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Power Line Technical Loss Evaluation Based Online Current from Unbalanced Faults

Ademola Abdulkareem, C.O.A. Awosope and A.U. Adoghe
Department of Electrical and Information Engineering, College of Engineering,
Covenant University, Ota, Nigeria

Abstract: The literature is awash with different methods of loss estimation in transmission lines but in these approaches, there is a clear gap between the practical information and the theoretical one which tends to be poor and imprecise. Therefore, the need arises to develop a new approach of assessing the steady and transient value of technical losses on power lines for high degree of accuracy. The simulations of various aspects of asymmetrical faults were carried out at every bus of a three-phase power line to examine their effects on the voltage magnitude, line current and the maximum fault current in the test system. The test system is the existing 28 bus, 330 kV power system in Nigeria. A MATLAB program was written to efficiently and accurately perform the many calculations for the loss analysis of all the 28 faulted buses considered. This method captured the peak technical losses classified under the three categories of maximum line current, namely; low, medium and high current that are likened to the trio of steady-state, subtransient and transient currents. The corresponding power line losses obtained for low, medium and high current levels were 146.73, 322.24 and 738.28 MW, respectively.

Key words: Technical losses, steady and transient value, asymmetrical faults, maximum line current, power line

INTRODUCTION

Electricity demand has increased drastically due to growing population and industrialising countries and therefore, it has become important to operate energy that is delivered to transmission and distribution lines at maximum efficiency. The global problem of the lower power availability to consumers is a consequence of power loss and no matter how carefully the power system network is designed, losses are inevitable. Moreover, the present situation of losses in the power sectors is worrisome. For instance, the Nigerian electricity grid has a large proportion of transmission and distribution losses and these amounts to a whopping 40%. According to Makoju, the power sector of Nigeria is characterized by high energy losses (about 30-35% from generation to billing) and low access to electricity by the populace (about 36%). Based on the Power Holding Company of Nigeria's (PHCN) annual reports for the 2004 and 2005, the transmission line losses alone were estimated at 9.2% (PHCN National Control Centre Oshogbo, 2004). In India, electricity losses during transmission and distribution are extremely high and they vary between 30 and 45% in 2001. In 2004-05, electricity demand in India outstripped supply by 7-11%. The losses in some other countries like Iraq, Moldova, Sudan, Venezuelan RB, Syrian Korea Republic, Yemen Republic, Pakistan, Tanzania, México, Taiwan, USA and Japan are 42, 40, 28, 27, 26, 25, 22, 20, 16, 9, 6 and 5%, respectively. These losses, due to discrepancy between energy produced and energy sold to end-users are wasteful energy dissipated in the system and cannot be accounted for. All these losses (comprise technical and non-technical losses) translate to high operating costs as well as huge revenue losses to utilities and consequently they result in high cost of electricity and unfair proportion between the cost incurred by electricity supplier and the amount paid by end-user. Since, system loss translate to a considerable cost for utilities, customers and host country, its evaluation and reduction have been recognized as a unique area of interest by researchers. Fundamentally, the present effort reported in this study will evaluate the technical losses associated with the power lines on the existing Nigerian 330 kV transmission network using the symmetrical components of unbalanced faults.

Characterization of losses: Electric power transmission and distribution losses include losses in transmission

Corresponding Author: Ademola Abdulkareem, Department of Electrical and Information Engineering, College of Engineering, Covenant University, Ota, Nigeria

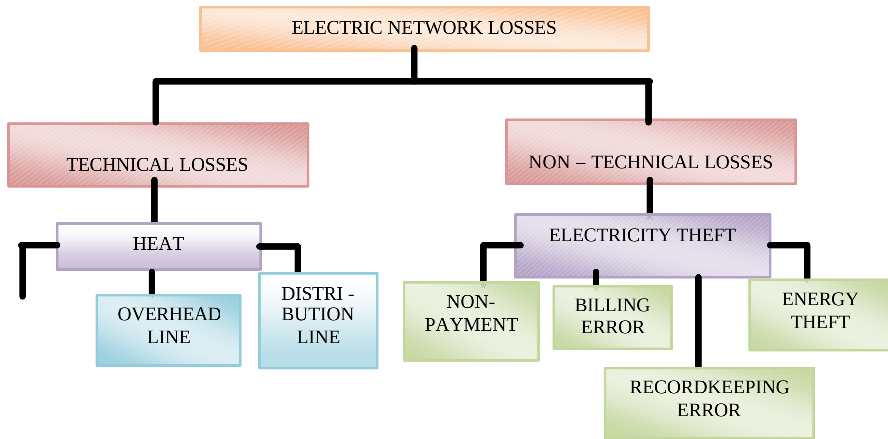

Fig. 1: Classification of electric network losses

Table 1: Yearly energy balance summary 2005-2011

Years	Energy delivered on transmission line (GWH)	Energy available for sale (GWH)	Transmission line losses (GWH)	Line Losses as percentage of energy delivered (%)
2005	23403.26	21401.87	2001.39	8.55
2006	22576.02	21024.39	1551.63	6.87
2007	22255.76	20419.07	1836.69	8.25
2008	20765.71	18885.51	1880.19	9.05
2009	20329.45	18620.10	1709.35	8.41
2010	24362.42	21931.67	2430.75	9.98
2011	26999.35	24204.62	2794.73	10.35
Total	-	-	14204.74	-

between source of supply and points of distribution (substation) and in the distribution to consumers. The global losses include losses in the generation, transmission and distribution. The transmission losses are associated with the systems for generation and transmission, distribution losses occur only within the distribution system (Raesaar *et al*., 2007). To show the overall electric network losses and to make losses easier to investigate, it is necessary to classify the network losses into different types as indicated in Fig. 1.

Disturbances on transmission system: Loss of power on transmission lines is a global problem and it is necessary to state here that the losses on transmission lines can result in line outages in the electric power system. For instance, the blackout in the North American transmission system, occurring in 2003 resulted in interrupted supply for over 50 million people and the related costs have been estimated to be in the range of $7,000-10,000M (Joo *et al*., 2007). The Italian blackout was initiated by overload on two 400 kV lines from France to Italy and trip of both. Many countries in sub-Saharan Africa are characterised by much higher system losses of up to 41%. In Zambia, on 21st and 22nd January 2008, the blackout was initiated by a spurious tripping on the only 330 kV transmission line available at the time from Kariba North Bank power station to Leopards hill substation and a collapse of the system voltage due to insufficient reactive power generation capacity respectively (Tambatamba, 2009). Table 1 gives a brief summary of the yearly energy balance that reflects a total loss of 14204.74 GWH from 2005-2011 as reported in the PHCN monthly energy balance summary. These transmission losses-calculated to be approximately 10.05% of the energy fed into the grid, clearly show that majority of the outages in NESI are the underlying problem in the transmission.

Therefore, a methodology is required to capture these additional losses due to system disturbances (or line fault) for accurate technical loss evaluation associated with transmission network Anderson.

Overview of the Nigerian 330 kV transmission network: The test network system is Nigeria 330 kV Transmission grid. The Nigerian transmission system is made up of interconnected network of 5650 km of 330 kV that spans the country nationwide. The single-line diagram of the Nigerian 330 kV network currently consists of sixty 330 kV

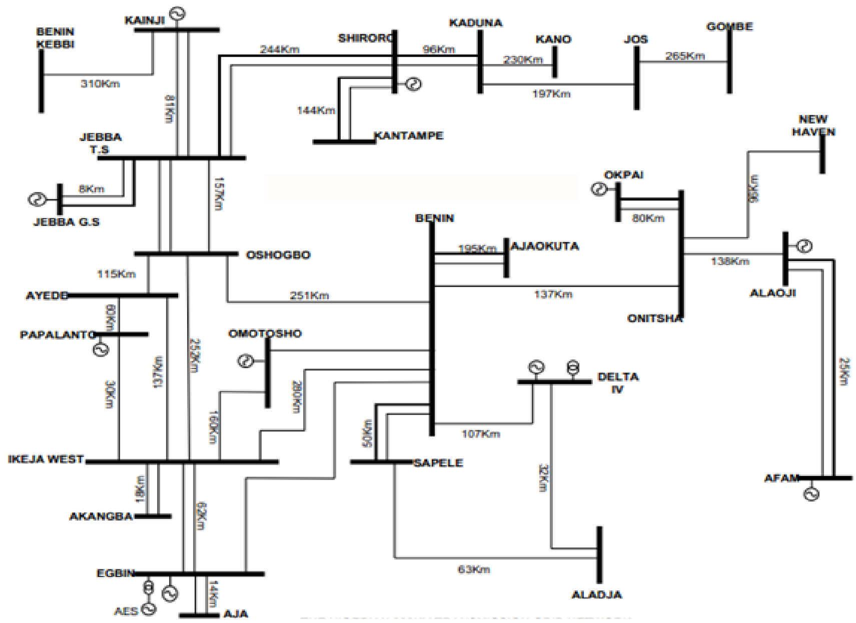

Fig. 2: The Nigerian 330 kV transmission grid network

transmission line circuits, eight effective generating stations, twenty load stations, twenty-eight buses (sub-stations) and thirty-three transmission lines as shown in Fig. 2.

