}^2\right]IM \quad (5.3)$$

where, IM = Incidence Matrix of network

IM^T = Transpose of IM

The network bus impedance matrices (for zero, positive and negative sequence networks) are obtained by inverting the matrices given in eq. 5.1 to 5.3

In case of a star grounded generator with a finite neutral reactance/impedance, it is incorporated in the generator model as explained in reference [7].

Here, the transformer model Y^{abc}, is represented with respect to it's connection type on primary & secondary side. If any of the transformer windings is star connected and grounded with reactance/impedance in the neutral circuit, it is to be incorporated in the sequence model as explained in references from [4] to [7].

4. FAULT CURRENT CALCULATION USING SYMMETRICAL COMPONENT METHOD

In this paper, the symmetrical component model of the network is represented by the overall sequence bus admittance matrix, Y_{BUS}^{012} of the system. For this, individual admittance matrices for generator, transformer & each distribution line are evaluated, as explained in Section III (B).

The impedance matrix of each distribution line in terms of sequence components is derived from equation (2), and the corresponding admittance matrix of the distribution line between buses 'i', 'j', i.e. Y_{ij}^{012} is obtained from it's inversion.

The sequence admittance matrix Y_{BUS}^{012} is inverted to get the network sequence impedance matrix, Z_{BUS}^{012} The short circuit current, I_{sc}^1 is then evaluated by equation (6), (7) and (8).

For Symmetrical three phase to ground (LLLG) fault, short circuit current in p.u., I_{sc}^f is given by eq. (6)

$$I_{sc}^{f} = I_{sc}^{1} = \frac{V_{pf}}{(Z_{ii}^{1} + z_f)} \quad (6)$$

For Single Line to ground (LG) fault, short circuit current in p.u., I_{sc}^{f} is given by eq. (7)

$$I_{sc}^{f} = \frac{3V_{pf}}{(Z_{ii}^{2} + Z_{ii}^{1} + Z_{ii}^{0} + z_f)} \quad (7)$$

For Double Line to ground (LLG) fault, short circuit current in p.u., I_{sc}^{f} is given by eq. (8)

$$I_{sc}^{f} = I^{b} + I^{c} \quad (8)$$

I^b and I^c are the phase currents of phase 'b' and phase 'c' respectively, in p.u. and can be evaluated by matrix solution of eq. (9)

$$I^{abc} = A^{-1}\, I^{012} \quad (9)$$

I^1, I^2 and I^0 are the positive, negative and zero sequence currents respectively, in p.u. and are given by eq. (10), (11) and (12)

$$I^{1} = \frac{V_{pf}}{Z_{ii}^{1} + \frac{Z_{ii}^{2}(Z_{ii}^{0} + 3z_f)}{Z_{ii}^{2} + Z_{ii}^{0} + 3z_f}} \quad (10)$$

$$I^{2} = -\frac{(V_{pf} - Z_{ii}^{1} I^{1})}{Z_{ii}^{2}} \quad (11)$$

$$I^{0} = \frac{-(V_{pf} - Z_{ii}^{1} I^{1})}{Z_{ii}^{0} + 3z_f} \quad (12)$$

where,

V_{pf} = prefault bus voltage = 1 p.u.

Z_{ii}^{1} = positive sequence impedance of bus i, in p.u.

Z_{ii}^{2} = negative sequence impedance of bus i, in p.u.

Z_{ii}^{0} = zero sequence impedance of bus i, in p.u.

z_f = fault impedance = 0, for bolted faults

5. FAULT CURRENT CALCULATION USING PHASE COORDINATE METHOD

Here, the Short Circuit capacity of any bus 'i', using phase model is evaluated by following process.

The Short Circuit current, I_i^{sc} in pu, at any bus, 'i', is evaluated by equation (13)

$$I_i^{sc} = \frac{V_{pf}^{abc}}{Z_f + Z_{ii}^{abc}} \quad (13)$$

where, V_{pf}^{abc} = Bus voltage prior to the fault

$$= \begin{bmatrix} 1 \\ \alpha^2 \\ \alpha \end{bmatrix} V_{pf}^{a}$$

Z_{ii}^{abc} = (3x3) 3-phase impedance matrix of bus 'i', obtained from overall impedance matrix Z_{BUS} of the system

Z_f = (3x3) Fault impedance matrix, whose element entries depend on the type of fault

The elements of the fault impedance matrix Z_f, vary with the type of fault. For the three types of considered faults, the matrix is defined by equations (14), (15) and (16) .

