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Investigation of nigerian 330 kv electrical network with distributed generation penetration – part I: basic analyses

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Abstract: The first part of this paper presents the basic analyses carried out on Nigerian 330 kV electrical network with distributed generation (DG) penetration. The analyses include load flow, short circuit, transient stability, modal/eigenvalues calculation and harmonics. The proposed network is an expanded network of the present network incorporating wind, solar and small-hydro sources. The choice of some locations of distributed generation has been proposed by energy commission of Nigeria (ECN). The conventional sources and distributed generation were modeled using a calculation program called PowerFactory, written by digsilent. Short-circuit analysis is used in determining the expected maximum currents, while transients stability and modal analyses are considered during the planning, design and in determining the best economical operation for the proposed network. One common application of harmonic analysis is providing solution to series resonance problems. Also, they are very valuable for setting the proper protection devices to ensure the security of the system.

Keywords: Distributed Generation, Load Flow, Short-Circuit, Transient Stability, Modal Analysis, Eigenvalues Calculation, Harmonics Analysis, Powerfactory, Digsilent

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1. Introduction

Nigeria is a vast country with a total of 356, 667 sq miles (923,768 km2), of which 351,649 sq. miles (910,771 sq km or 98.6% of total area) is land. The nation is made up of six geo-political zones subdivided into 36 states and the Federal Capital Territory (F.C.T.). Furthermore, the vegetation cover, physical features and land terrain in the nation vary from flat open savannah in the North to thick rain forests in the south, with numerous rivers, lakes and mountains scattered all over the country with population of 162, 470, 737 Million people. The total installed capacity of the currently generating plants is 7, 876 MW, but the available capacity is around 4,000 MW with peak value of 4, 477.7 MW on 15th August 2012. Seven of the fourteen generation stations are over 20 years old and the average daily power generation is below 4,000 MW, which is far below the peak load forecast of 8,900MW for the currently existing infrastructure. As a result, the nation experiences massive load shedding [1-5].

This paper looks at the conventional energy generation as well as the distributed generation sources: small-hydro, solar and wind energy potentials in Nigeria. The solar, small-hydro and wind energies are ways of accelerating the sluggish nature of the federal government of Nigeria rural electrification programmes. Nigeria receives an average solar radiation of about 7.0kWh/m2-day in the far north and about 3.5kWh/m2-day in the coastal latitudes [6]. Wave and tidal energy is about 150,000 TJ/year and the highest average speeds of about 3.5 m/s and 7.5 m/s in the south and north areas respectively [7-10].

Wind energy generating stations were proposed in the Northern part of the Country and along the coast in the southern part where average wind speeds are high, while solar stations were proposed for every state, having potentials to produce energy from the sun because of high solar radiation (minimum value of 50 MW per state). Offshore wind power was proposed for states along the coast which include: Lagos, Ondo, Delta, Bayelsa, and Akwa-Ibom (minimum value of 50 MW per state). It involves the construction of wind farms in bodies of water to generate electricity from wind. Better wind speeds are available offshore compared to on land, so offshore wind power’s contribution in terms of electricity supplied is higher. However, offshore wind farms are relatively expensive. This proposition coupled with ECN investigated sites were used to prepare the proposed electrical network for the Country (37-bus system) as shown in Figure 1, the power generation and allocation are shown in Table 1 (Appendix).

However, penetration of DG can affect the stability of the system by either improving or deteriorating the stability of the system. The power system faces many problems when distributed generation is added in the already existing system. The addition of generation could influence power quality problems, degradation in system reliability, reduction in the efficiency, over voltages and safety issues [11-13].

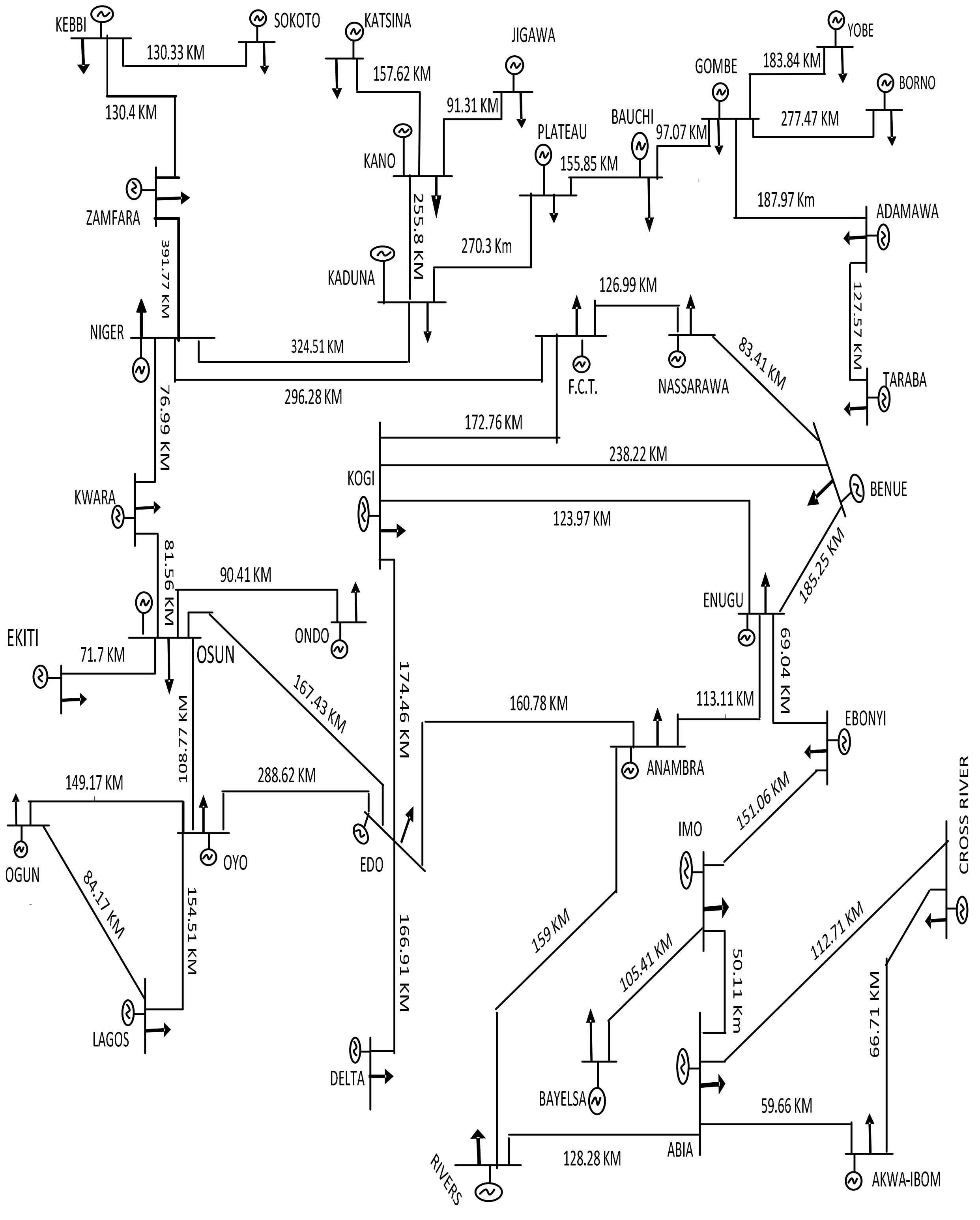

Figure 1. *Proposed Nigerian 330 kV electrical network (37-bus system).*

Table 1. *Proposed Power generation and Allocation per State.*

S/N	State	Total Capacity Per State (Mw)	Population Size	Real Power Allocation (P)	Reactive Power Allocatn (Q)
1	F.C.T.	535	1,405,201	906.79	363
2	Abia	2,404	2,833,999	820.42	328
3	Adamawa	100	3,168,101	917.14	367
4	Akwa-Ibom	1,790	3,920,208	1,134.87	454
5	Anambra	1,705	4,182,032	1,210.67	484
6	Bauchi	742.6	4,676,465	1,353.80	542
7	Bayelsa	350	1,703,358	493.11	197
8	Benue	2,130	4,219,244	1,221.44	489
9	Borno	120.8	4,151,193	1,201.74	481
10	Cross River	705	2,888,966	836.33	335
11	Delta	5,900	4,098,391	1,186.45	475
12	Ebonyi	230	2,173,501	629.21	252
13	Edo	1,000	3,218,332	931.68	373
14	Ekiti	70	2,384,212	690.21	276
15	Enugu	1,050	3,257,298	942.96	377
16	Gombe	400	2,353,879	681.43	273
17	Imo	425	3,934,899	1,139.12	456
18	Jigawa	146.2	4,348,649	1,258.90	504
19	Kaduna	379.2	6,066,562	1,756.22	702
20	Kano	246	9,383,682	3,216.50	1,287
21	Katsina	111	5,792,578	1,676.91	671
22	Kebbi	240	3,238,628	937.56	375
23	Kogi	1,804	3,278,487	949.10	380
24	Kwara	90	2,371,089	686.41	275
25	Lagos	1,616	9,013,534	3,609.35	1,444
26	Nassarawa	196	1,863,275	539.40	216
27	Niger	2,710	3,950,249	1,143.57	457
28	Ogun	2,125	3,728,098	1,079.26	432
29	Ondo	920	3,441,024	996.15	398
30	Osun	65	3,423,535	991.09	396
31	Oyo	3,800	5,591,589	1,618.72	647
32	Plateau	245.4	3,178,712	920.21	368
33	Rivers	3,924	5,185,400	1,501.13	600
34	Sokoto	133.6	3,696,999	1,070.25	428
35	Taraba	3,735	2,300,736	666.05	266
36	Yobe	140	2,321,591	672.08	269
37	Zamfara	246	3,259,846	943.70	377
	Total	42,529.95	140,003,542	42,529.95	17,012

2. Methodology

The conventional and distributed generation sources were modeled using a calculation program called PowerFactory, written by DIgSILENT version 14.1. The name DIgSILENT stands for "DIgital SImuLation and Electrical NeTwork calculation program" [14]. It is a computer aided engineering tool for the analysis of industrial, utility, and commercial electrical power systems. It has been designed as an advanced integrated and interactive software package dedicated to electrical power system and control analysis in order to achieve the main objectives of planning and operation optimization.