The system may be divided into three geographical zones-North, South-East and the South-West. The North is connected to the South through the one-triple circuit lines between Jebba and Oshogbo while the West is linked to the East through one transmission line from Oshogbo to Benin and one double line from Ikeja to Benin. The transmission grid is centrally controlled from the National Control Centre (NCC) located at Oshogbo in Osun State while there is a back-up or Supplementary National Control Centre (SNCC) at Shiroro in Niger State. In addition to these two centres are three Regional Control Centres (RCCs) located at Ikeja West (RCC1), Benin (RCC2) and Shiroro (RCC3).

MATERIALS AND METHODS

Mathematical formulation (methodology): Any power system can be analysed by calculating the system voltages and currents under normal and abnormal scenarios. Therefore, mathematical expressions depicting the evolution of current and voltage on a typical transmission line are formulated, models are derived to predict available current and voltage, respectively, at any point on the transmission line. However, the two factors that influence technical losses are current value and resistance value that are related by:

$$P_{loss} = I^2R \tag{1}$$

So, the major task is how to determine the current value since the resistance value can be obtained from the transmission line parameter data. Current dependent load model is used in which load changing is in direct proportion to current at constant voltage and constant power, since the evaluation of power line losses was carried out from the point of supply to the point of distribution (load not included). To increase the level of current flow in the line (since, the current level has the biggest effect on line loss), there is the need to simulate fault for higher line current level in order to determine the peak power line losses a methodology to capture the majority of transmission losses.

Propagation of unbalanced fault in transmission network: In contrast to fault studies where unbalanced faults unbalance the network at the fault location with the assumption that network is terminated at the faulted bus (bus k), electromagnetic waveactually propagates down the entire transmission lines in this work. The method of approach reveals the propagation characteristics and electrical behaviour of current and voltage in the system Here, unbalanced short-circuit calculations analysis is developed for a three-phase network and these unbalanced faults are Simulated; Line to-Ground (SLG), Line to-Line (LL) and Double Line-to-Ground (DLG) at every single node of the network using symmetrical component method of unbalanced faults. The symmetrical components of the fault current Eq. 2-4 are given as follows:

$$I_K^1 = \frac{V_K(0)}{Z_K^1 + \frac{Z_{KK}^2\left(Z_{KK}^0 + 3Z_K\right)}{Z_{KK}^1 + Z_{KK}^2 + Z_f}} \quad (2)$$

$$I_K^2 = \frac{V_K(0) - Z_{KK}^1 I_{KK}^1}{Z_{KK}^2} \quad (3)$$

$$I_K^0 = \frac{V_K(0) - Z_{KK}^1 I_{KK}^1}{Z_{KK}^0 + 3Z_f} \quad (4)$$

Bus voltage and line currents during fault: Using the sequence network components of the fault current, the symmetrical components of the ith bus voltages during fault are obtained as:

$$V_i^0(F) = 0 - Z_{KK}^0 I_K^0 \quad (5)$$

$$V_i^1(F) = V_K(0) - Z_{KK}^1 I_{KK}^1 \quad (6)$$

$$V_i^2(F) = 0 - Z_{KK}^2 I_K^2 \quad (7)$$

where, V_i^1 (0) = V_i (0) is the prefault phase voltage at bus I. The phase voltages during fault are:

$$V_K^{abc} = A V_K^{012} \quad (8)$$

The symmetrical components of fault current flowing from line i to j are given by:

$$I_{ij}^0 = \frac{V_i^0(F) - V_j^0(F)}{Z_{ij}^0} \quad (9)$$

$$I_{ij}^1 = \frac{V_i^1(F) - V_j^1(F)}{Z_{ij}^1} \quad (10)$$

$$I_{ij}^2 = \frac{V_i^2(F) - V_j^2(F)}{Z_{ij}^2} \quad (11)$$

where, z_{ij}^0, z_{ij}^1 and z_{ij}^2 are the zero, positive and negative-sequence components of the actual line impedance between buses i and j.

Power Line Network Injection Model (PLNIM): Basically, a power line is a material such as overhead line or any pair of conductors that are used to move electromagnetic energy from one place to another. Therefore, the schematic representation of PLNIM is as shown in Fig. 3. Since, current is required to flow in every branch of the network, the injection model of the current is constructed to flow in all branches of the power line when a fault is simulated at bus k, ∀k = 1, 2,…… .n.

Therefore, for a three-phase system when the constant power is used to represent the load, the complex power (S_K) at the output terminal of the generator will be constant but the voltage (V_K) will change in any iteration when a fault current is simulated to determine the losses using fault analysis. Figure 4 represents a view of a typical fault simulated bus at node K. The current flowing through the power line at any node K can then be determined using:

$$I_K^* = \frac{S_K}{\sqrt{3}V_K} = \frac{P_K + Q_K}{\sqrt{3}V_K} \quad (12)$$

If I^*_K in Eq. 12 is decoupled into two separate parts we shall have:

$$I^*_K = I_{K(real)} + I_{K(Im\,ag)} \quad (13)$$

Then, the real and imaginary components of bus current in terms of bus power and the bus voltages are, respectively given as:

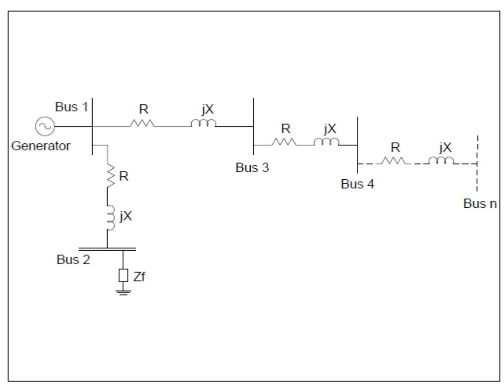

Fig. 3: Power line network injection model

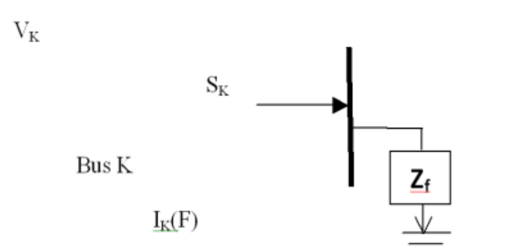

Fig. 4: A typical bus K

$$I_{K(real)} = \frac{1}{\sqrt{3}IV_K I}(P_K \cos\delta_K + Q_K \sin\delta_K) \quad (14)$$

$$I_{K(Imag)} = \frac{1}{\sqrt{3}IV_K I}(P_K \sin\delta_K - Q_K \cos\delta_K) \quad (15)$$

If this fault is simulated using Eq. 2-11 at all nodes in a given network, the mathematical model of Eq. 12 and 13 and a result file containing fault voltages is created at each node for every unbalanced fault, then Eq. 12 can be rewritten as:

$$\sum_{k=1}^{n} I_K^*(F) = \frac{S_K}{V_K} \quad (16)$$

By using the sequence network components of fault current for various unbalanced faults at every bus k for k = 1 to n, the symmetrical components of the ith bus voltage, line current magnitude and fault current during fault are obtained.

RESULTS AND DISCUSSION

Software and simulation results: Since, symmetrical components method includes many matrix operations, MATLAB is selected as the simulation tool in this work. In addition, any code can be edited and modified easily to handle any future cases using the command edit window. MATLAB has also many unique features that allow users to develop an algorithm in order to resolve any specific case as applied to this research.

The MATLAB code used to solve the problem statement in this project starts by identifying the system input arguments. These variables are mainly positive and zero sequence impedances for Nigerian 330 kV transmission system branches. This step is to form the system impedance data; PHCN data for positive and zero sequence impedances for Nigerian 330 kV transmission lines. This is followed by a complete and unambiguous set of computational steps in a particular sequence performed for single line-to-ground, line-to-line and double line-to-ground faults using MATLAB codes. The flowchart of the algorithm developed for obtaining the result is shown in Fig. 5.

Simulation strategy of 330 kV power lines network: Simulation of different types of unbalanced short-circuit faults (SLG, L-L, DLG) in the network is carried out at every bus for the entire 28 buses of the three-phase test system using unbalanced fault algorithm written in flexible Matlab program environment. The simulation of various aspects of asymmetrical faults (for fault impedance, Z_f = j0.1 and Z_f = j0) are performed on the test system (Nigeria 330 kV transmission system) to examine their effects on the voltage magnitude, line current and the maximum fault current in the system. The test system consists of 28 buses, 8 generators and 33 branches as shown in Table 2. Samples of the results of various aspects of faulted bus simulations for each of the 33 branches and 28 buses of line current and voltage magnitudes respectively are as presented in Table 2 and 3 when Z_f = j0.1 and Table 4 and 5 when Z_f = j0. For each of the spectrum of line current and voltage magnitudes obtained for every single faulted bus, the corresponding graphical representations are as shown in Fig. 6-17.

Procedure for maximum line currents determination on the test system: The results of all the line current magnitudes obtained in study 3 in the simulation of various aspects of faults on the three-phase power line of the test system are analysed or streamlined in order to rigorously establish a categorical data of maximum line current magnitudes. The results of this analysis are generated for two scenarios for comparison: case 1 is when the fault Z_f = 0 and it forms the category that creates tremendous amount of current while case two is when the fault impedance, Z_f = 0.1. A graphical representation of the results obtained for the two configurations are presented Fig. 18a, b for Z_f = j0.1 and Fig. 19a,b for Z_f = j0, respectively. The analysis is carried out by using the graphical results obtained in Fig. 18a, b and 19a, b for the line current magnitude to determine the available maximum current on each line for all the various types of asymmetrical fault considered.

