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Investigation of nigerian 330 kv electrical network with distributed generation penetration – part III: deterministic and probabilistic analyses

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Abstract: The concluding part of this work (Part III) presents the non-probabilistic (deterministic) assessment of failure effects under given contingencies and reliability analysis is an automation and probabilistic extension of contingency evaluation. Also, PowerFactory generation adequacy tool is design specifically for testing of system adequacy using Monte-Carlo method. Running adequacy analysis produces convergence plots, distribution plots and Monte-Carlo draw plots. PowerFactory's contingency analysis module offers two distinct contingency analysis methods: single time phase and multiple time phase contingency analysis, while an analytical assessment of the network reliability indices is initiated by the following actions (failure modeling, load modeling, system state production, failure effect analysis (FEA), statistical analysis and reporting) within PowerFactory. Lastly, voltage sag analysis is a calculation that assesses the expected frequency of voltage sags within a network.

Keywords: Deterministic, Assessment, Probabilistic, Contingencies, Generation Adequacy, Monte-Carlo Method, Reliability, Failure, Failure Effect Analysis, Statistical Analysis, Voltage Sag, Powerfactory

1. Introduction

This paper uses probabilistic and non-probabilistic assessment to solve contingency cases using PowerFactory by DIgSILENT. The assessment of reliability indices for a power system network or of parts thereof, is the assessment of the ability of that network to provide the connected customers with electric energy of sufficient availability, as one aspect of power quality. The reliability assessment module of PowerFactory offers two distinct calculation functions for the analysis of network reliability under probabilistic scenarios [1]:

• network reliability assessment: The probabilistic assessment of interruptions during an operating period of the power system;

• voltage sag assessment: the probabilistic assessment of the frequency and severity of voltage sags during an operation period.

Contingency analysis is performed to ascertain the risks that contingencies pose to an electrical power system.

PowerFactory's contingency analysis module offers two distinct contingency analysis methods: single time phase and multiple time phase contingency analysis, while generation adequacy is the ability of the power system to be able to supply system load under all possible load conditions is known as 'System Adequacy'. This relates to the ability of the generation to meet the system demand.

Contingency analysis is critical in many routine power system and market analyses to show potential problems with the system. However, contingency analysis is computationally very expensive as many different combinations of power system component failures must be analyzed. Analyzing several million such possible combinations can take inordinately long time and it is not be possible for conventional systems to predict blackouts in time to take necessary corrective actions. To address this issue, PowerFactory software provides a probabilistic contingency analysis scheme that processes severe and most probable contingencies.

The liberalization of electricity markets in countries all over the world has lead to tremendous changes for electric utilities. This evolution calls for enhanced power system planning tools. The software used in this paper can provide reliability indices at any system bus, while voltage sags caused by the short-circuit faults in transmission and distribution lines have become one of the most important power quality problems facing industrial customers and utilities. Voltage sags are normally described by characteristics of both magnitude and duration. A simple and practical method is proposed in this paper which is discussed in Section 6.

2. Methodology

The proposed Nigerian 330 kV electrical network (37-bus system shown in Figure 1) was built in PowerFactory 14.1 software and the following analyses were carried out using PowerFactory tools. 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 [1].

Data used are stated in Table 1 (Appendix), while solar farm (minimum value of 50 MW per state) was proposed for every state, having potentials to produce energy from the sun because of high solar radiation. 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) and some Northern states.