PowerFactory works with three different classes of graphics: single line diagrams, block diagrams, and virtual instruments. They constitute the main tools used to design new power systems, controller block diagrams and displays of results. In order to meet today's power system analysis requirements, the DIgSILENT power system calculation package was designed as an integrated engineering tool which provides a complete 'walk-around' technique through all available functions, rather than a collection of different software modules [14]. Analyses carried out using PowerFactory software in this part include load flow, transient stability, modal analysis/eigenvalues calculation and harmonics analysis. These are discussed in sections 4 – 8.

3. Network Modeling in Power Factory

The network model contains the electrical and graphical information for the grid. To further enhance manageability, this information is split into two subfolders: diagrams and network data. An additional subfolder, Variations, contains all expansion stages for planning purposes. The network model folder contains the all graphical and electrical data which defines the networks and the single line diagrams of the power system under study. This set of data is referred as the network data model. The proposed Nigerian 330 kV electrical network (37 buses), shown in Fig. 1.0, was modelled using this software. The DGs are limited to solar, small-hydro and wind sources. The elements data used to carry out PowerFactory analyses are shown in Appendix. The base apparent power used is 100 MVA, while the transmission line lengths (in Kilometers, Km) were per-unitized on the base value of 100 Km.

4. Load Flow Analysis

In PowerFactory, the nodal equations used to represent the analyzed networks are implemented using two different formulations:

- Newton-Raphson (current equations)
- Newton-Raphson (power equations, classical)

In both formulations, the resulting non-linear equation systems are solved by an iterative method. Load flow calculations are used to analyze power systems under steady-state and non-faulted (short-circuit-free) conditions. The load flow calculates the active and reactive power flows for all branches, and the voltage magnitude and phase for all nodes under A.C. balanced, A.C. unbalanced and D.C. load flow calculation methods.

The machine currents at steady-state are calculated from [15]:

$$I_i = \frac{S_i^*}{V_i^*} = \frac{P_i - jQ_i}{V_i^*} \tag{1}$$

where
i = 1, 2,..., m
m is the number of generators;
V_i is the terminal voltage of the ith generator; and P_i and Q_i are the generator real and reactive powers.

For n-bus system, the node-voltage equation in matrix form is:

$$\begin{bmatrix} I_1 \\ I_2 \\ .. \\ .. \\ I_i \\ .. \\ I_n \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1i} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & \cdots & Y_{2i} & \cdots & Y_{2n} \\ .. & & & & & \\ Y_{i1} & Y_{i2} & .. & Y_{ii} & .. & Y_{in} \\ .. & \cdots & \cdots & \cdots & \cdots & \cdots \\ Y_{n1} & Y_{n2} & \cdots & Y_{ni} & \cdots & Y_{nn} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ .. \\ .. \\ V_i \\ .. \\ V_n \end{bmatrix} \tag{2}$$

Or

$$I_{bus} = Y_{bus} V_{bus} \tag{3}$$

where I_{bus} is the vector of the injected bus currents and V_{bus} is the vector of bus voltages measured from the reference node. Y_{bus} is known as the bus admittance matrix. The diagonal element of each node is the sum of admittances connected to it. It is known as self-admittance given as:

$$Y_{ii} = \sum_{j=0}^{n} y_{ij} \quad j \neq i \tag{4}$$

The off-diagonal element is equal to the negative of the admittance between the nodes. It is known as mutual admittance, that is:

$$Y_{ij} = Y_{ji} = -y_{ij} \tag{5}$$

A load flow calculation determines the voltage magnitude (V) and the voltage angle (θ) of the nodes, and the active (P) and reactive (Q) power flow on branches. The network nodes are represented by specifying two of these four quantities. PowerFactory uses the Newton-Raphson (power equation, classical) method as its non-linear equation solver. This method is used for large transmission systems, especially when heavily loaded. It was used for A.C. load flow.

From Kirchhoff's Current law (KCL), the current at bus I is given by:

$$I_i = V_i \sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} y_{ij} V_j \quad j \neq i \tag{6}$$

The real and reactive powers at bus i are:

$$P_i + jQ_i = V_i I_i^{\bullet} \tag{7}$$

$$P_i - jQ_i = |V_i| \angle - \delta_i \sum_{j=1}^{n} |Y_{ij}| |V_j| \angle \theta_{ij} + \delta_j \tag{8}$$

$$P_i = \sum_{j=1}^{n} |V_i| |V_j| |Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \tag{9}$$

$$Q_i = -\sum_{j=1}^{n} |V_i| |V_j| |Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) \tag{10}$$

After calculating P_i and Q_i, the voltage and phase angle for each bus are computed iteratively using:

$$\begin{aligned} \delta_i^{(k+1)} &= \delta_i^{(k)} + \Delta\delta_i^{(k)} \\ \left|V_i^{(k+1)}\right| &= \left|V_i^{(k)}\right| + \left|\Delta V_i^{(k)}\right| \end{aligned} \tag{11}$$

where k is the iteration step, while $\Delta V_i^{(k)}$ and $\Delta\delta_i^{(k)}$ are calculated from Jacobian matrix. The results of the analysis are shown and discussed in section 9.

5. Short-Circuit Analysis

The short-circuit calculation in PowerFactory is able to simulate single faults as well as multiple faults of almost unlimited complexity. As short-circuit calculations can be used for a variety of purposes, PowerFactory supports different representations and calculation (IEC60906, VCE0102, ANSI and complete) methods for the analysis of short-circuit currents. One application of short-circuit calculations is to check the ratings of network equipment during the planning stage. This is used in determining the expected maximum currents (for the correct sizing of components) and the minimum currents (to design the protection scheme). A single phase 'a' to ground was introduced on a transmission line linking Niger and F.C.T. generating stations using IEC60906 and ANSI methods, results are discussed in section 9 [16,17].

6. Transient Analysis

The transient simulation functions available in DIgSILENT PowerFactory are able to analyze the dynamic behavior of small systems and large power systems in the time domain. These functions therefore make it possible to model complex systems such as industrial networks and large transmission grids in detail, taking into account electrical and mechanical parameters. Transients, stability problems and control problems are important considerations during the planning, design and operation of modern power systems.

Short circuit switching events were created on transmission line linking Niger and F.C.T. generating stations, Benue, Sokoto, Kebbi, Borno generating stations, and loss of Rivers state load. These are transient faults carried out using electromechanical transients simulation method in PowerFactory software [11-13, 17-20].

7. Eigenvalues/Modal Analysis

The modal analysis calculates the eigenvalues and eigenvectors of a dynamic multi-machine system including all controllers (defined before transient analysis) and power plant models. This calculation can be performed not only at the beginning of a transient simulation but also at every time step when the simulation is stopped. The eigenvalue analysis allows for the computation of modal sensitivities with respect to generator or power plant controllers, reactive compensation or any other equipment. The calculation of eigenvalues and eigenvectors is the most powerful tool for oscillatory stability studies. Starting from these 'bare natural' modes, the effects of controllers (structure, gain, time constants etc.) and other additional models can be calculated as the second step [14].

One of the conjugate complex pair of eigenvalues is given by:

$$\lambda = \sigma_i + j\omega_i \tag{12}$$

Then the oscillatory mode will be stable, if the real part of the eigenvalue is negative, that is, $\sigma_i \langle\, 0$

The period and damping of this mode are given by:

$$\tau_i = \frac{2\pi}{\omega_i} \tag{13}$$

$$d_i = -\sigma_i = \frac{1}{T_{p.}} \ln\left(\frac{A_n}{A_{n+1}}\right) \tag{14}$$

where A_n and A_{n+1} are amplitudes of two consecutive swing maxima or minima respectively.

The oscillatory periods of local generator oscillations are typically in the range of 0.5 to 5 Hz. Higher frequencies of the natural oscillations, that is, those which are normally not regulated out, are often damped to a greater extent than slower oscillations. The oscillatory period of the oscillations of areas (inter-area oscillations) is normally a factor of 5 to 20 times greater than that of the local generator oscillations

[14].

The absolute contribution of an individual generator to the oscillation mode which has been excited as a result of a disturbance can be calculated by:

$$\underline{\omega_i(t)} = \sum_{i=1}^{n} c_i \phi_i e^{\lambda_i t} \tag{15}$$

The nomenclature is given in Appendix.

'c' is set to the unit vector, that is, c = [1, ...,1], which corresponds to a theoretical disturbance which would equally excite all generators with all natural resonance frequencies simultaneously. The elements of the eigenvectors Φ_i then represents the mode shape of the eigenvalue i and shows the relative activity of a state variable, when a particular mode is excited. They show for example, the speed amplitudes of the generators when an eigenfrequency is excited, whereby those generators with opposite signs in Φ_i oscillate in opposite phase.

The right eigenvectors Φ_i can thus be termed the "observability vectors". The left eigenvectors Ψ_i measures the activity of a state variable x in the i-th mode, thus the left eigenvectors can be termed the "relative contribution vectors". Normalization is performed by assigning the generator with the greatest amplitude contribution the relative contribution factor 1 or -1 respectively. For n-machine power system, n-1 generator oscillation modes will exist and n-1 conjugate complex pairs of eigenvalues λ_i will be found. The mechanical speed ω_i of the n generators will then be described by [14]:

$$\begin{bmatrix} \omega_1 \\ \omega_2 \\ \cdots \\ \omega_n \end{bmatrix} = c_1 \begin{bmatrix} \phi_{12} \\ \phi_{22} \\ \cdots \\ \phi_{1n} \end{bmatrix} e^{\lambda_1 t} + c_2 \begin{bmatrix} \phi_{21} \\ \phi_{22} \\ \cdots \\ \phi_{2n} \end{bmatrix} e^{\lambda_2 t} + \ldots + c_n \begin{bmatrix} \phi_{n1} \\ \phi_{n2} \\ \cdots \\ \phi_{nn} \end{bmatrix} e^{\lambda_n t} \tag{15}$$

The problem of using the right or left eigenvectors for analyzing the participation of a generator in a particular mode i is the dependency on the scales and units of the vector elements. Hence the eigenvectors Φ_i and Ψ_i are combined to a matrix **P** of participation factor by:

$$\underline{P_i} = \begin{bmatrix} P_{1i} \\ p_{2i} \\ \cdots \\ P_{ni} \end{bmatrix} = \begin{bmatrix} \phi_{1i}.\Psi_{i1} \\ \phi_{2i}.\Psi_{i2} \\ \cdots\cdots \\ \phi_{ni}.\Psi_{in} \end{bmatrix} \tag{16}$$

The elements of the matrix P_{ij} are called the participation factors. They give a good indication of the general system dynamic oscillation pattern. They may be used easily to determine the location of eventually needed stabilizing devices in order to influence the system damping efficiently. Furthermore the participation factor is normalized so that the sum for any mode is equal to 1[21, 22].