Evaluation of technical power loss on the power line test system: The calculation of technical power losses is carried out on the power line test system, i.e., the Nigerian 330 kV transmission system, using the results obtained in Fig. 17 and 18a, b based on the established peak line currents for both average (LC/MC) and maximum (HC/AMC) line magnitude.

Typical base values at 100 MVA base for the 330 kV grid system:

$$Vb = \frac{V_L}{\sqrt{3}} = \frac{330\times10^3}{\sqrt{3}} = 190.5255\text{kV}$$

$$1_b = \frac{MVA_b}{3V_b} = \frac{100\times10^6}{3\times190.5255\times10^3} =$$

174.9546 Aor0.175 kA

$$R_b = \frac{V_b}{1_b} = \frac{190.5255\times10^3}{174.9546} = 1089\Omega$$

Table 2: Spectrum of line currents for faulted bus at Kainji (Bus 1) when $Z_f = j0.1$

	Line current magnitude (SLG)			Line current magnitude (L-L)			Line current magnitude (DLG)		
From to bus	Phase a (pu)	Phase b (pu)	Phase c (pu)	Phase a (pu)	Phase b (pu)	Phase c (pu)	Phase a (pu)	Phase b (pu)	Phase c (pu)
1-2	0.4217	0.4217	0.4217	0.4217	0.4217	0.4217	0.4217	0.4217	0.4217
3-1	4.162	0.52	0.3801	0.0807	6.439	6.3656	0.2314	18.7656	16.4299
4-3	2.4037	0.704	1.0632	0.8953	2.3195	1.4243	0.8927	9.3842	8.2384
5-3	1.4198	1.0004	0.745	0.9008	3.0357	3.7182	0.8648	5.1596	4.4045
6-5	1.0274	1.0853	0.9485	1.0245	1.2451	0.6681	1.013	0.9919	0.7578
7-6	0.4595	0.2771	0.3945	0.7639	1.1179	0.4824	0.3387	1.3437	1.1754
8-6	0.1899	0.0902	0.1053	0.3273	0.4473	0.6425	0.0981	0.7554	0.6805
8-7	0.3191	0.2758	0.1535	0.2185	0.4395	0.2249	0.2114	0.8723	0.6944
8-5	0.7758	0.7658	0.7494	0.0955	0.2372	0.3115	0.757	1.4778	1.2481
8-9	2.8835	2.8835	2.8835	2.8835	2.8835	2.8835	2.8835	2.8835	2.8835
10-8	4.2336	4.0692	4.0928	4.068	4.0559	4.83	4.0818	6.5076	6.2523
10-11	2.1338	2.1338	2.1338	2.1338	2.1338	2.1338	2.1338	2.1338	2.1338
12-8	0.2477	0.1431	0.2852	0.0899	0.1636	0.0829	0.2174	0.4275	0.3301
12-13	0.8483	0.8453	0.7958	0.2078	0.2077	0.2633	0.8193	1.3671	1.3424
13-10	0.1021	0.079	0.0964	0.8163	0.8149	0.9927	0.088	0.2613	0.2192
3-8	0.9555	0.9178	0.9004	0.904	0.9048	1.165	0.9087	1.7422	1.6875
13-5	0.7542	0.4732	0.5677	0.5077	0.812	1.1563	0.5227	2.5456	2.2951
13-18	1.2761	1.277	1.2557	1.2653	1.3434	1.2028	1.2658	1.0681	0.9048
14-13	0.7034	0.7034	0.7034	0.7034	0.7034	0.7034	0.7034	0.7034	0.7034
15-13	0.5676	0.4142	0.4604	0.4281	0.5893	0.8392	0.4384	1.7159	1.555
15-17	0.1561	0.1556	0.1577	0.1568	0.1585	0.1516	0.1567	0.1409	0.1393
16-13	0.4233	0.2993	0.3423	0.3135	0.4404	0.6277	0.3219	1.2997	1.1733
16-17	0.1574	0.1579	0.1558	0.1568	0.1553	0.1621	0.1568	0.1735	0.1746
18-20	1.4943	1.4943	1.4943	1.4943	1.4943	1.4943	1.4943	1.4943	1.4943
9-18	5.1746	5.1746	5.1746	5.1746	5.1746	5.1746	5.1746	5.1746	5.1746
21-22	5.0621	4.9879	5.0003	4.9992	5.0366	5.1357	4.9943	5.4109	5.2386
22-18	0.1168	0.02	0.035	0.031	0.1509	0.1712	0.0267	0.4456	0.3839
23-3	0.977	0.0891	0.1338	0.0284	1.4998	1.5256	0.0701	4.4233	3.8822
23-24	1.4096	1.4096	1.4096	1.4096	1.4096	1.4096	1.4096	1.4096	1.4096
23-25	5.0005	5.0005	5.0005	5.0005	5.0005	5.0005	5.0005	5.0005	5.0005
25-26	2.216	2.216	2.216	2.216	2.216	2.216	2.216	2.216	2.216
25-27	0.9441	0.9441	0.9441	0.9441	0.9441	0.9441	0.9441	0.9441	0.9441
27-28	0.9319	0.9319	0.9319	0.9319	0.9319	0.9319	0.9319	0.9319	0.9319

Table 3: Voltage magnitude for faulted bus at kainji (Bus 1) when $Z_f = j0.1$

	Bus voltage magnitude (SLG)			Bus voltage magnitude (L-L)			Bus voltage magnitude (DLG)		
Bus No.	Phase a (pU)	Phase b (pu)	Phase c (pu)	Phase a (pU)	Phase b (pu)	Phase c (pu)	Phase a (pU)	Phase b (pu)	Phase c (pu)
1	0.9805	1.1438	1.0073	1.05	1.138	0.8098	1.0715	0.5022	0.5022
2	0.9421	1.1038	0.9674	1.01	1.0998	0.7711	1.0315	0.4904	0.4772
3	1.0178	1.1478	0.9737	1.048	1.0874	0.9202	1.0561	0.6375	0.715
4	1.022	1.1452	0.9778	1.05	1.0883	0.9273	1.0571	0.6536	0.7272
5	0.9901	1.048	0.970	1.005	1.02	0.9482	1.007	0.8093	0.8532
6	0.9592	0.9963	0.9457	0.969	0.98	0.9279	0.9697	0.8275	0.8559
7	0.9669	0.9963	0.9565	0.975	0.9848	0.9388	0.9753	0.8514	0.8736
8	0.9658	0.9913	0.9568	0.973	0.9822	0.9393	0.9732	0.8584	0.8775
9	0.9158	0.9413	0.9068	0.923	0.9323	0.8893	0.9232	0.8086	0.8275
10	1.0473	1.0609	1.0389	1.05	1.0564	1.0298	1.0493	0.9805	0.9903
11	1.0103	1.0239	1.0019	1.013	1.0194	0.9928	1.0123	0.9436	0.9533
12	1.073	1.0843	1.0635	1.074	1.0769	1.0651	1.0733	1.0405	1.0501
13	1.0417	1.0541	1.0339	1.044	1.0481	1.029	1.0434	0.9915	1.0022
14	1.0837	1.0961	1.0759	1.086	1.0901	1.071	1.0854	1.0334	1.0442
15	1.0495	1.0562	1.0429	1.05	1.0533	1.0401	1.0492	1.0152	1.0208
16	1.0496	1.0562	1.0429	1.05	1.0533	1.0403	1.0492	1.0159	1.0215
17	1.0465	1.0532	1.0399	1.047	1.0503	1.0372	1.0462	1.0126	1.0181
18	0.9889	0.9973	0.9839	0.991	0.992	0.9788	0.9902	0.9502	0.9629
19	1.0479	1.0563	1.0429	1.05	1.051	1.0378	1.0492	1.0092	1.0219
20	0.9479	0.9563	0.9429	0.95	0.951	0.9378	0.9492	0.9092	0.9219
21	1.0511	1.0527	1.0469	1.05	1.0532	1.048	1.0496	1.0413	1.0381
22	0.9936	0.9963	0.9892	0.993	0.9958	0.9895	0.9926	0.9794	0.9788
23	1.0444	1.0833	1.0172	1.05	1.0658	1.0019	1.0485	0.8846	0.9128
24	0.9875	1.0263	0.9602	0.993	1.0089	0.945	0.9915	0.8282	0.8559
25	0.8978	0.9363	0.8702	0.903	0.9191	0.8551	0.9015	0.7392	0.7662
26	0.7465	0.7844	0.7183	0.751	0.7676	0.7033	0.7496	0.5898	0.6148
27	0.84	0.8783	0.8123	0.845	0.8613	0.7972	0.8435	0.6821	0.7084
28	0.7644	0.8024	0.7363	0.769	0.7855	0.7213	0.7676	0.6074	0.6327

Table 4: Spectrum of line currents for faulted bus at Birnin-Kebbi (Bus 2) when $Z_f = j0.0$