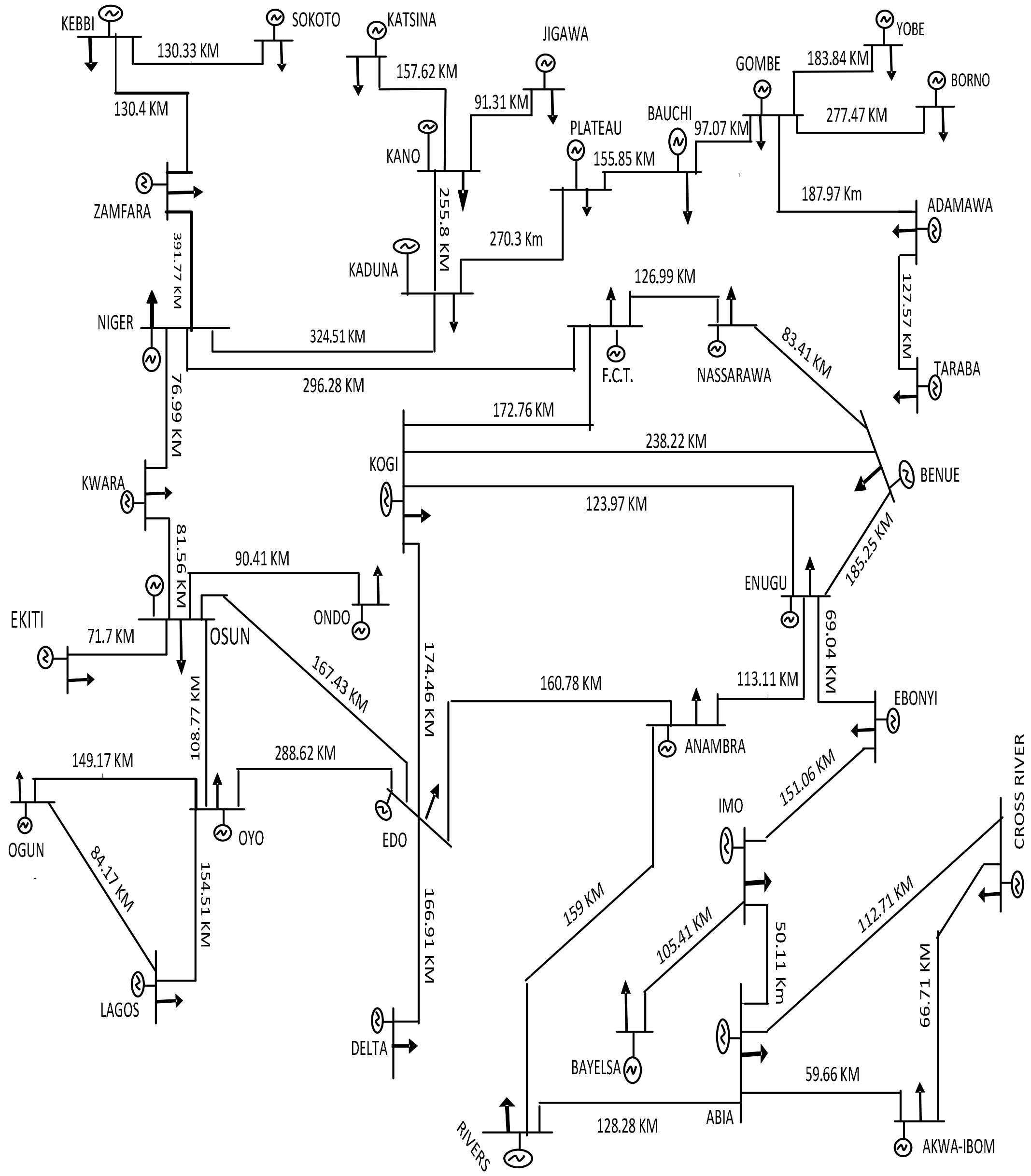


Figure 1. *Proposed Nigerian 330 kV electrical network (37-bus system).*

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**

3. Generation Adequacy

The ability of the power system to be able to supply system load under all possible load conditions is known as 'System Adequacy'. This relates to the ability of the generation to meet the system demand, while also considering typical system constraints such as:

• generation unavailability due to fault or maintenance requirements;

• variation in system load on a monthly, hourly and minute by minute basis;

• variations in renewable output (notably wind generation output), which in turn affects the available generation capacity.

PowerFactory generation adequacy tool is design specifically for testing of system adequacy. This tool is used to determine the contribution of wind and solar generations to overall system capacity and to determine the probability of 'Loss of Load' (LOLP) and the 'Expected Demand Not Supplied' (EDNS) [1, 2-4].

The analytical assessment of generation adequacy requires that each generator in the system is assigned a number of 'probabilistic states' which determine the likelihood of a generator operating at various output levels.