8. Harmonics Analysis

One of several aspects of power quality is the harmonic content of voltages and currents. Harmonics can be analyzed in either the frequency domain, or in the time-domain with post-processing using Fourier analysis. The PowerFactory harmonics functions allow the analysis of harmonics in the frequency domain, it could be used to analyse both balanced and unbalanced network. Two different functions are provided by PowerFactory [14]:

- Harmonic load flow;
- Frequency sweep.

In the case of a symmetrical network and balanced harmonic sources, characteristic harmonics either appear in the negative sequence component (5th, 11th, 19th, etc.), or in the positive sequence component. Hence, at all frequencies a single-phase equivalent (positive or negative sequence) are used for the analysis, while for analyzing non-characteristic harmonics (3rd-order, even-order, inter-harmonics), or harmonics in non-symmetrical networks, the unbalanced option for modeling the network in the phase-domain is selected.

ency sweep is used to calculate frequency dependent impedances, the impedance characteristic can be computed for a given frequency range using ComFsweep in PowerFactory [14]. Harmonic analysis by frequency sweep is used for analyzing self- and mutual- network impedances. The voltage source models available in PowerFactory allow the definition of any spectral density function. Hence, impulse or step responses of any variable can be calculated in the frequency domain.

Balanced, positive sequence uses a single-phase, positive sequence network representation, valid for balanced symmetrical networks. A balanced representation of unbalanced objects is used, while unbalanced, 3 Phase (ABC) uses a full multiple-phase, unbalanced network representation.

The second function is the frequency sweep performed for the frequency range defined by the 'Start Frequency' and the 'Stop Frequency', using the given Step Size. An option is available which allows an adaptive step size. Enabling this option will normally speed up the impedance calculation, and enhance the level of detail in the results by automatically using a smaller step size when required [23, 24].

9. Results and Discussion

Simulations were performed on the proposed 37-bus network using PowerFactory by DIgSILENT [14]. Tables 2-4 show results of calculation methods used which are A.C. load flow (balanced system and unbalanced) and DC load flow respectively. The base apparent power used was 100 MVA, while the transmission line lengths (in Kilometers, Km) were per-unitized on the base value of 100 Km.

Detailed reports can be provided in the 'output of results-complete system report' icon provided by the software.

Secondly, short-circuit calculation was carried out on transmission line connecting F.C.T. and Niger generating stations.

Table 2. *Balanced A. C. load flow – summary report.*

Parameters			
No. of Substations	37		
No. of Loads	37		
No. of Terminals	663		
No. of syn. Machines	36		
No. of Lines	43		
Parameters	MW	Mvar	MVA
Generation	425.53	46.91	428.11
External infeed	0.00	0.00	0.00
Load P(U)	425.31	116.45	440.96
Load P(Un)	425.41	116.47	441.07
Load P(Un-U)	0.10	0.02	0.00
Motor Load	0.00	0.00	0.00
Grid Losses	0.22	-69.93	0.00
Line Charging	0.00	-69.93	0.00
Compensation ind.	0.00	0.00	0.00
Compensation cap.	0.00	0.00	0.00
Installed Capacity	533.44	0.00	0.00
Spinning Reserve	107.91	0.00	0.00
Total Power Factor:	[-]		
Generation	0.99		
Load	0.96		
Motor	0.00		

Table 3. *Unbalanced A. C. load flow – summary report.*

Parameters			
No. of Substations	37		
No. of Loads	37		
No. of Terminals	663		
No. of syn. Machines	36		
No. of Lines	43		
Parameters	MW	Mvar	MVA
Generation	425.53	46.91	428.11
External Infeed	0.00	0.00	0.00
Load P(U)	425.31	116.45	440.96
Load P(Un)	425.41	116.47	441.07
Load P(Un-U)	0.10	0.02	0.00
Motor Load	0.00	0.00	0.00
Grid Losses	0.22	-69.55	0.00
Line Charging	0.00	-69.93	0.00
Compensation ind.	0.00	0.00	0.00
Compensation cap.	0.00	0.00	0.00
Installed Capacity	533.44	0.00	0.00
Spinning Reserve	107.91	0.00	0.00
Total Power Factor:	[-]		
Generation	0.99		
Load	0.96		
Motor	0.00		

Table 4. *D. C. load flow – summary report.*

Parameters			
No. of Substations	37		
No. of Loads	37		
No. of Terminals	663		
No. of syn. Machines	36		
No. of Lines	43		
Parameters	MW	Mvar	MVA
Generation	425.41	0.00	0.00
External infeed	0.00	0.00	0.00
Inter Grid Flow	0.00	0.00	0.00
Load P(U)	425.41	0.00	0.00
Load P(Un)	425.41	0.00	0.00
Load P(Un-U)	0.00	0.00	0.00
Motor Load	0.00	0.00	0.00
Grid Losses	0.00	0.00	0.00
Line Charging	0.00	0.00	0.00
Compensation ind.	0.00	0.00	0.00
Compensation cap.	0.00	0.00	0.00
Installed Capacity	533.44	0.00	0.00
Spinning Reserve	108.03	0.00	0.00
Total Power Factor:	[-]		
Generation	0.00		
Load	0.00		
Motor	0.00		

Table 5. *IEC60909 method - complete report.*

Short-Circuit Duration:					
Break Time					0.10 s
Fault Clearing Time					0.40 s
c-Factor					1.1
Fault distance from terminal i: ... k					1.48km
Fault Location (line 28)					50.00%
Phase	**Bus-voltage (kV) degree**		**c-factor**	**Sk" (MVA)**	
A	0	0	1.1	1366.43	
B	191.22	-107.72		0	
C	193.01	110.91		0	
Ik" (kA) (deg)		**ip (kA)**	**Ib (kA)**	**Sb (MVA)**	**EFF (-)**
7.17	-86.99	17.97	7.17	1366.43	0
0	0	0	0	0	0.93
0	0	0	0	0	0.9

Table 6. *ANSI method - complete report.*

Pre-fault Voltage					**1.00 p.u.**
Fault distance from terminal i: ... k					1.48 km
Fault Location (line 28)					50.00%
Asym.RMS X/R based [kA]					10.286
Asym. Peak X/R based [kA]					12.453
Parameters	**Equivalent Impedance R[Ohm] X[Ohm]**		**Symmetrical Current [kA] [deg]**		**App. power (MVA)**
Mom.Duty	2.925	35.542	6.409	-87.74	1221.171
Zero-Seq	0.296	18.023	0	0	0
Neg.-Seq	0.297	35.542	0	0	0
Int.Duty	2.925	35.542	6.409	-87.74	1221.171
Zero-Seq	0.296	18.023	0	0	0
Neg.-Seq	0.297	35.542	0	0	0
30-cycle	4.239	53.062	5.355	-87.41	1020.274
Zero-Seq	0.296	18.023	0	0	0
Neg.-Seq	0.297	35.542	0	0	0
Parameters	**X/R ratio**	**Sym.Base [kA]**	**Tot.Base [kA]**		
Mom.Duty	26.341	0	0		
2 cycles	0	6.764	9.529		
3 cycles	0	6.899	8.347		
5 cycles	0	6.874	7.611		
8 cycles	0	7.044	7.045		

Table 7. *Complete method (multiple faults).*

Short-Circuit Duration:						
Break Time					0.10 s	
Fault Clearing Time					0.40 s	
c-Factor					1	
Fault distance from terminal i: ... k					1.48 km	
Fault Location (line 28)					50.00%	
Phase	**Bus (kV) deg.**	**Voltage**	**c-factor**	**Sk" (MVA)**	**Ik" (kA) deg.**	
A	0	0	1	1198.47	6.29	-87.95
B	173.85	-107.54		0	0	0
C	174.56	110.44		0	0	0
Ik' (kA) (deg)		Ip (kA)	Ib (kA)	Ib (kA)	EFF (-)	
5.22	-88.5	15.88	5.31	8.18	0	
0	0	0	0	0	0.93	
0	0	0	0	0	0.9	

Next is transient stability analysis, short circuit switching events were created on transmission line linking Niger and F.C.T. generating stations, Benue, Sokoto, Kebbi, Borno generating station, and loss of Rivers state load using 3-phase unbalanced electromechanical transients simulation method. The switching events start by initializing the system (performing balanced load flow), followed by opening and closing phase ‘a’ of line (28) at 0.2s and 0.3s respectively and opening the three phases (‘a’, ‘b’ and ‘c’). Other components were then selected and short circuit events defined. The results are shown in Figure 2-8.