	Line current magnitude (SLG)			Line current magnitude (L-L)			Line current magnitude (DLG)		
From to bus	Phase a (pU)	Phase b (pu)	Phase c (pu)	Phase a (pU)	Phase b (pu)	Phase c (pu)	Phase a (pU)	Phase b (pu)	Phase c (pu)
2-1	5.7715	0.4217	0.4217	0.4217	8.0049	7.999	0.4217	8.521	8.0249
3-1	2.2042	0.3199	0.257	0.0807	2.8665	2.8636	0.2475	3.1702	2.801
4-3	1.9447	0.8256	0.8763	0.9008	2.1666	2.1517	0.8228	2.3478	2.2124
5-3	0.2731	0.9769	0.8745	0.8953	0.5519	0.388	0.9354	0.3598	0.1069
6-5	0.8097	1.0654	1.0185	1.0245	0.8213	0.7917	1.0482	0.7381	0.7703
7-6	0.5387	0.7721	0.7572	0.7639	0.53	0.4868	0.7647	0.453	0.4506
8-6	0.4706	0.2922	0.3342	0.3273	0.4679	0.4773	0.3065	0.5145	0.48
8-7	0.1723	0.0902	0.0976	0.2185	0.1279	0.0986	0.2403	0.0642	0.0658
8-5	0.0895	0.2546	0.2167	0.0955	0.1914	0.196	0.0933	0.2074	0.1978
8-9	2.8835	2.8835	2.8835	2.8835	2.8835	2.8835	2.8835	2.8835	2.8835
10-8	4.3577	4.0541	4.0817	4.068	4.4194	4.4491	4.0683	4.4962	4.4683
10-11	2.1338	2.1338	2.1338	2.1338	2.1338	2.1338	2.1338	2.1338	2.1338
12-8	0.2706	0.17	0.2119	0.0899	0.0631	0.0427	0.0856	0.0541	0.0404
12-13	0.8672	0.827	0.8218	0.2078	0.2332	0.2363	0.1803	0.2668	0.2391
13-10	0.0624	0.087	0.0871	0.8163	0.8974	0.9051	0.8277	0.9053	0.9085
13-8	0.9959	0.9057	0.9098	0.904	1.023	1.0388	0.9094	1.0456	1.0432
13-5	0.757	0.4753	0.5195	0.5077	0.7955	0.817	0.4934	0.8617	0.8211
13-18	1.2213	1.2703	1.2668	1.2653	1.2324	1.2008	1.2699	1.2135	1.2017
14-13	0.7034	0.7034	0.7034	0.7034	0.7034	0.7034	0.7034	0.7034	0.7034
15-13	0.582	0.4104	0.4371	0.4281	0.612	0.6209	0.4223	0.6525	0.6249
15-17	0.1552	0.1562	0.1566	0.1568	0.1543	0.1537	0.1563	0.154	0.1536
16-13	0.4333	0.2978	0.3205	0.3135	0.4539	0.4611	0.3076	0.4863	0.4638
16-17	0.1583	0.1573	0.1569	0.1568	0.1593	0.1598	0.1572	0.1595	0.1599
18-20	1.4943	1.4943	1.4943	1.4943	1.4943	1.4943	1.4943	1.4943	1.4943
19-18	5.1746	5.1746	5.1746	5.1746	5.1746	5.1746	5.1746	5.1746	5.1746
21-22	5.0495	4.999	4.9934	4.9992	5.0622	5.0432	4.9948	5.0682	5.0575
22-18	0.0825	0.0312	0.0257	0.031	0.0948	0.0893	0.0266	0.1002	0.0953
23-3	0.5569	0.0316	0.0703	0.0284	0.7094	0.7113	0.0299	0.7904	0.694
23-24	1.4096	1.4096	1.4096	1.4096	1.4096	1.4096	1.4096	1.4096	1.4096
23-25	5.0005	5.0005	5.0005	5.0005	5.0005	5.0005	5.0005	5.0005	5.0005
25-26	2.216	2.216	2.216	2.216	2.216	2.216	2.216	2.216	2.216
25-27	0.9441	0.9441	0.9441	0.9441	0.9441	0.9441	0.9441	0.9441	0.9441
27-28	0.9319	0.9319	0.9319	0.9319	0.9319	0.9319	0.9319	0.9319	0.9319

Table 5: Voltage magnitude for faulted bus at Kainji (bus 1) when $Z_f = j00$

	Bus voltage magnitude (SLG)			Bus voltage magnitude (L-L)			Bus voltage magnitude (DLG)		
Bus No.	Phase a (pU)	Phase b (pu)	Phase c (pu)	Phase a (pU)	Phase b (pu)	Phase c (pu)	Phase a (pU)	Phase b (pu)	Phase c (pu)
1	1.39E-17	1.2174	1.2937	1.05	0.525	0.525	1.3083	1.75E-16	1.74E-16
2	0.04	1.1789	1.2546	1.01	0.5062	0.5062	1.2683	0.04	0.04
3	0.3194	1.3236	1.2362	1.048	0.6933	0.6696	1.3321	0.3773	0.5204
4	0.3513	1.3158	1.2244	1.05	0.7078	0.6819	1.3215	0.4015	0.5437
5	0.6828	1.1251	1.068	1.005	0.8387	0.8274	1.1282	0.7044	0.7709
6	0.7487	1.0476	1.0036	0.969	0.8474	0.8377	1.0477	0.7558	0.8023
7	0.7912	1.0372	0.9999	0.975	0.8677	0.8585	1.0364	0.7922	0.8301
8	0.8074	1.0271	0.9932	0.973	0.8729	0.8639	1.0257	0.8054	0.8392
9	0.7574	0.9771	0.9434	0.923	0.8231	0.8141	0.9757	0.7554	0.7892
10	0.9487	1.0876	1.0569	1.05	0.9893	0.9812	1.0821	0.9444	0.971
11	0.9117	1.0506	1.0199	1.013	0.9524	0.9442	1.0451	0.9074	0.9341
12	1.0078	1.1094	1.0803	1.074	1.0471	1.0431	1.1041	1.0129	1.0376
13	0.9618	1.0782	1.0507	1.044	0.999	0.9945	1.0736	0.9615	0.9859
14	1.0038	1.1202	1.0927	1.086	1.041	1.0365	1.1156	1.0035	1.0279
15	0.9962	1.0743	1.0511	1.05	1.02	1.0154	1.0685	0.9934	1.0125
16	0.9967	1.0744	1.0511	1.05	1.0206	1.0161	1.0686	0.9941	1.0132
17	0.9935	1.0714	1.0481	1.047	1.0173	1.0127	1.0655	0.9908	1.0098
18	0.9344	1.0154	0.9923	0.991	0.9552	0.9576	1.0097	0.9298	0.9522
19	0.9934	1.0744	1.0513	1.05	1.0142	1.0166	1.0687	0.9888	1.0112
20	0.8934	0.9744	0.9513	0.95	0.9142	0.9167	0.9687	0.8888	0.9112
21	1.03	1.0606	1.0504	1.05	1.0431	1.0357	1.0581	1.0309	1.0364
22	0.9674	1.0058	0.9935	0.993	0.9817	0.9759	1.0027	0.9675	0.9758
23	0.783	1.1629	1.0796	1.05	0.9077	0.8883	1.1476	0.7808	0.8603
24	0.7263	1.1061	1.023	0.993	0.8511	0.8316	1.0906	0.7238	0.8036
25	0.6369	1.0164	0.934	0.903	0.7619	0.742	1.0007	0.6338	0.7141
26	0.4862	0.8651	0.784	0.751	0.6117	0.591	0.8489	0.4818	0.5633
27	0.5793	0.9586	0.8766	0.845	0.7045	0.6843	0.9428	0.5758	0.6565
28	0.504	0.883	0.8017	0.769	0.6294	0.6089	0.8669	0.4998	0.5811