Likewise, each of the system loads is assigned a time-based characteristic that determine the actual system load level for any point of time. However, as the number of generators, generator states, loads and load states increase, the degrees of freedom for the analysis rapidly expands so that it becomes impossible to solve in a reasonable amount of time. Such a problem is ideally suited to Monte Carlo simulation [5]. Monte Carlo methods are a class of computational algorithms that rely on repeated random sampling to compute their results. Monte Carlo methods are often used in computer simulations of physical and mathematical systems.

These methods are most suited to calculation by a computer and tend to be used when it is infeasible to compute an exact result with a deterministic algorithm. In the Monte Carlo method, a sampling simulation is performed. Using uniform random number sequences, a random system sate is generated. This system state consists random generating operating states and of random time points. The generating operating states will have a corresponding generation power output, whereas the time points will have a corresponding generation power output, whereas the time the time points will have a corresponding power demand [5].

The value of demand not supplied (DNS) is then calculated for such state for such state. This process is done for a specific number of draws (iterations). At the end of the simulation, the values of the loss of load probability (LOLP), loss of load expectancy (LOLE), expected demand not supplied (EDNS), and loss of energy expectancy (LOEE) indices are calculated as average values from all the iterations performed.

There are several database objects in PowerFactory specifically related to the generation adequacy analysis such as:

• stochastic model for generation object (StoGen);

• power curve type (TypPowercurve); and

• Meteorological station.

Stochastic model for generation object was used for this work. Generation object (StoGen) was used for defining the availability states of a generator. An unlimited number of states is possible with each state divided into:

• availability of generation (in %);

• probability of occurrence (in %).

This means that for each state, the total available generation capacity in % of maximum output must be specified along with the probability that this probability that this availability occurs. The probability column is automatically constrained, so that the sum of the probability of all states must equal 100%.

The generator maximum output is calculated as:

$$S_{nom} \cos \theta .$$

where S_{nom} is the nominal apparent power and $\cos\theta$ is the nominal power factor [2].

4. Contingencies Analysis

Contingency analysis is performed to ascertain the risks that contingencies pose to an electrical power system. PowerFactory's contingency analysis module offers two distinct contingency analysis methods:

• single time phase contingency analysis: the non-probabilistic (deterministic) assessment of failure effects under given contingencies, within a single time period.

• multiple time phase contingency analysis: the non-probabilistic (deterministic) assessment of failure effects under given contingencies, performed over different time periods, each of which defines a time elapsed after the contingency occurred. It allows the definition of user defined post-fault actions.

Contingency analyses can be used to determine power transfer margins or for detecting the risk inherent in changed loading conditions [1, 6-8].

5. Reliability Assessment

Reliability analysis is an automation and probabilistic extension of contingency evaluation. The planner is not required to pre-define outage events, but can optionally select that all possible outages to be considered for analysis. The relevance of each outage is considered using statistical data about the expected frequency and duration of outages according to component type. The effect of each outage is analyzed in an automated way, meaning that the software simulates the protection system and the network operator's actions to re-supply interrupted customers. As statistical data regarding the frequency of each event is available, the results can be formulated in probabilistic terms. An analytical assessment of the network reliability indices (transmission, sub-transmission or distribution level) is initiated by the following actions within PowerFactory:

- failure modeling;
- load modeling;
- system state production;
- failure effect analysis (FEA);
- statistical analysis; and
- reporting.

The system state production module uses the failure models and load models to build a list of relevant system states. Each of these system states may have one or more faults. It is the task of the FEA module to analyze the faulted system states by imitating the system reactions to these faults, given the current load demands. The FEA will normally take the power system through a number of operational states which may include:

- fault clearance by tripping protection breakers;
- fault separation by opening separating switches;
- power restoration by closing normally open switches;
- overload alleviation by load transfer and load shedding.