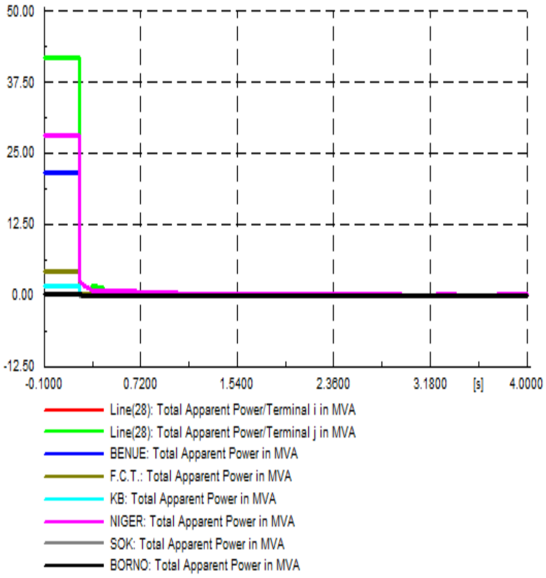

Figure 2. *Total apparent power (MVA).*

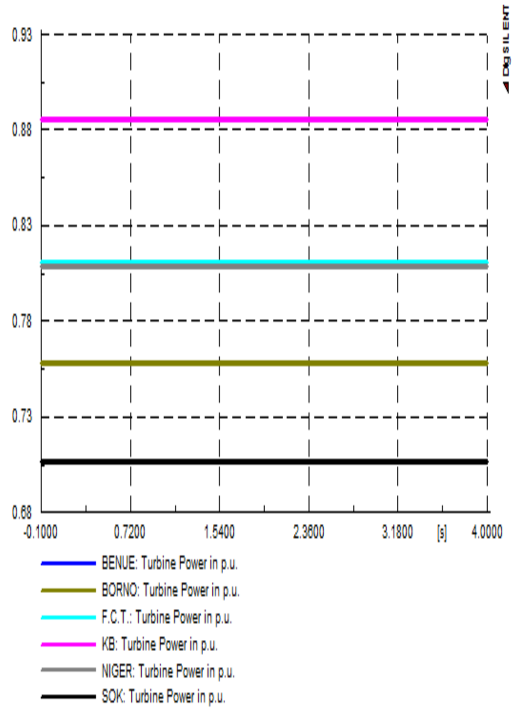

Figure 3. *Turbine power (p.u.).*

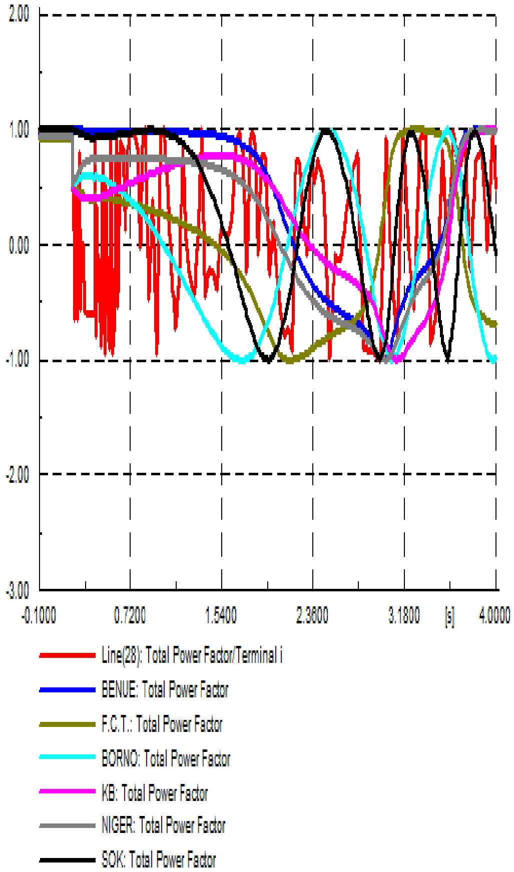

Figure 4. *Total power factor.*

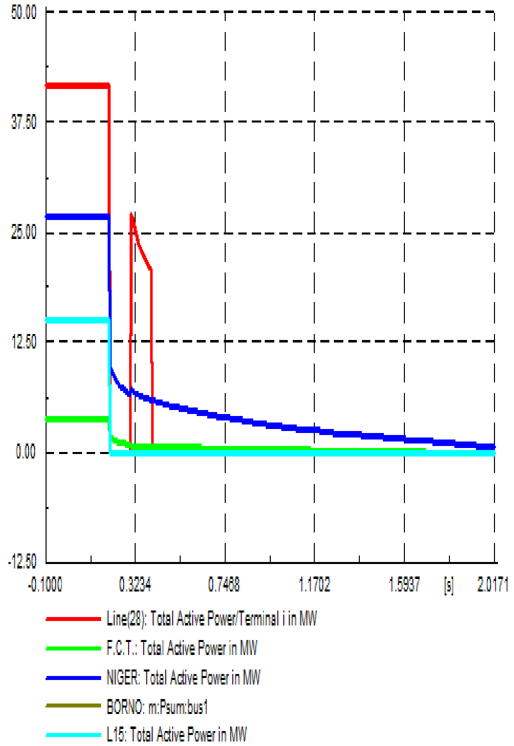

Figure 5. *Total active power (MW).*

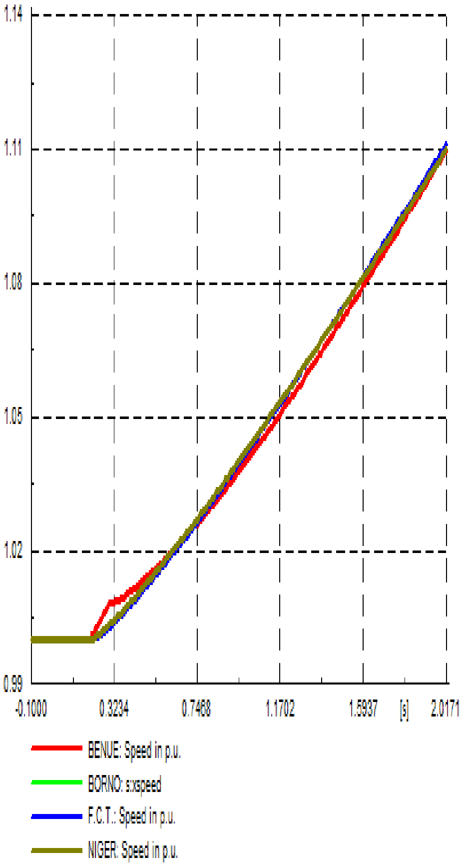

Figure 6. *Speed (p.u.).*

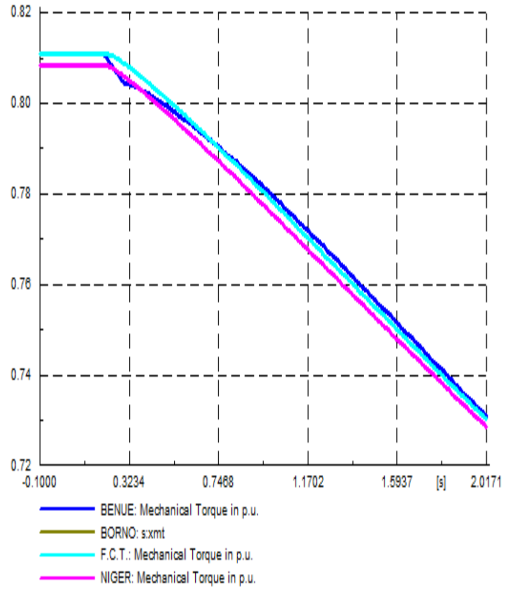

Figure 7. *Mechanical torque (p.u.).*

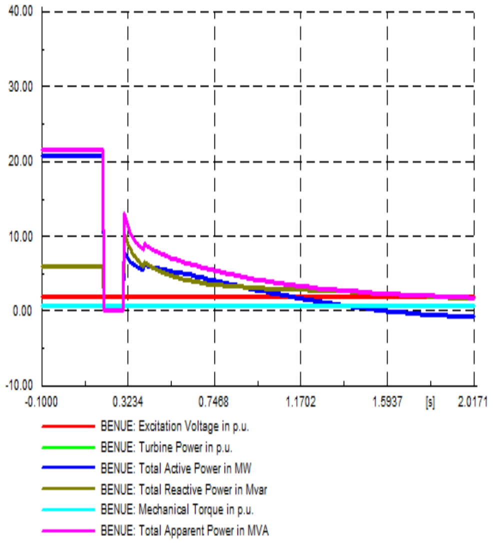

Figure 8. *Benue hydro generating station parameters.*

Next is modal analysis tool, it was used to calculate the eigenvalues and eigenvectors of a dynamic multi-machine system including all controllers and power plant models. This calculation can be performed not only at the beginning of a transient simulation but also at every time step when the simulation is stopped. A modal analysis started when a balanced steady-state condition was reached in a dynamic calculation. Normally, such a state is reached by a balanced load-flow calculation, followed by a calculation of initial conditions.

Two methods were used for modal analysis: QR-method (this method is the 'classical' method for calculating all the system eigenvalues), while selective modal analysis method, also called Arnoldi/Lanczos calculated a subset of the system eigenvalues around a particular reference point-often used for very large system. In the later method, the reference point on the real-imaginary plain must be entered in the field provided and the number of eigenvalues calculated is limited by the number selected at 'Number of Eigenvalues' field [14]. Speed was set as state variable in this paper.

The eigenvalue plots in Figure 9 and 10 show the calculated eigenvalues in a two-axis coordinate system. For the vertical axis, it is possible to select among the imaginary part, the period or the frequency of the eigenvalue, while the horizontal shows the real part. Stable eigenvalues are shown in green, and unstable (none in this case) are in red. Each eigenvalue can be inspected in details by double-clicking it on the plot (in the package). This shows the index, complex representation, polar representation and oscillation parameters of the mode. Although, in selective method, an eigenvalue is on the imaginary axis making the system to be marginally stable.

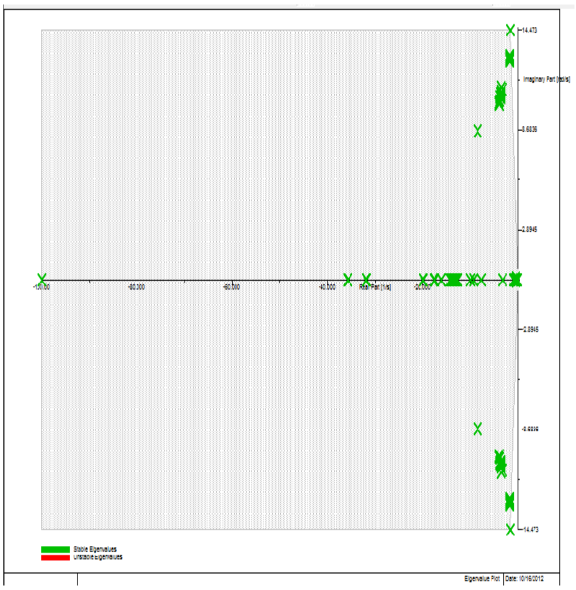

Figure 9. *Eigenvalue plot – QR method.*

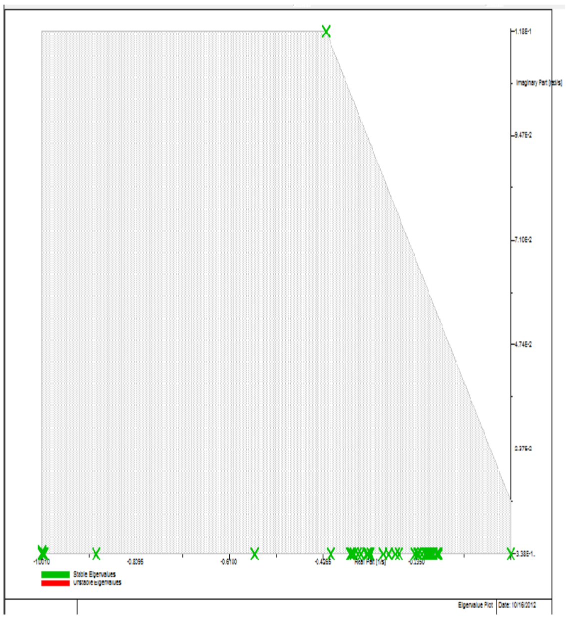

Figure 10. *Eigenvalue plot - selective method.*

The mode bars in Figures 11, 12 and 13 show controllability, observability and participation factors of variables for a user selected eigenvalue in bar chart form. This allows for easy visual interpretation of these parameters. Double clicking on any of the bar (in the software package), displays the magnitude, phase and sign of the variables for controllability, observability and participation in the selected mode.