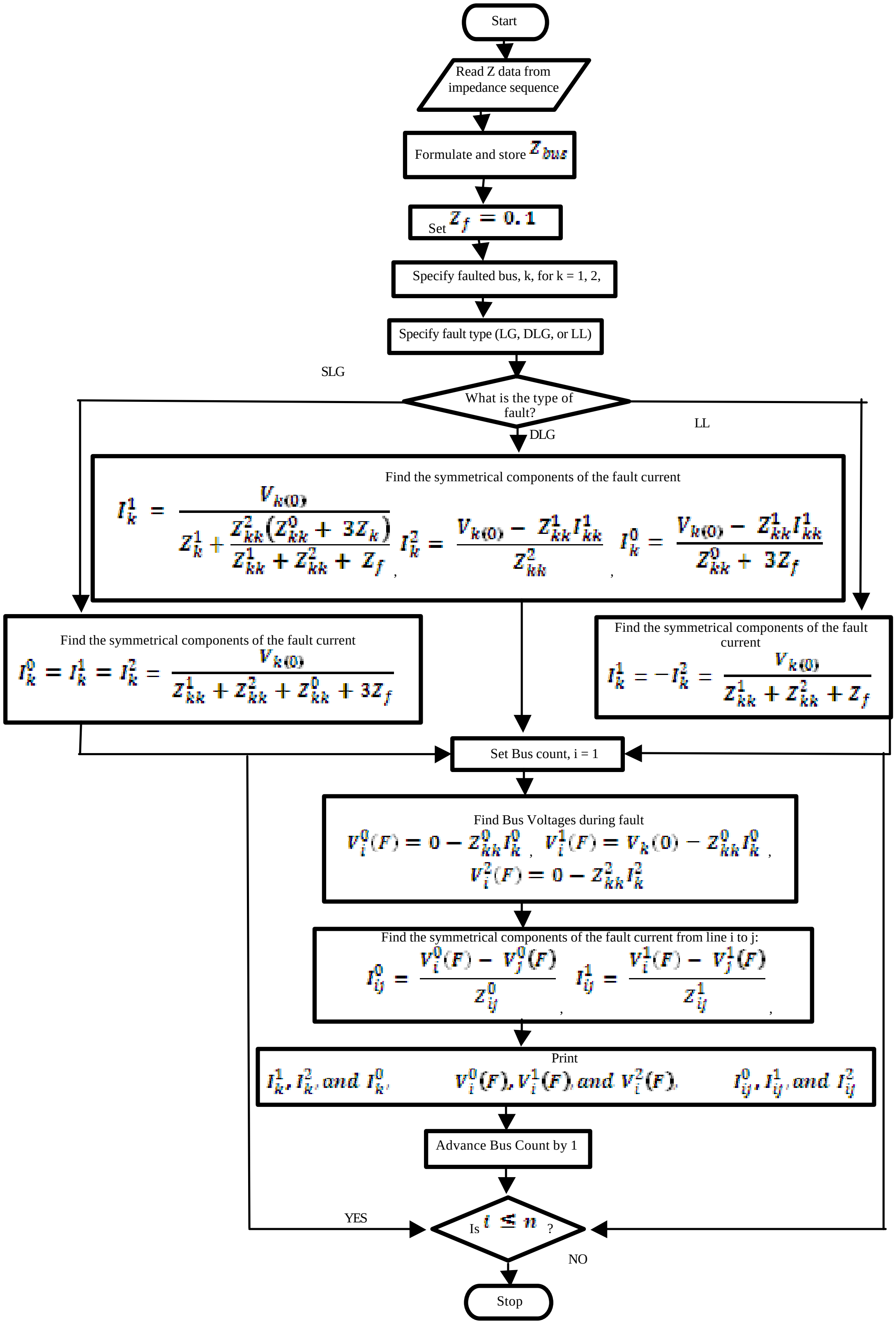

Fig. 5: Flow chart of the developed algorithm

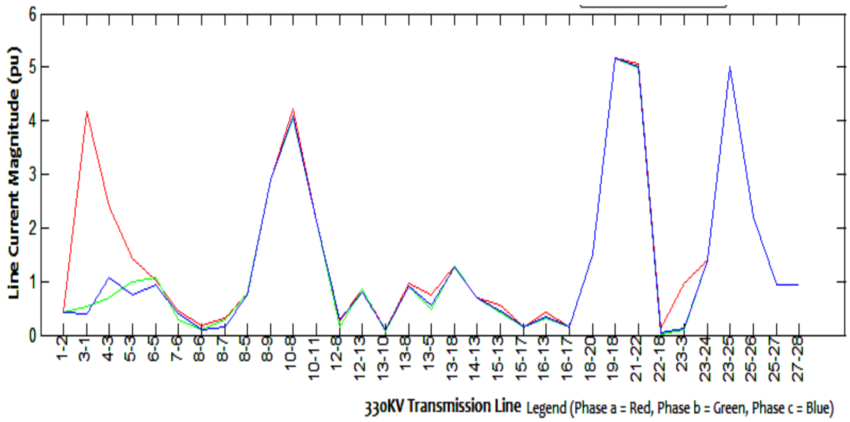

Fig. 6: Line current magnitude of the SLG faulted kainji (bus 1)

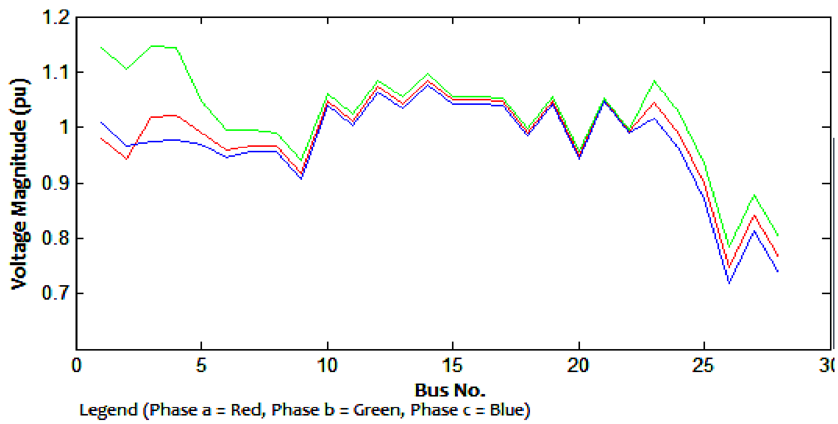

Fig. 7: Voltage magnitude of the SLG faulted Kainji (bus 1)

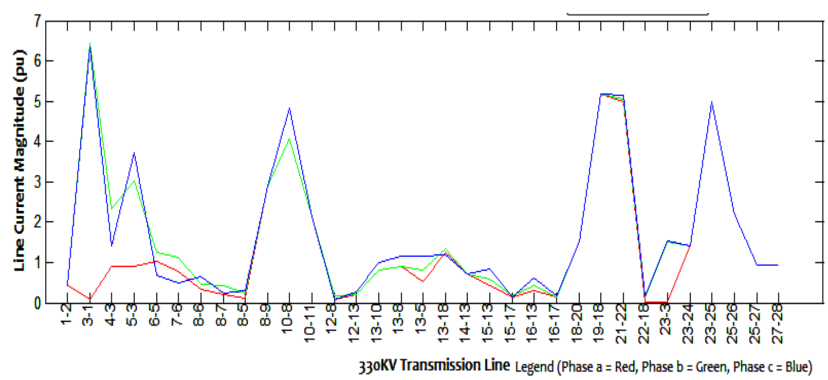

Fig. 8: Line current magnitude of the L-L faulted Kainji (bus 1)

Using the above base values, the pu line current magnitude and line resistance are converted to their actual values. Thus, the power losses for LC, MC, HC and AMC are computed as in Eq. 1. Recall Eq. 1 $P = I^2R$; the power losses for the various categories are calculated as shown in Table 6-9. Therefore, the power losses in the power line test system for LC, MC, HC and AMC are presented as 146.73, 323.24, 737.79 and 738.77 MW, respectively. The graphical representations of the power losses calculated for LC, MC, HC and AMC are shown in Fig. 19.

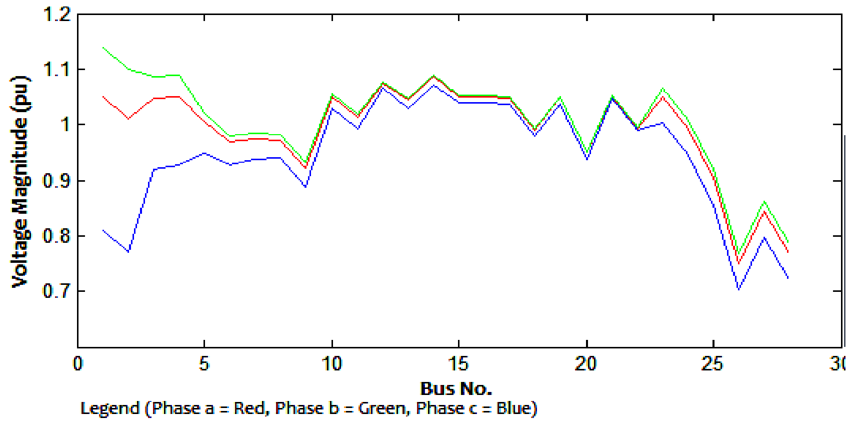

Fig. 9: Voltage magnitude of the L-L faulted Kainji (bus 1)

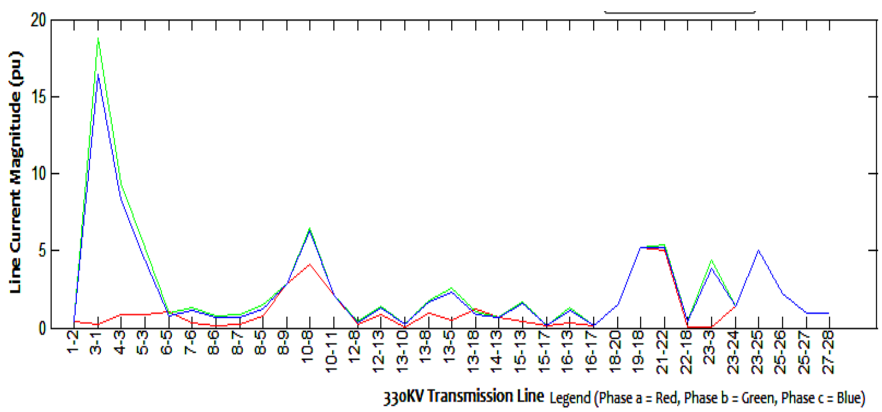

Fig. 10: Line current magnitude of the DLG faulted Kainji (bus 1)