The basic task of the FEA functions is to find out whether system faults will lead to load interruptions and if so, which loads will be interrupted and for how long. The results of the FEA are combined with the data that is provided by the system state production module to update the statistics. The system state data describes the expected frequency of occurrence of the system state and its expected duration. The duration of these system states should not be confused with the interruption duration. A system state with a single line on outage (that is, due to a short- circuit on that line), will normally have a duration equal to the time needed to repair that line. In the case of a double feeder, however, no loads may suffer any interruption. In the case that loads are interrupted by the outage, the power may be restored by network reconfiguration (that is, by fault separation and closing a back-stop switch). The interruption duration will then equal the restoration time, and not the repair duration (=system state duration).

A stochastic model describes how and how often a certain object changes. A line, for example, may suffer an outage due to a short-circuit. After this kind of outage, repair will begin and the line will be put into service again following successful repair. If two states for line ‘A’ are defined (that is, "in service" and "in repair"). The repair durations are also called the "Time To Repair" (TTR). The service durations are called the "life-time" or "Time To Failure" (TTF). Both the TTR and the TTF are stochastic quantities. By gathering failure data about a large group of similar components in the power system, statistical information about the TTR and TTF, such as the mean value and the standard deviation, can be calculated. The statistical information is then used to define a stochastic model. There are many ways in which to define a stochastic model. The so-called "homogenous Markov-model" is a highly simplified but generally used model. A homogenous Markov model with two states is defined by:

a constant failure rate lambda (λ); and

a constant repair rate mu (μ).

These two parameters can be used to calculate the following quantities:

- mean time to failure, $TTF = 1/\lambda$;
- mean time to repair, $TTR = 1/\mu$; (1.0)
- availability, $P = TTF/(TTF + TTR)$;
- unavailability $Q = 1 - P = TTR/(TTF + TTR)$.

The availability gives the fraction of time during which the component is in service; the unavailability gives the fraction of time during which it is in repair; and $P + Q = 1.0$.

These equations also introduce some of the units used in the reliability assessment:

frequencies are normally expressed in [1/a] = "per annum";

- lifetimes are normally expressed in [a] = "annum";
- repair times are normally expressed in [h] = “hours”;
- probabilities or expectancies are expressed as a fraction or as time per year ([h/a],[min/a]) [1, 9-12].

6. Voltage Sag Analysis

Voltage sag analysis is a calculation that assesses the expected frequency of voltage sags within a network. The PowerFactory voltage sag tool calculates a short-circuit at the selected load points within the system and uses the failure data of the system components to determine the voltage sag probabilities. Voltage sag analysis has a lot in common with probabilistic reliability analysis. Both use fault statistics to describe the frequency of faults and then use these statistics to weight the results of each event and to calculate the overall effects of failures.

Reliability analysis looks for sustained interruptions as one aspect of quality of supply, whereas voltage sag analysis calculates the voltage drop during the fault until the protection system has disconnected the defective component. The voltage sag analysis simulates various faults at all relevant busbars. It starts with the selected load points, and proceeds to neighboring busbars until the remaining voltage at all load points does not drop below the defined Exposed area limit. The remaining voltages and the short-circuit impedances for all load points are written to the result file specified by the Results parameter. After all relevant busbars have been analyzed, the sag table assessment continues by analyzing short-circuits at the midpoint of all lines and cables that are connected between the relevant busbars. Again, the remaining voltages and short-circuit impedances for all load points are written to the result file.

After the complete exposed area has been analyzed in this way, the result file contains the values for the two ends of all relevant lines and cables and at their midpoints. The written impedances are interpolated between the ends of a line and the middle with a two-order polynomial. From them, and from the written remaining voltages, the various source impedances are estimated. These estimated impedances are also interpolated between the ends and the midpoint. The interpolated impedances are then used to estimate the remaining voltages between the ends and the midpoints of the lines or cables. This quadratic interpolation gives very good results also for longer lines, and also for long parallel or even triple parallel lines. The main advantage is a substantial reduction in computation and an increase in the overall calculation speed [1, 13-17].

7. Results and Discussion

For voltage sag, busbars at Ekiti, Kano, Cross River, Enugu, Jigawa and Delta were first defined in the network and then the voltage sag table assessment tool was used to carry out the analysis. Single-phase to ground fault (phase-b) was considered using complete short circuit method. The break time is 0.1 seconds and the fault clearing time of 0.4 seconds. The results are shown Figures 2-5. The voltage sag plot shows the annual frequency of occurrence on the y-axis.