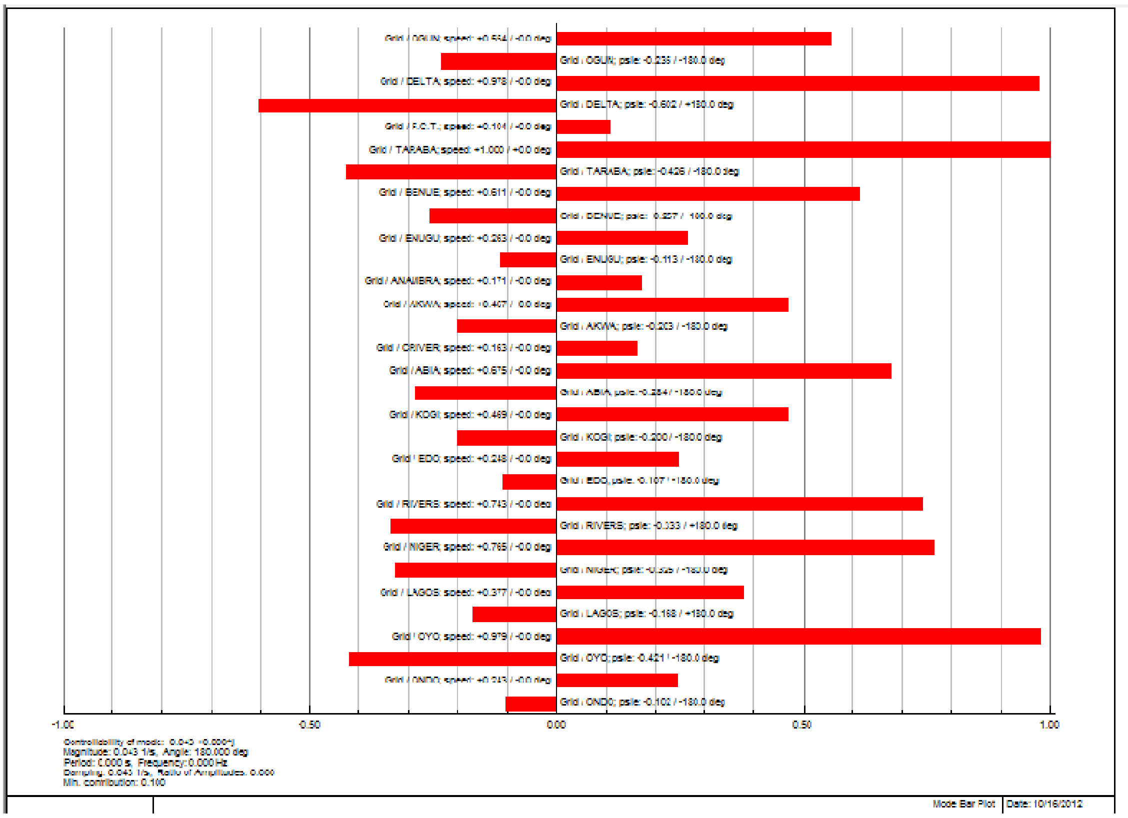

Figure 11. Mode bar plot – controllability.

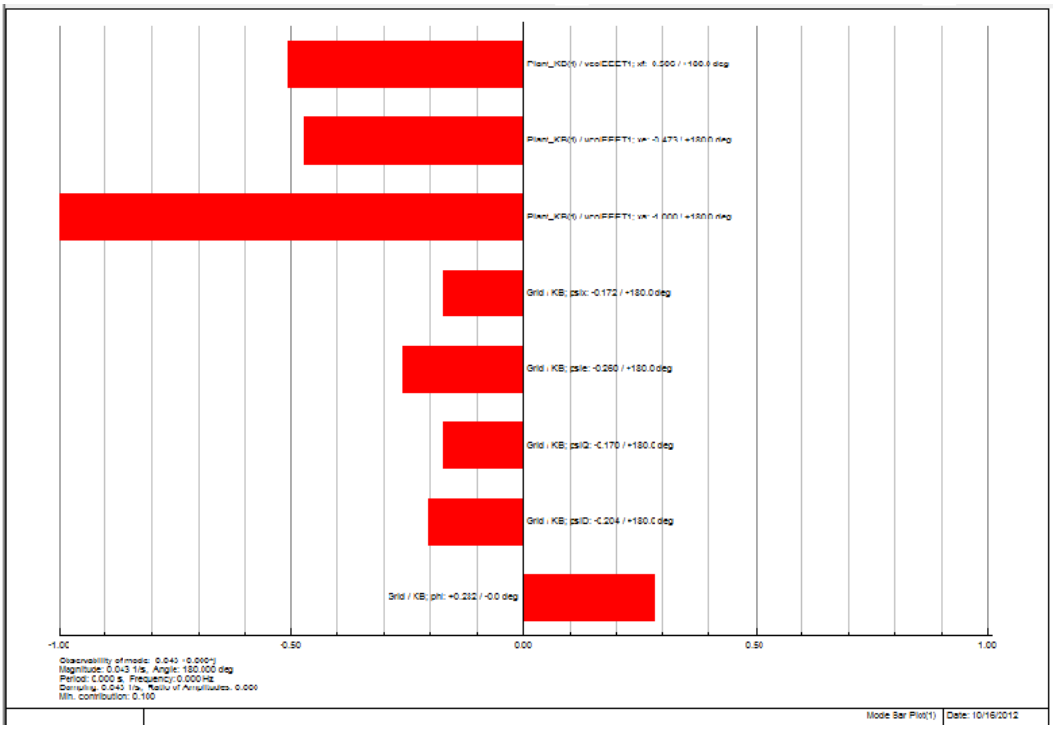

Figure 12. Mode bar plot – observability.

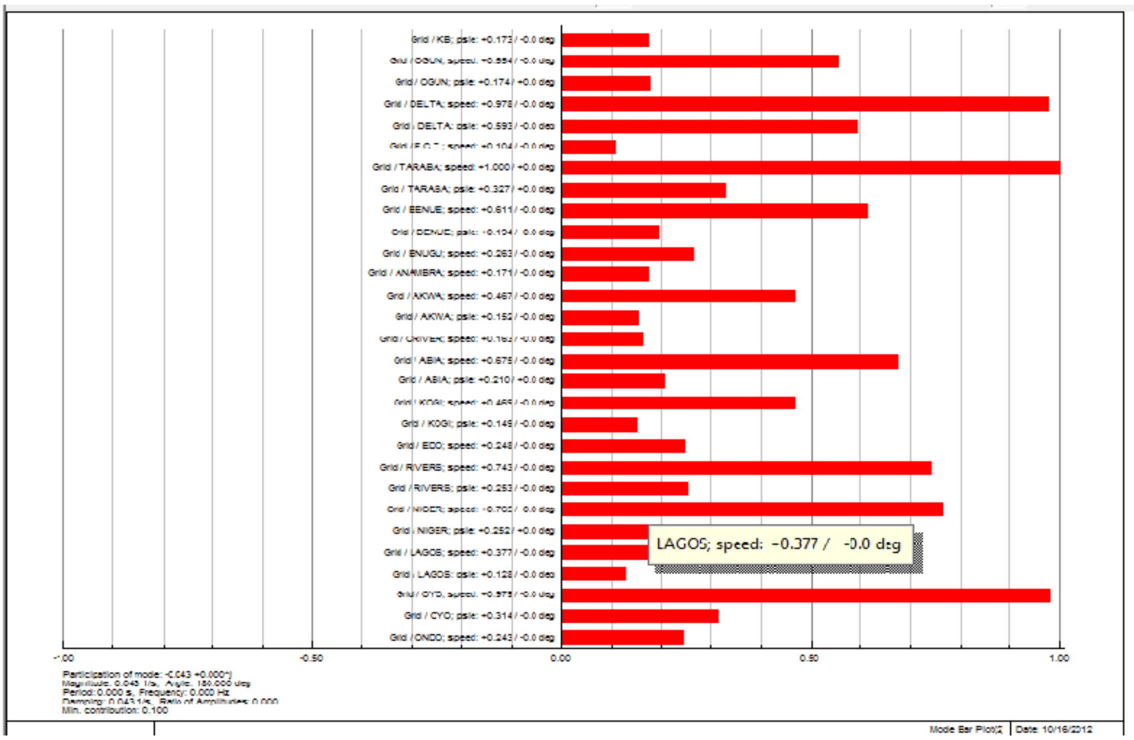

Figure 13. Mode bar plot - participation facto .

The mode phasor plot displays the controllability, observability and participation factors of the system generators (according to the state variable selected in the modal analysis command) in a selected mode by means of a phasor diagram. Variables are grouped and coloured identically if their angular separation is less than a user defined parameter (set at 3 degrees). Double clicking any of the bars in the plot shows the detailed dialogue as shown in Figures 14, 15 and 16.