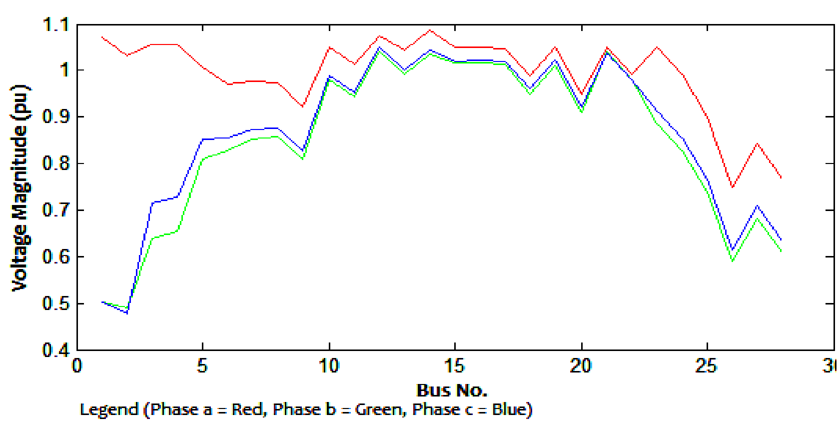

Fig. 11: Voltage magnitude of the L-L faulted Kainji (bus 1)

It can be seen in Fig. 20 that the equality of HC and AMC is confirmed and that it is a justifiable approximation of equality. Therefore, the average of the HC and AMC which is 738.28 MW is considered as the possible available peak loss in the power line test system. Now for this study, there are three categories of power loss level determined to be associated with the power line test system, namely:

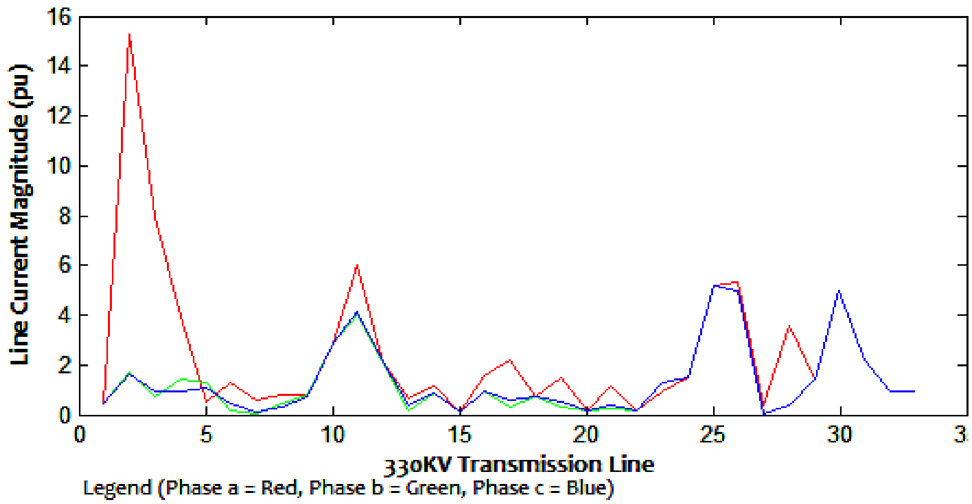

Fig. 12: Line current magnitude of the SLG faulted kainji (bus 1) when $Z_f = j0$

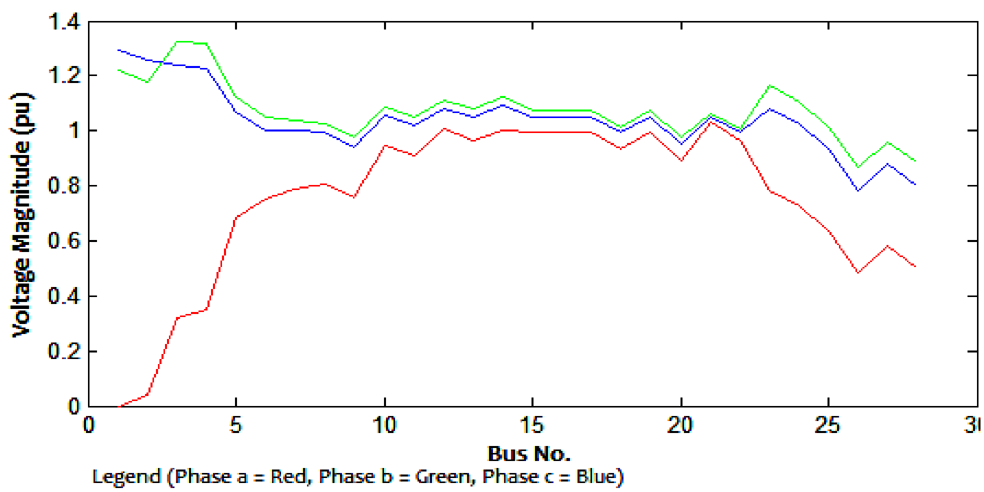

Fig. 13: Voltage magnitude of the SLG faulted kainji (bus 1) when $Z_f = j0$

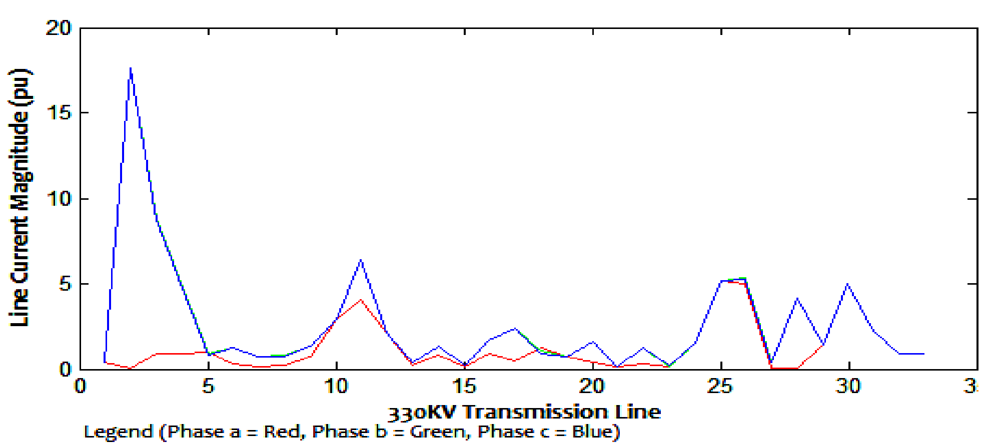

Fig. 14: Line current magnitude of the SLG faulted kainji (bus 1) when $Z_f = j0$

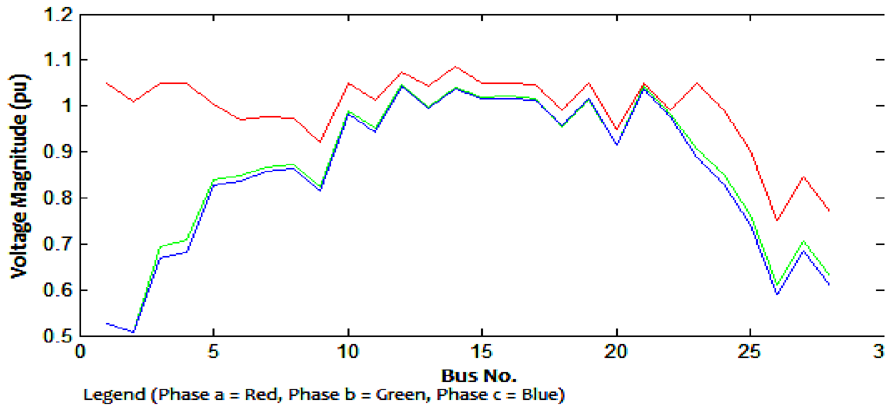

Fig. 15: Voltage magnitude of the DLG faulted kainji (bus 1) when $Z_f = j0$

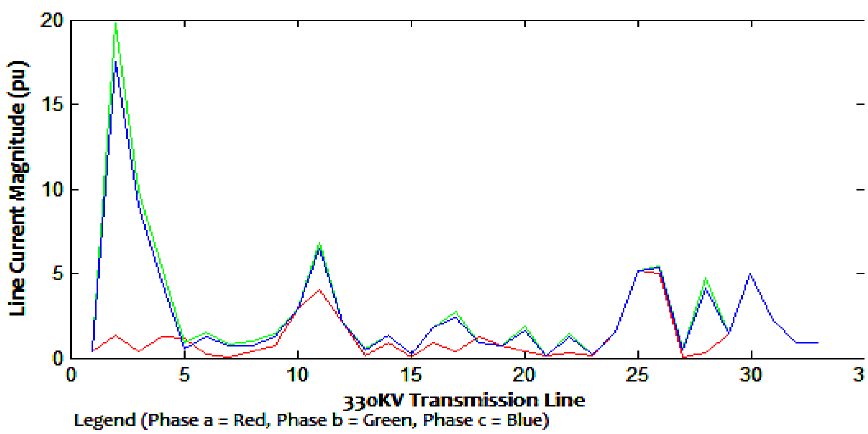

Fig. 16: Line current magnitude of the DLG faulted kainji (bus 1) when $Z_f = j0$

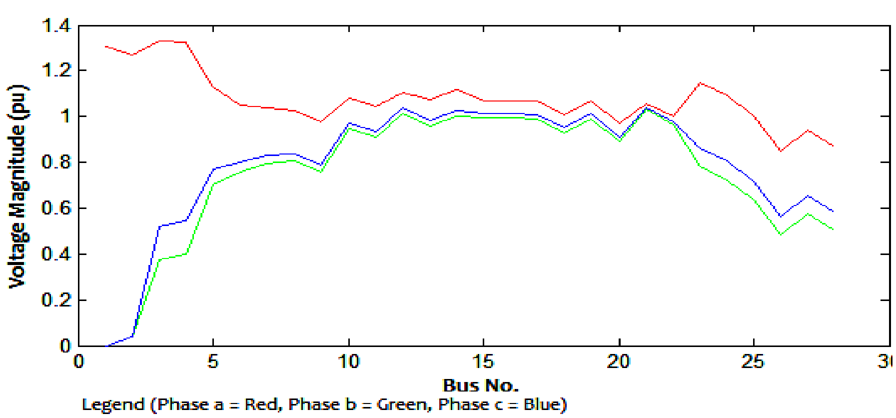

Fig. 17: Voltage magnitude of the DLG faulted kainji (bus 1) when $Z_f = j0$

low power line loss (146.73 MW) obtained from LC, medium power line loss (323.24 MW) obtained from MC, high power line loss (738.28 MW) obtained by HC/AMC.