For Symmetrical three phase to ground (LLLG) fault, Z_f is given by eq. (14)

$$Z_f = \begin{bmatrix} z_f + z_g & z_g & z_g \\ z_g & z_f + z_g & z_g \\ z_g & z_g & z_f + z_g \end{bmatrix} \quad (14)$$

For Single Line to ground (LG) fault, Z_f is given by eq. (15)

$$Z_f = \begin{bmatrix} z_f & 0 & 0 \\ 0 & \infty & 0 \\ 0 & 0 & \infty \end{bmatrix} \quad (15)$$

For Double Line to ground (LLG) fault, Z_f is given by eq.(16)

$$Z_f = \begin{bmatrix} \infty & 0 & 0 \\ 0 & z_f + z_g & z_g \\ 0 & z_g & z_f + z_g \end{bmatrix} \quad (16)$$

where,

z_f = fault impedance, at the considered bus
= **0**, for bolted faults

z_g = neutral reactance/impedance of star connected generator or transformer connected to the respective bus

The neutral reactances/ impedances of the generator or transformer are to be incorporated in the phase model as 'z_g' for the current evaluation for a particular type of fault, at that respective bus.

The Short Circuit Capacity in p.u., of any bus 'i', is thus evaluated by equation (17)

$$\text{S.C.C. (p.u.)} = I_i^{sc} \quad (17)$$

To evaluate the Short Circuit Capacity in MVA, multiply equation (17) by base MVA of the system.

6. RESULTS

Following the procedure mentioned in the above sections, the 'fault current' or 'short circuit capacity' at each bus of the network given in Fig.1, is evaluated by symmetrical component model first and verified by the phase model analysis, for three types of faults, namely 'Single line to ground (LG)', 'Symmetrical three phase to ground (LLLG)' and 'Double line to ground (LLG)' fault.

Table 2: Short circuit capacity of bus ' I ', for IEEE 34-node Multiphase Distribution System (Fig. 1)

S.N.	BUS 'i'	Short Circuit Capacity Calculation of bus 'i' (in pu), for LLLG or Symmetrical Fault			Short Circuit Capacity Calculation of bus 'i' (in pu), for LG or Single line to ground Fault			Short Circuit Capacity Calculation of bus 'i' (in pu), for LLG or Double line to ground Fault		
		Phase Model	Symmetrical Components	% Error	Phase Model	Symmetrical Components	% Error	Phase Model	Symmetrical Components	% Error
1.	890	22.218	22.218	0	22.218	22.218	0	22.218	22.218	0
2.	888	21.2787	21.276	0.012	20.8860	20.88	0	20.5366	20.4989	0.018
3.	832	10.87	10.8695	0	10.7665	10.765	0	10.6729	10.662	0.102
4.	858	7.368	7.3772	-0.124	6.562	6.5576	0.067	5.954	5.8971	0.95
5.	834	5.2083	5.2099	-0.03	3.4495	3.6495	-5.7	2.5408	2.3998	5.54
6.	860	4.712	4.7178	-0.123	3.1798	3.3695	-5.9	2.3643	2.97	-4.47
7.	836	4.1785	4.1885	-0.23	2.8778	3.0009	-4.27	2.1624	2.2395	-3.56
8.	840	4.0313	4.0421	-0.26	2.7291	2.798	-2.52	2.1044	2.148	-2.07
9.	862	4.1296	4.1397	-0.24	2.8494	3.0034	-5.4	2.1432	2.209	-3.07
10.	842	5.1338	5.136	0.042	3.4097	3.4924	-2.42	2.515	2.6315	-4.63
11.	844	4.801	4.8058	0.099	3.2289	3.3374	-3.36	2.3966	2.425	-1.18
12.	846	4.0799	4.0904	-0.25	2.8205	2.9853	-5.84	2.1236	2.1782	-2.57
13	848	3.992	4.0031	-0.27	2.769	2.7178	-0.317	2.0887	2.1237	-1.67
14	852	10.7879	10.8354	-0.44	10.6815	10.7277	-.432	10.6564	10.6221	0.32
15	854	2.1661	2.1891	-1.06	1.7698	1.7676	0.124	1.4971	1.4689	1.88
16	830	2.141	2.1639	-1.06	1.7489	1.7467	0.125	1.4791	1.4511	1.89
17	828	1.4694	1.4877	-1.24	1.1943	1.1916	0.26	1.0037	0.9827	2.09
18	824	1.4506	1.4689	-1.26	1.1789	1.1762	0.229	0.9907	0.9698	2.11
19	816	1.2561	1.2723	-1.28	1.0197	1.0167	0.294	0.8554	0.8366	2.19
20	850	1.251	1.2672	-1.62	1.0154	1.0125	0.28	0.8519	0.8332	2.19
21	814	1.2503	1.2668	-1.31	1.0149	1.0122	0.26	0.8517	0.8329	2.2
22	812	0.9722	0.9847	-1.28	0.7761	0.7726	0.45	0.6448	0.6283	2.55
23	808	0.7591	0.7685	-1.23	0.5988	0.5947	0.68	0.494	0.4794	2.95
24	806	0.6387	0.6464	-1.2	0.5007	0.4964	0.85	0.4116	0.3983	3.23
25	802	0.6334	0.641	-1.19	0.4964	0.492	0.86	0.408	0.3947	3.25
26	800	0.6254	0.633	-1.21	0.49	0.4857	0.87	0.4026	0.3895	3.25
27	864	--N.A--			5.6102	5.6070	0.057	--N.A--		
28	838	--N.A--			2.8494	2.6836	5.8	--N.A--		
29	856	--N.A--			1.7698	1.697	4.1	--N.A--		
30	826	--N.A--			1.1789	1.1089	1	--N.A--		
31	810	--N.A--			0.5988	0.5819	2.82	--N.A--		
32	818	--N.A--			0.9903	0.9874	0.29	--N.A--		
33	820	--N.A--			0.5449	0.5435	0.25	--N.A--		
34	822	--N.A--			0.4826	0.4814	0.25	--N.A--		