Figure 2 shows minimum line-to-ground voltage with x-variable which is short-circuit type. The burbars could be seen to suffer deep sag, while Figure 3 displays minimum line-line voltages with x-variable of fault clearing time. Plots in Figures 4 and 5 show the voltage sag of minimum line-line and line-ground voltages; and positive-sequence voltage.

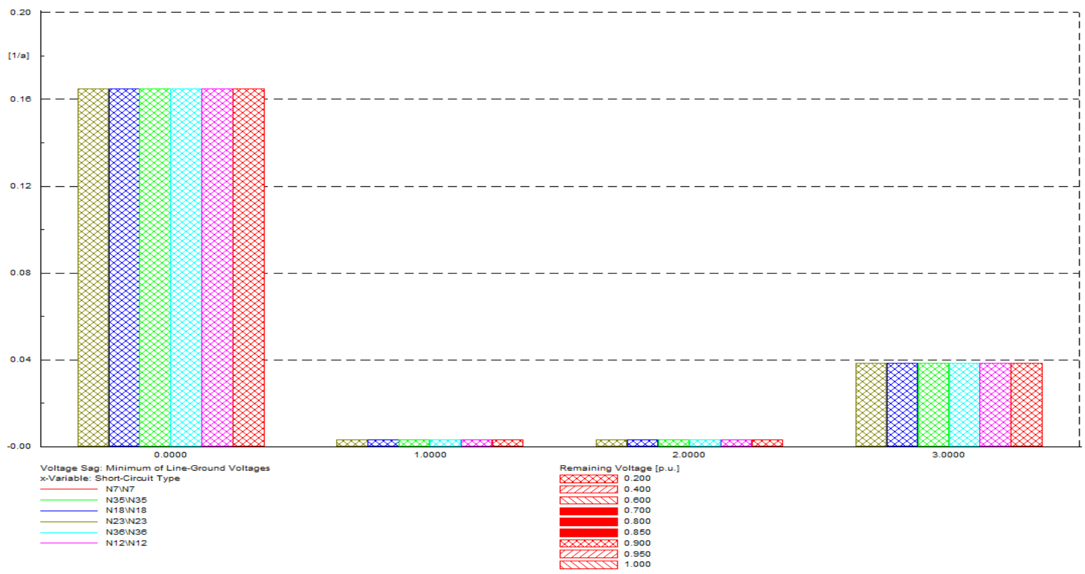


Figure 2. *Voltage sag of minimum line-ground voltages.*

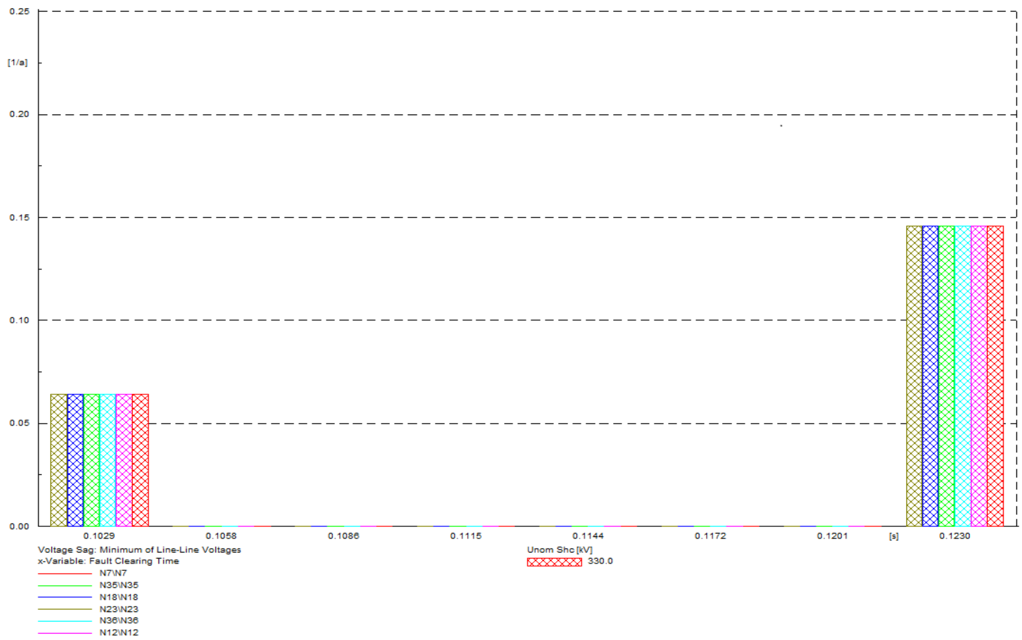


Figure 3. *Voltage sag of minimum line-line voltage.*

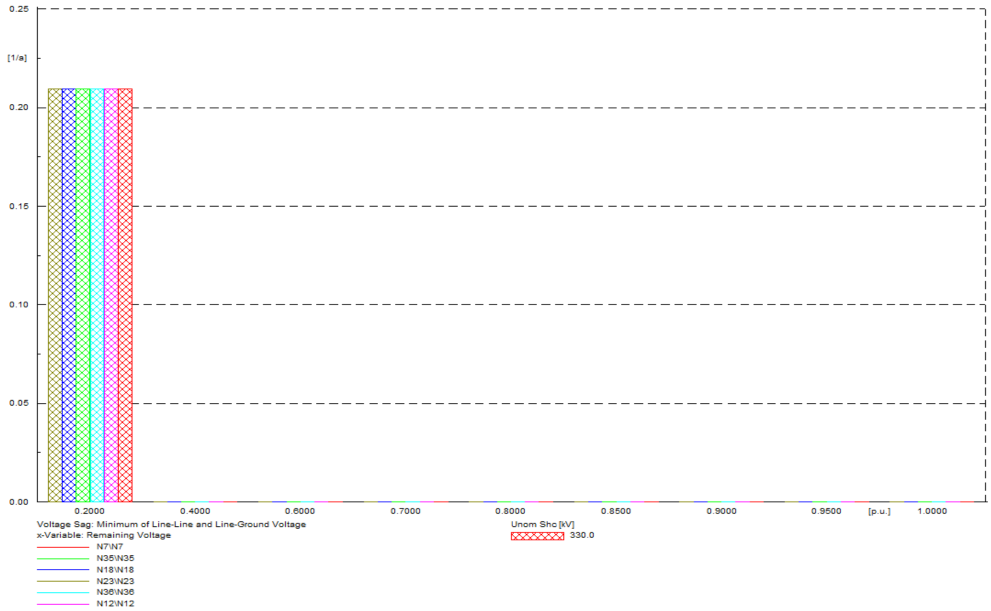


Figure 4. *Voltage sag of minimum line-line and line-ground voltages.*

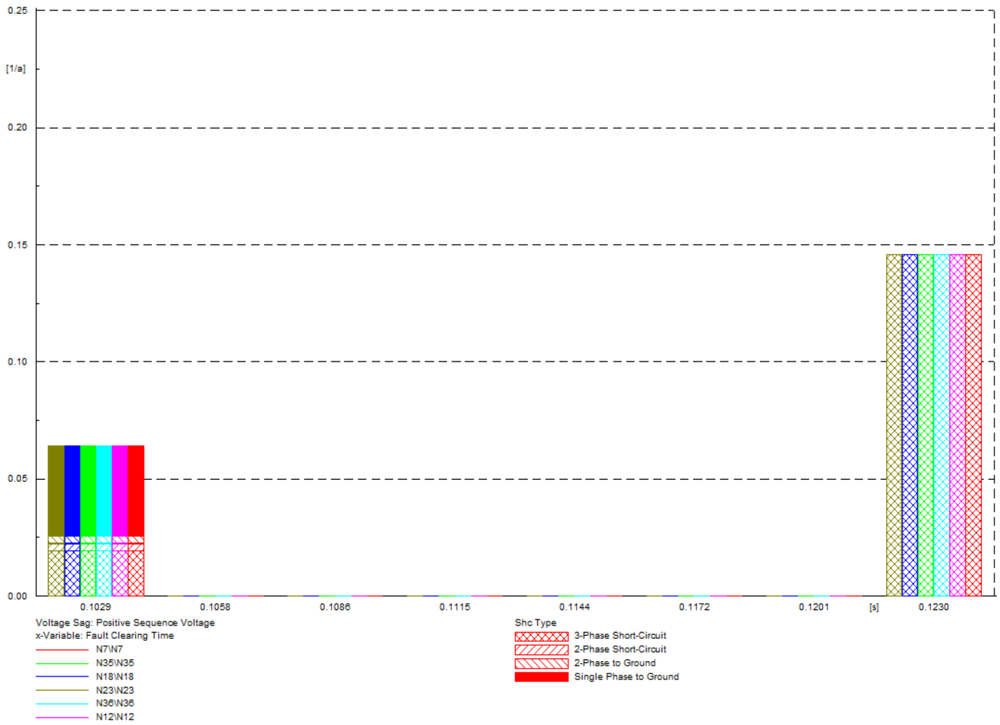