The three power loss level scenarios are likened to the trio of steady-state, subtransient and transient currents level.

Table 6: Power losses calculation for LC

From bus	To bus	LC (pu)	Ipu X 0.175 (kA)	R (pu)	R pu X 1089 (ohm)	Power line losses (MW)
1	2	4.7596	0.8329	0.0111	12.0879	8.3863
1	3	3.1828	0.5570	0.0029	3.1581	0.9798
3	4	3.2043	0.5608	0.0003	0.3267	0.1027
3	5	3.7182	0.6507	0.0056	6.0984	2.5820
3	23	2.4969	0.4370	0.0067	7.2963	1.3931
5	6	3.5445	0.6203	0.0041	4.4649	1.7179
5	8	6.2204	1.0886	0.0049	5.3361	6.3232
5	13	9.2560	1.6198	0.0089	9.6921	25.4297
6	7	1.4389	0.2518	0.0022	2.3958	0.1519
6	8	3.5589	0.6228	0.0049	5.3361	2.0698
7	8	1.0787	0.1888	0.0010	1.0890	0.0388
8	9	4.6204	0.8086	0.0022	2.3958	1.5663
8	10	3.3964	0.5944	0.0022	2.3958	0.8464
8	12	2.1338	0.3734	0.0057	6.2073	0.8655
8	13	1.0363	0.1814	0.0100	10.8900	0.3582
10	11	4.7743	0.8355	0.0022	2.3958	1.6724
10	13	7.7994	1.3649	0.0078	8.4942	15.8242
12	13	4.3169	0.7555	0.0043	4.6827	2.6725
13	14	3.5524	0.6217	0.0070	7.6230	2.9461
13	15	2.6306	0.4604	0.0018	1.9602	0.4154
13	16	4.6151	0.8076	0.0023	2.5047	1.6338
13	18	9.8673	1.7268	0.0049	5.3361	15.9110
15	17	3.4523	0.6042	0.0023	2.5047	0.9142
16	17	1.5931	0.2788	0.0023	2.5047	0.1947
18	19	2.5873	0.4528	0.0090	9.8010	2.0093
18	20	7.0294	1.2301	0.0036	3.9204	5.9326
18	22	10.8159	1.8928	0.0049	5.3361	19.1172
21	22	3.8533	0.6743	0.0090	9.8010	4.4567
23	24	3.5248	0.6168	0.0052	5.6628	2.1546
23	25	5.1388	0.8993	0.0034	3.7026	2.9944
25	26	4.8543	0.8495	0.0090	9.8010	7.0729
25	27	4.3860	0.7676	0.0081	8.8209	5.1967
27	28	2.9706	0.5199	0.0095	10.3455	2.7959
Total	-	-	-	-	-	146.7261

Table 7: Power loss calculation for MC

From bus	To bus	MC (pu)	Ipu X 0.175 (kA)	R (pu)	R pu X 1089 (ohm)	Power line losses (MW)
1	2	7.1658	1.2540	0.0111	12.0879	19.0089
1	3	8.5218	1.4913	0.0029	3.1581	7.0237
3	4	5.6150	0.9826	0.0003	0.3267	0.3154
3	5	3.7935	0.6639	0.0056	6.0984	2.6876
3	23	4.1506	0.7264	0.0067	7.2963	3.8495
5	6	5.8310	1.0204	0.0041	4.4649	4.6492
5	8	10.5410	1.8447	0.0049	5.3361	18.1578
5	13	12.3477	2.1608	0.0089	9.6921	45.2550
6	7	3.2273	0.5648	0.0022	2.3958	0.7642
6	8	5.6907	0.9959	0.0049	5.3361	5.2921
7	8	3.6238	0.6342	0.0010	1.0890	0.4380
8	9	7.3992	1.2949	0.0022	2.3958	4.0169
8	10	5.3705	0.9398	0.0022	2.3958	2.1162
8	12	8.3932	1.4688	0.0057	6.2073	13.3916
8	13	3.6871	0.6452	0.0100	10.8900	4.5339
10	11	7.8635	1.3761	0.0022	2.3958	4.5369
10	13	7.7994	1.3649	0.0078	8.4942	15.8242
12	13	4.3787	0.7663	0.0043	4.6827	2.7496
13	14	10.7760	1.8858	0.0070	7.6230	27.1092
13	15	8.2326	1.4407	0.0018	1.9602	4.0687
13	16	8.6404	1.5121	0.0023	2.5047	5.7266
13	18	13.8204	2.4186	0.0049	5.3361	31.2134
15	17	5.4213	0.9487	0.0023	2.5047	2.2544
16	17	5.8227	1.0190	0.0023	2.5047	2.6006
18	19	2.5873	0.4528	0.0090	9.8010	2.0093
18	20	10.6699	1.8672	0.0036	3.9204	13.6687
18	22	13.9714	2.4450	0.0049	5.3361	31.8992
21	22	5.7873	1.0128	0.0090	9.8010	10.0531
23	24	5.5056	0.9635	0.0052	5.6628	5.2567
23	25	5.1385	0.8992	0.0034	3.7026	2.9940
25	26	6.7731	1.1853	0.0090	9.8010	13.7696
25	27	6.3477	1.1108	0.0081	8.8209	10.8848
27	28	4.0220	0.7039	0.0095	10.3455	5.1252
Total	-	-	-	-	-	323.2443

Table 8: Power loss calculation for HC

From bus	To bus	HC (pu)	IpuX 0.175 (kA)	R (pu)	R puX 1089 (ohm)	Power line losses (MW)
1	2	8.9730	1.5703	0.0111	12.0879	29.8059
1	3	9.3828	1.6420	0.0029	3.1581	8.5147
3	4	16.4165	2.8729	0.0003	0.3267	2.6964
3	5	5.1681	0.9044	0.0056	6.0984	4.9882
3	23	5.2994	0.9274	0.0067	7.2963	6.2753
5	6	11.4695	2.0072	0.0041	4.4649	17.9877
5	8	23.9129	4.1848	0.0049	5.3361	93.4468
5	13	12.3477	2.1608	0.0089	9.6921	45.2550
6	7	7.5392	1.3194	0.0022	2.3958	4.1704
6	8	12.0213	2.1037	0.0049	5.3361	23.6158
7	8	7.6034	1.3306	0.0010	1.0890	1.9281
8	9	12.4105	2.1718	0.0022	2.3958	11.3007
8	10	11.3709	1.9899	0.0022	2.3958	9.4867
8	12	8.3932	1.4688	0.0057	6.2073	13.3916
8	13	4.2561	0.7448	0.0100	10.8900	6.0411
10	11	14.2855	2.5000	0.0022	2.3958	14.9733
10	13	9.7498	1.7062	0.0078	8.4942	24.7281
12	13	4.4479	0.7784	0.0043	4.6827	2.8372
13	14	10.7761	1.8858	0.0070	7.6230	27.1095
13	15	8.2326	1.4407	0.0018	1.9602	4.0686
13	16	21.9803	3.8466	0.0023	2.5047	37.0595
13	18	22.6256	3.9595	0.0049	5.3361	83.6566
15	17	24.0364	4.2064	0.0023	2.5047	44.3170
16	17	7.9062	1.3836	0.0023	2.5047	4.7948
18	19	4.1100	0.7193	0.0090	9.8010	5.0703
18	20	15.7524	2.7567	0.0036	3.9204	29.7920
18	22	25.4175	4.4481	0.0049	5.3361	105.5761
21	22	6.8982	1.2072	0.0090	9.8010	14.2830
23	24	7.4560	1.3048	0.0052	5.6628	9.6408
23	25	9.6733	1.6928	0.0034	3.7026	10.6103
25	26	7.7021	1.3479	0.0090	9.8010	17.8059
25	27	7.6950	1.3466	0.0081	8.8209	15.9958
27	28	4.5520	0.7966	0.0095	10.3455	6.5650
Total	-	-	-	-	-	737.7880