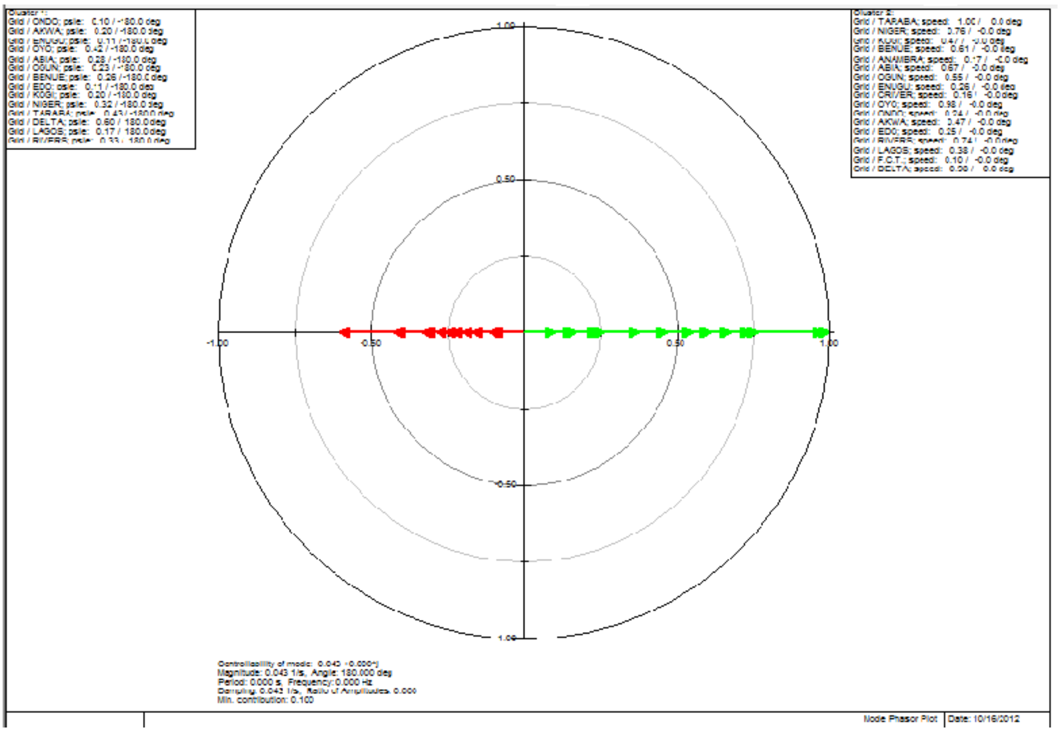

Figure 14. Mode phasor plot - controllability (0,0 origin).

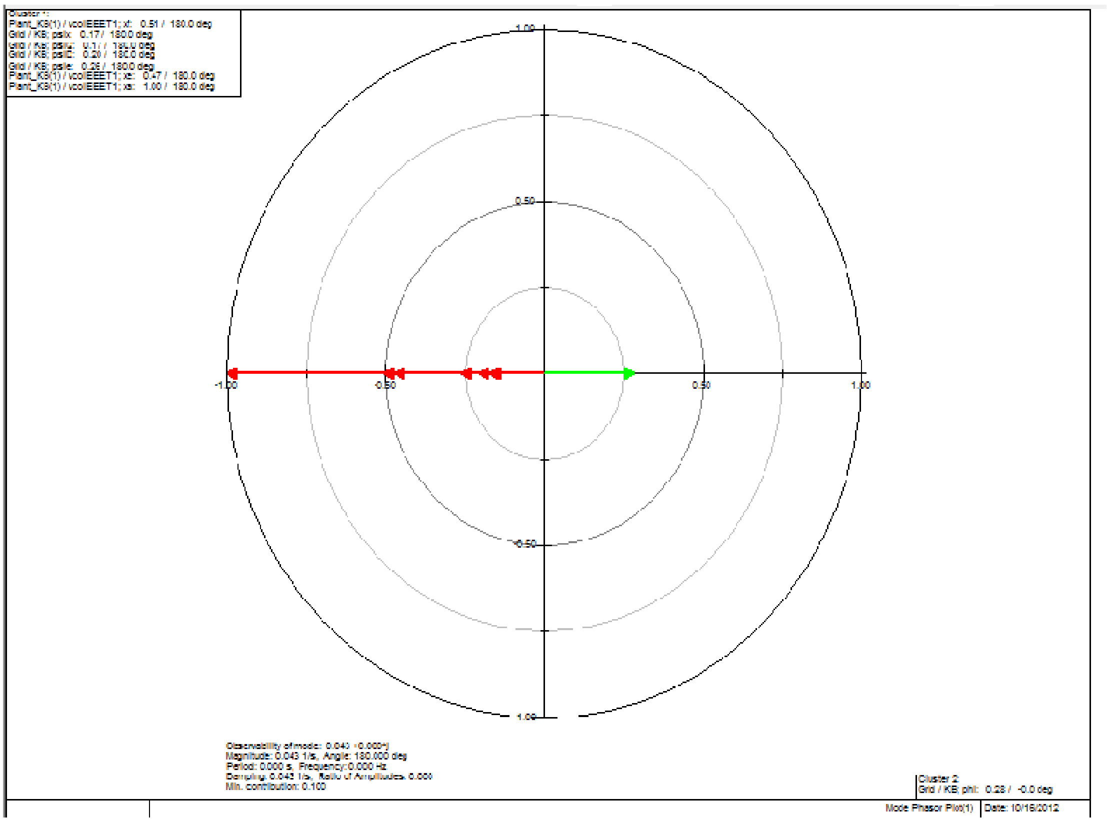

Figure 15. Mode phasor plot - observability (0,0 origin).

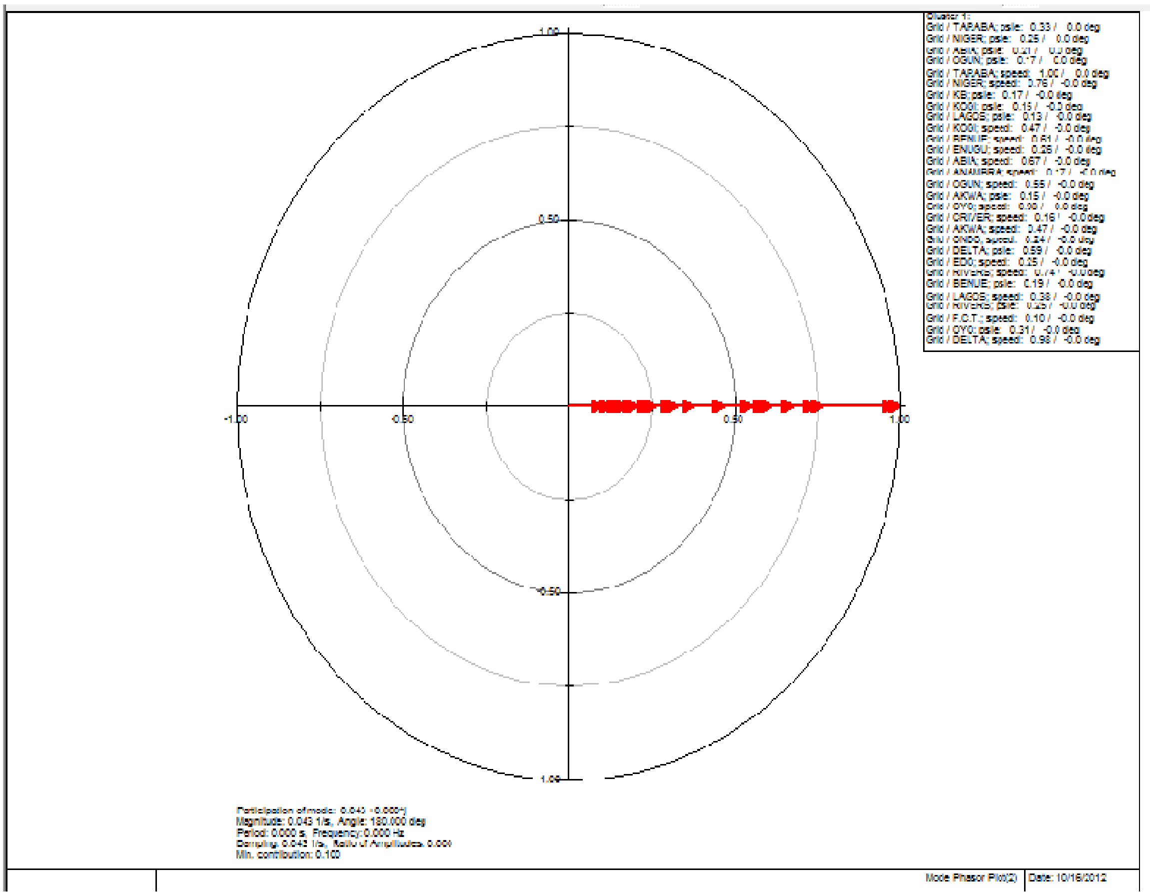

Figure 16. Mode phasor plot - participation factor.

Lastly, PowerFactory's harmonic load flow calculated actual harmonic indices related to voltage or current distortion, and harmonic losses caused by harmonic sources (usually non-linear loads such as current converters). Harmonic sources can be defined by a harmonic current or a harmonic voltage spectrum. In the harmonic load flow calculation, PowerFactory carries out a steady-state network analysis at each frequency at which harmonic sources are defined. Bauchi-wind and Edo-solar generating stations, transmission line (line 28) connecting F.C.T. and Niger; Jigawa state busbar were defined for the analysis.

Frequency sweep function was used for the calculation of network impedances. The result of this calculation facilitates the identification of series and parallel resonances in the network.