The assumptions taken in the process of making the symmetrical component model of the multiphase system are elaborated in the previous sections.

The results obtained by application of symmetrical component method, are verified by the analysis of the phase model, and are presented in Table-3. The bus at which short circuit capacity is evaluated, is indicated in column 2, in both the tables.

The percentage error at each bus, in the results obtained by the symmetrical component model, is evaluated with respect to the results obtained by the phase model.

It can be observed clearly from the results (Table 3) that the percentage error in the fault current is very less.

7. CONCLUSIONS

From the obtained results as summarized in Table 3, we can conclude that the results obtained by the symmetrical component model, for an unbalanced multiphase distribution system with mutually coupled lines are very near to the results obtained by the phase model, if the symmetrical component model of the system is modeled as per the assumptions and explanations given in the paper.

Thus, we can apply the existing software tools based on symmetrical component model for the fault analysis, or the short circuit capacity evaluation, for any unbalanced multiphase distribution network with mutually coupled lines, by suitably modifying the network.

REFERENCES

[1] Mamdouh Abdel-Akher, Khalid Mohamed Nor, "Fault Analysis of Multiphase Distribution Systems Using Symmetrical Components", IEEE Transactions on Power Delivery, Vol. 25, No. 4, October 2010.

[2] W. H. Kersting, "Radial distribution test feeders," in Proc. PES Winter Meeting, Jan. 28 / Feb. 1, 2001, Vol. 2, No. 28, pp. 908–912 [Online] Available: http://ewh.ieee.org/soc/pes/dsacom/test feeders.html

[3] Stagg, El-Abiad, "Computer Methods in Power System Analysis", International Student Ed., McGraw-Hill Inc., 1968.

[4] M.A. Laughton, "Analysis of unbalanced polyphase networks by the method of phase coordinates, Part-I : System representation in phase frame of reference", Proc. IEEE, Vol.115, No. 8, 1968, pp 1163-1172.

[5] M.A. Laughton, "Analysis of unbalanced polyphase networks by the method of phase coordinates, Part-II : Fault Analysis", Proc. IEEE, Vol.116, No. 5, 1969, pp 857-865.

[6] A. Brameller, R.S. Pandey, "General fault analysis using phase frame of reference", Proc. IEEE, Vol.121, No. 5, 1974, pp 366-368.

[7] L. Roy, N.D. Rao, "Exact Calculation of simultaneous faults involving open conductors and line to ground short circuits on inherently unbalanced power systems", IEEE Trans. on Power Apparatus and Systems, Vol. PAS-101, No. 8, Aug. 1982, pp 2738-2746.

[8] W.D. Stevenson, " Elements of Power System Analysis ", Mc Graw Hill International Edition, 1982.

[9] Hadi Saadat, "Power System Analysis", T.M.H., 2nd Ed., 16th Reprint, 2002

[10] M.A. Pai, "Computer Techniques in Power System Analysis", T.M.H., 2nd Ed., New Delhi, 2006

[11] Dr. Abdul Dib. Nasser Tleis, "Power System Modeling & Fault Analysis, Theory & Practice", Elseiver Ltd., 2008

[12] Ali Keyhani, "Design of Smart Power grid Renewable Energy Systems", IEEE Ed., John Wiley & Sons, Inc., Publication, 2011

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