Table 9: Power loss calculation for AMC

From bus	To bus	AMC (pu)	Ipu X 0.175 (kA)	R (pu)	R pu X 1089 (ohm)	Power line losses (MW)
1	2	8.5210	1.4912	0.0111	12.0879	26.8787
1	3	9.9115	1.7345	0.0029	3.1581	9.5013
3	4	16.6508	2.9139	0.0003	0.3267	2.7739
3	5	10.3859	1.8175	0.0056	6.0984	20.1456
3	23	4.1913	0.7335	0.0067	7.2963	3.9252
5	6	11.4168	1.9979	0.0041	4.4649	17.8228
5	8	23.6863	4.1451	0.0049	5.3361	91.6842
5	13	9.2419	1.6173	0.0089	9.6921	25.3523
6	7	7.5195	1.3159	0.0022	2.3958	4.1486
6	8	11.9210	2.0862	0.0049	5.3361	23.2234
7	8	7.4139	1.2974	0.0010	1.0890	1.8331
8	9	12.1840	2.1322	0.0022	2.3958	10.8920
8	10	11.4524	2.0042	0.0022	2.3958	9.6232
8	12	8.5784	1.5012	0.0057	6.2073	13.9892
8	13	4.2700	0.7473	0.0100	10.8900	6.0808
10	11	13.9620	2.4434	0.0022	2.3958	14.3028
10	13	9.7590	1.7078	0.0078	8.4942	24.7747
12	13	6.5929	1.1538	0.0043	4.6827	6.2334
13	14	10.8361	1.8963	0.0070	7.6230	27.4125
13	15	8.2957	1.4517	0.0018	1.9602	4.1312
13	16	21.8356	3.8212	0.0023	2.5047	36.5731
13	18	25.4906	4.4609	0.0049	5.3361	106.1843
15	17	23.8742	4.1780	0.0023	2.5047	43.7209
16	17	1.5931	0.2788	0.0023	2.5047	0.1947
18	19	4.1809	0.7316	0.0090	9.8010	5.2466
18	20	17.5902	3.0783	0.0036	3.9204	37.1491
18	22	24.1392	4.2244	0.0049	5.3361	95.2239
21	22	6.8395	1.1969	0.0090	9.8010	14.0407
23	24	7.1052	1.2434	0.0052	5.6628	8.7550
23	25	9.2940	1.6264	0.0034	3.7026	9.7945
25	26	7.4349	1.3011	0.0090	9.8010	16.5919
25	27	7.3189	1.2808	0.0081	8.8209	14.4704
27	28	4.3860	0.7676	0.0095	10.3455	6.0949
Total	-	-	-	-	-	738.7688

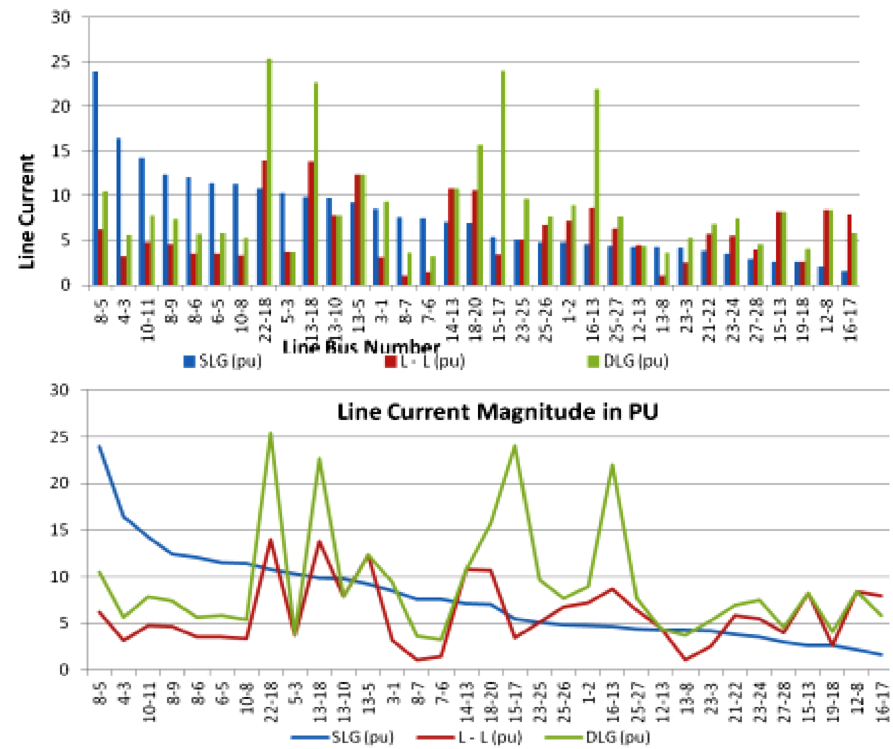

Fig. 18: Maximum line current obtained for SLG, L-L and DLG when Z_f = j0.1

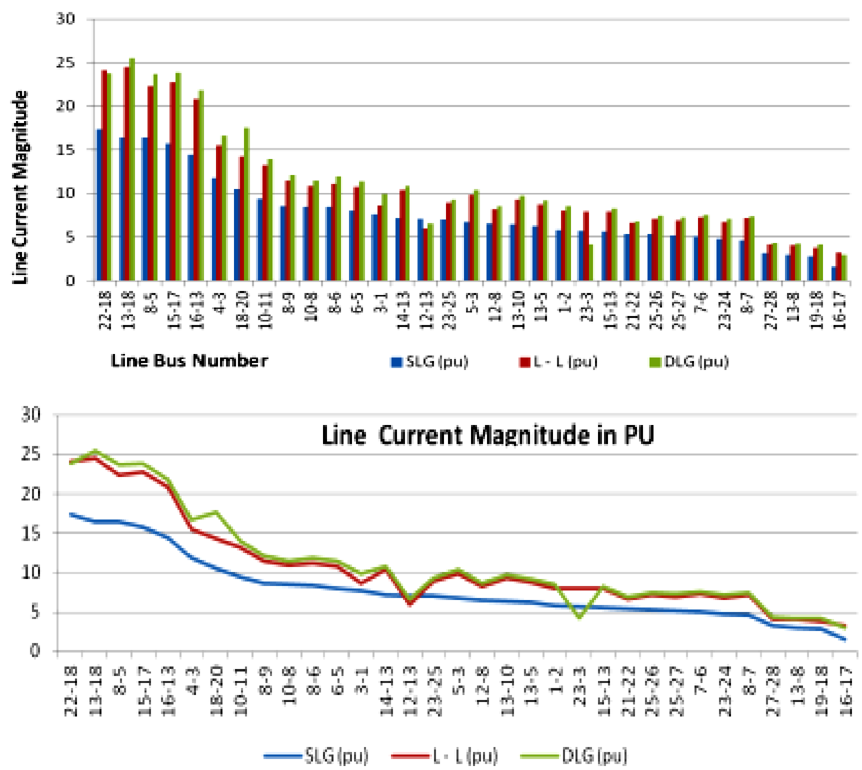

Fig. 19: Maximum line current obtained for SLG, L-L and DLG when Z_f = cj0

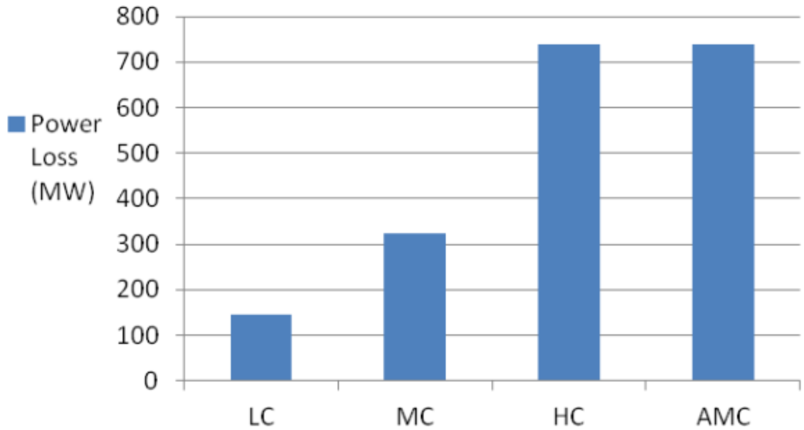

Fig. 20: Power losses calculated for LC, MC, HC and AMC

CONCLUSION

The technical losses' estimation is an important step when calculating the energy losses and planning grids and also it can lead to over or under procurement of supply. This research focused on technical losses on power line using Nigeria 330 kV transmission grid as a test system network. In this research, a suitable algorithm wasdeveloped and simulated for a set of unbalanced calculations model of the network using the symmetrical component theory of unbalanced fault to examine their effectson the line currents and the calculated power losses. This method assessed the steady and transient value (for high degree of accuracy) of technical losses on power line. Three categories of maximum line current, namely; low, medium and high current that are likened to a scenario of steady state, subtransient and transient were established and used accordingly to calculate the power losses. The corresponding power line losses obtained for low, medium and high current level were 146.73MW, 322.24 and 738.28 MW, respectively. These results revealed the high losses encountered and the inefficiency of Nigeria 330 kV transmission network. The results of load-flows were similar to the results obtained for low power loss level (steady-state current value) in the proposed method and this validates the steady-state power loss value of this research work. Also, the results of medium and high power level evaluate the disturbance which could not be captured at steady state.

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