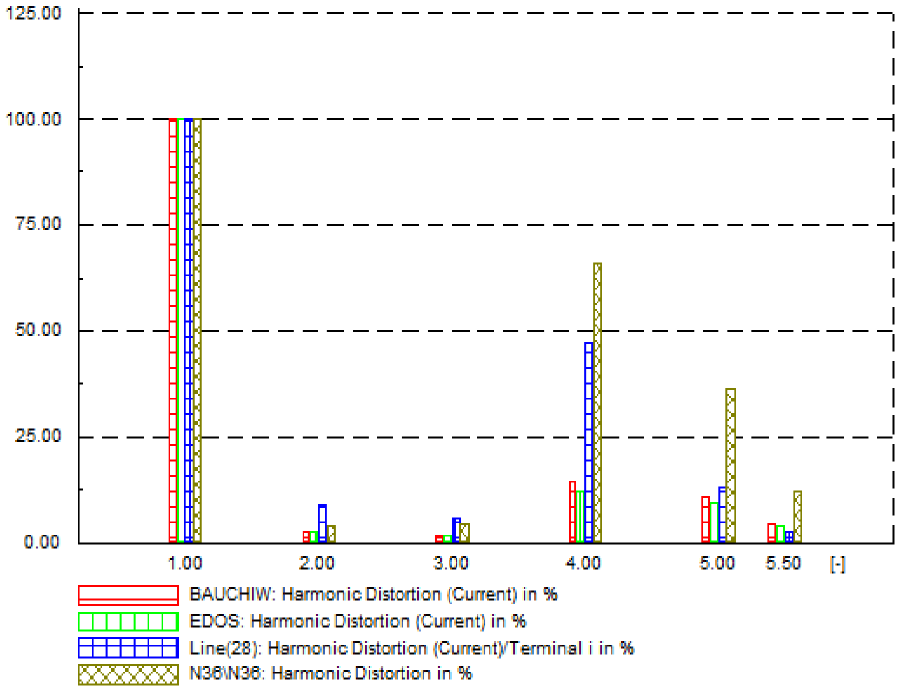

Figure 17. *Balanced network - harmonic distortion, A.*

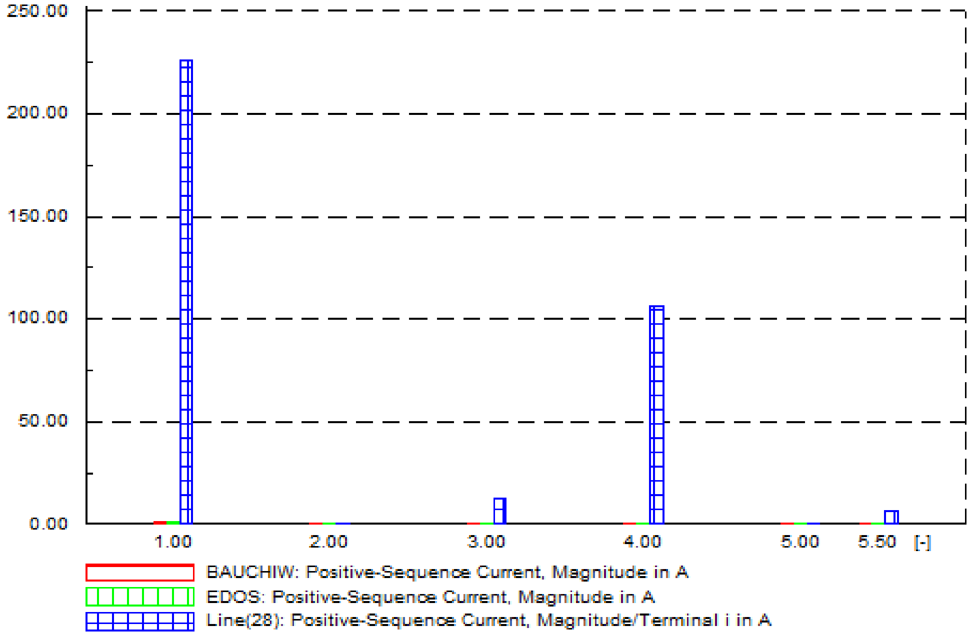

Figure 18. *Balanced network - positive-sequence current, A .*

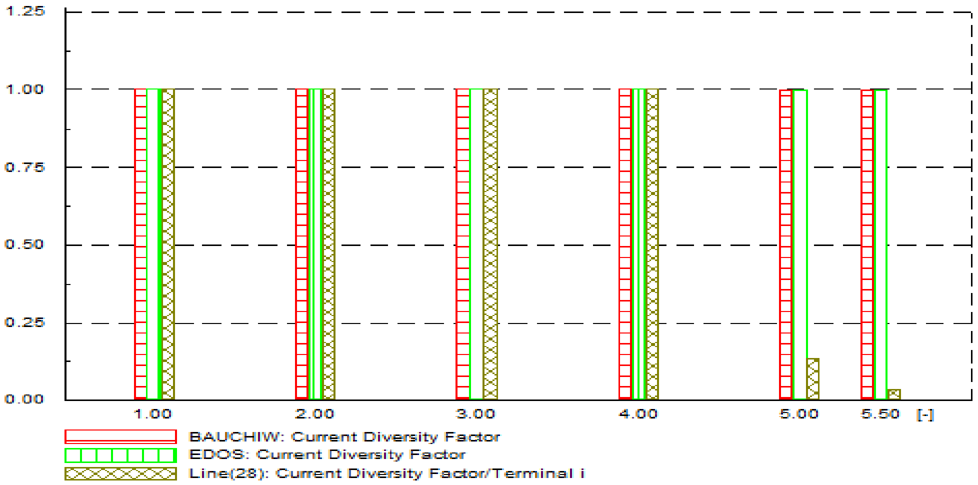

Figure 19. *Balanced network - current diversity factor.*

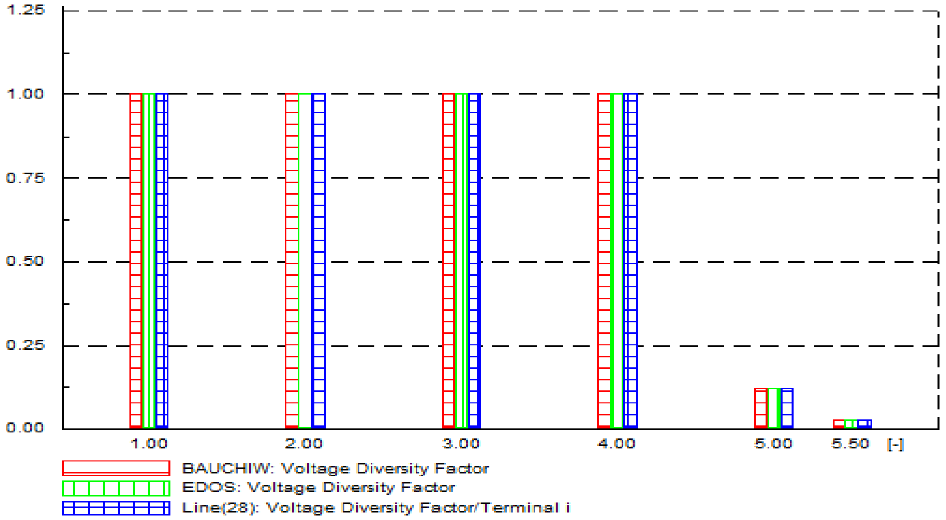

Figure 20. *Balanced network - voltage diversity factor.*

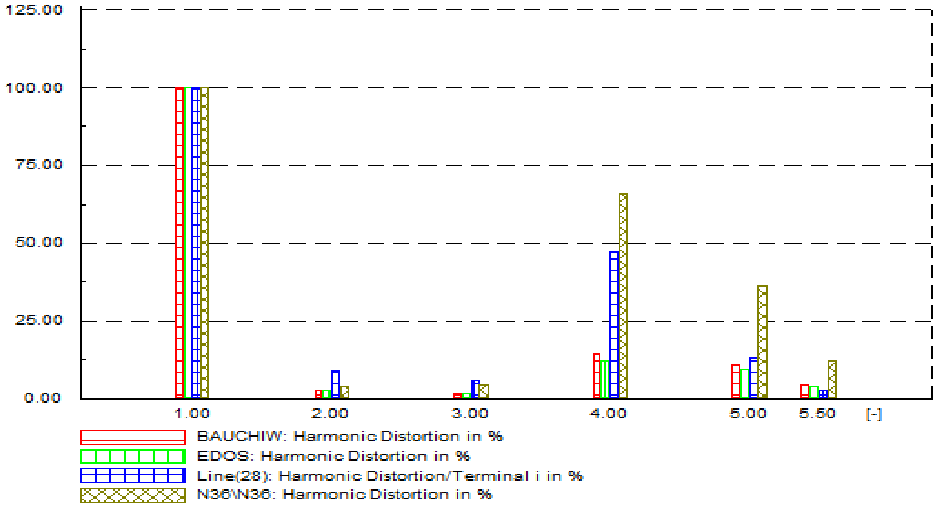

Figure 21. *Unbalanced network - harmonic distortion.*

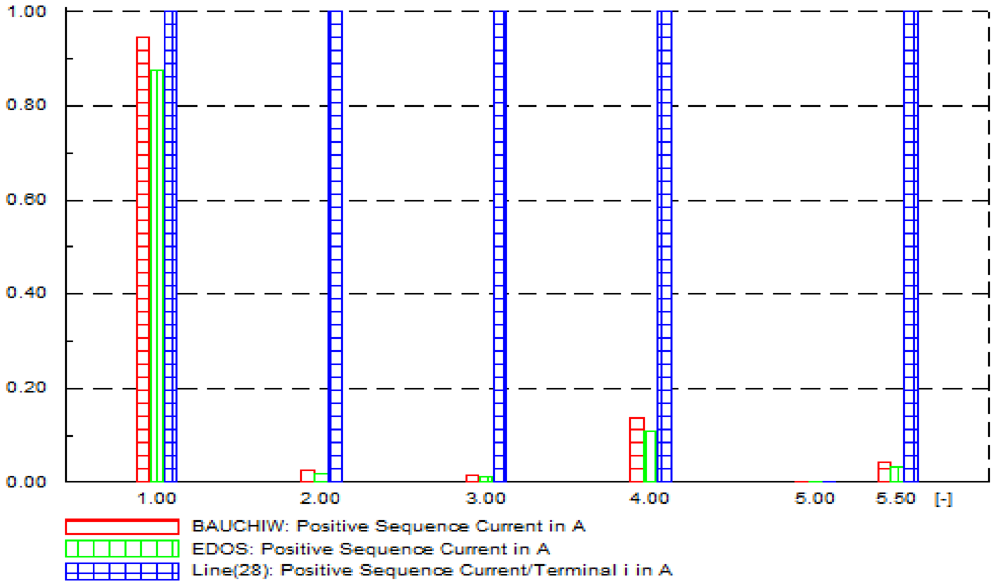

Figure 22. *Unbalanced network-positive-sequence current, A.*

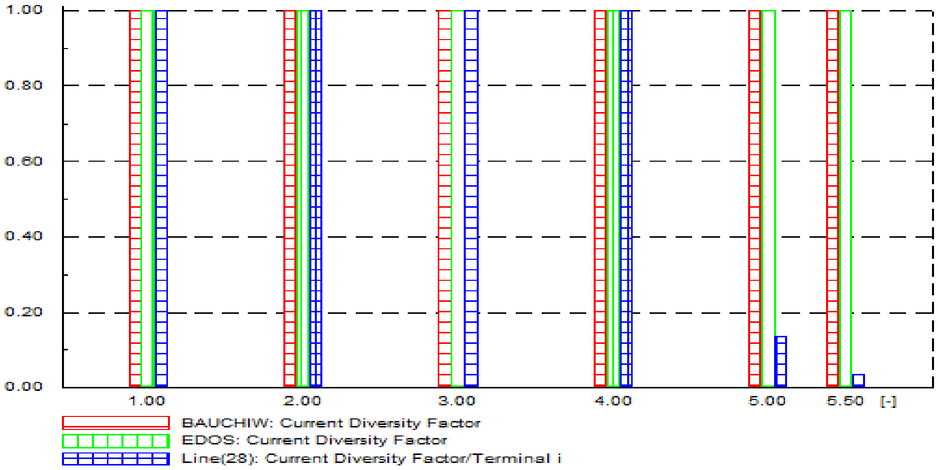

Figure 23. *Unbalanced network - current diversity factor.*

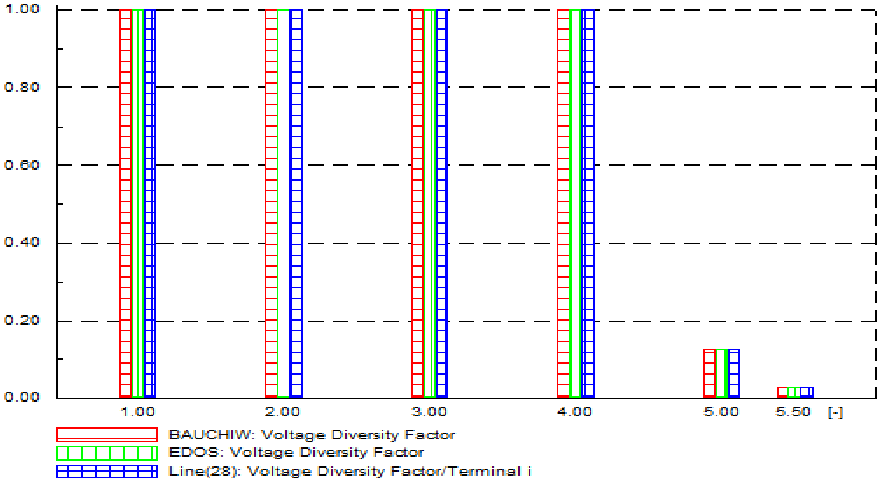

Figure 24. *Unbalanced network - voltage diversity factor.*

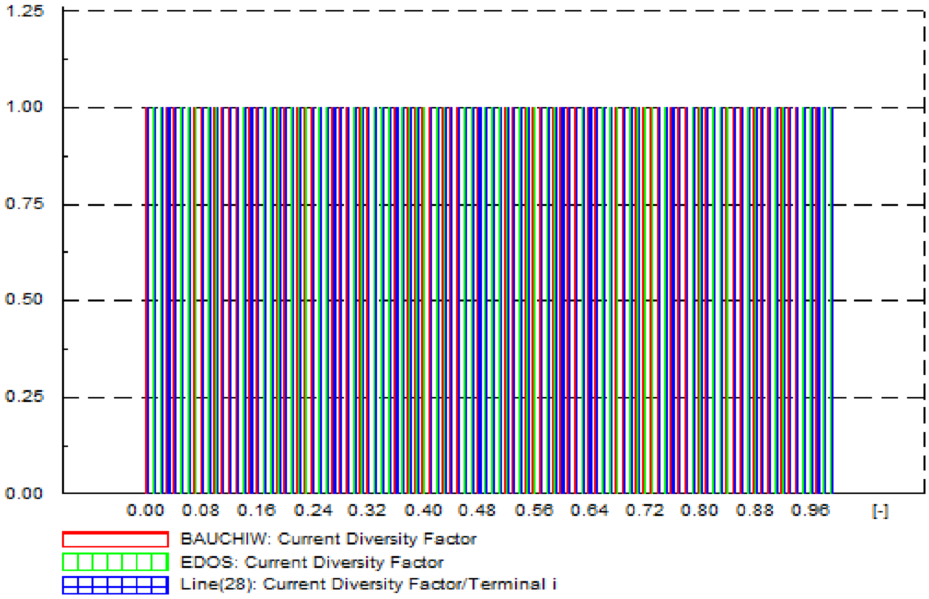

Figure 25. *Frequency sweep - current diversity factor.*

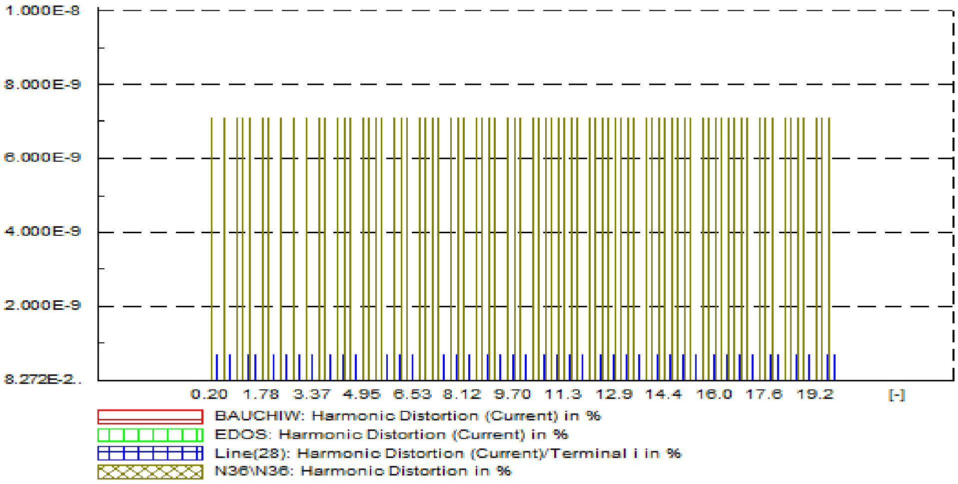

Figure 26. *Frequency sweep - harmonic distortion (current).*

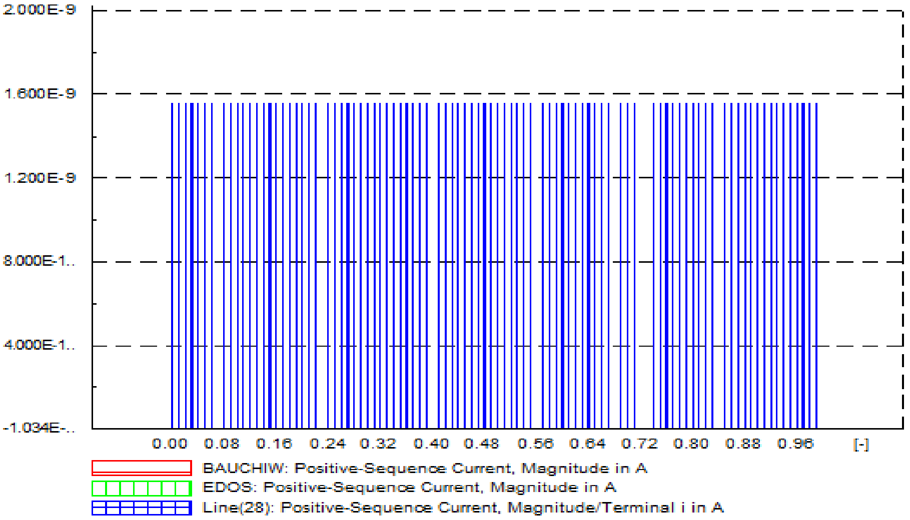

Figure 27. Frequency sweep - positive-sequence current

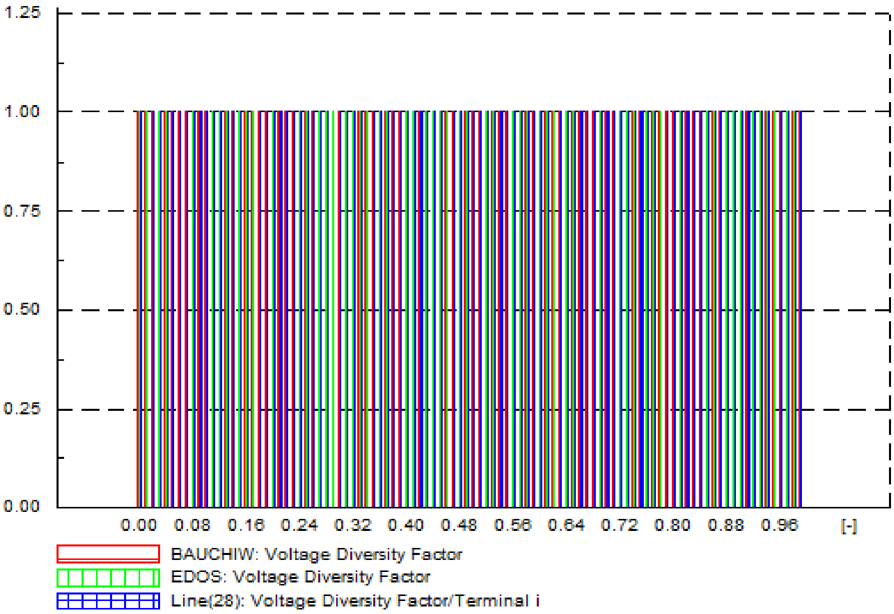

Figure 28. *Frequency sweep - voltage diversity factor*

10. Conclusion

Basic analyses were carried out in this paper (part I) and includes load flow, short-circuit calculation, transient stability, modal analysis/eigenvalues calculation and harmonics analysis. Short-circuit analysis is used in determining the expected maximum currents (for the correct sizing of components) and the minimum currents (to design the protection scheme), while transients, stability analyses important considerations during the planning, design and operation of modern power systems. One common application of harmonic analysis is providing solution to series resonance problems. These analyses have great importance in future expansion planning, in stability studies and in determining the best economical operation for the proposed network.

Nomenclature

i_p peak current;

I_b breaking current (RMS value);

i_b peak short-circuit breaking current;

$I_k^{"}$ initial symmetrical short-circuit current;

S_b peak breaking apparent power;

i_{DC} decaying d.c. component;

i_{th} thermal current;

i_{op} load current;

I_{kss} initial short-circuit current;

k factor for the calculation of i_p;

m factor for the heat effect of the d.c. component

n factor for the heat effect of the a.c. component;

$U_i; U_{n,i}$ are nominal conditions.

$\underline{\omega(t)}$ generator speed vector

λ_i ith eigenvalue

ϕ_i ith right eigenvector

c_i magnitude of excitation of the ith mode (at t=0);

n number of conjugate complex eigenvalues.

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