Figure 5. *Voltage sag of positive-sequence voltage.*

Furthermore, the simulation was first initialized before a generation adequacy analysis. The load flow command used was set to AC load-flow balanced, positive sequence. For fixed demand level selection (where all load characteristics were ignored and the total demand was calculated at the initial iteration and used for subsequent iterations), maintenance plans were considered on line 28 which connected Niger to F.C.T. The system losses were set to 3%. The period considered for generation adequacy was 2010. This variable does not influence the wind speed or wind power data of the wind model for the generator references time series data. Running adequacy analysis produces convergence plots, distribution plots and Monte-Carlo draw plots as shown in Figures 6 – 15.

Convergence plots (Fig. 6 and 7) show loss of load probability and expected demand not supplied. These two plots converge towards the final value as the number of iterations increases. The distribution plots are (Fig. 8-11) essentially the data from ‘Draws’ plot sorted in descending order, the data then becomes a cumulative probability distribution. The loss of load probability index was obtained by inspection directly from the plots.

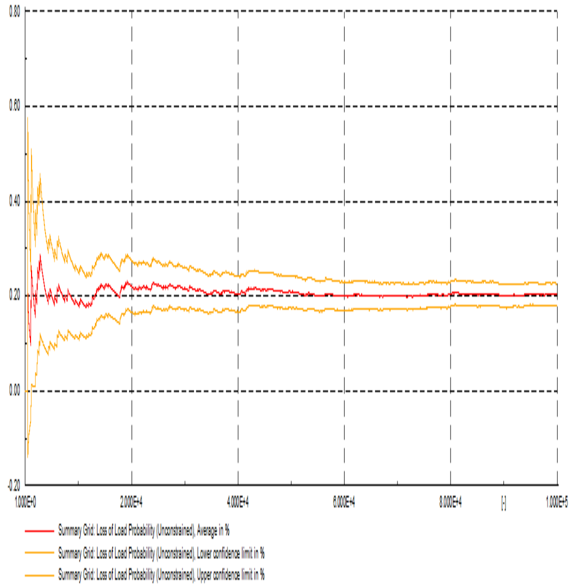


Figure 6. *Convergence plot of fixed demand for loss of probability.*

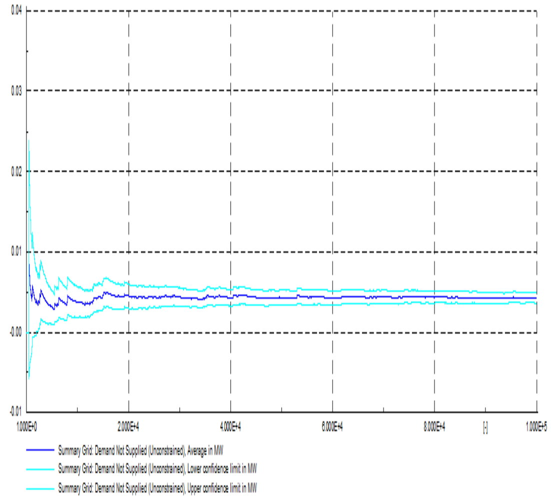


Figure 7. *Convergence plot of fixed demand for demand not supplied.*

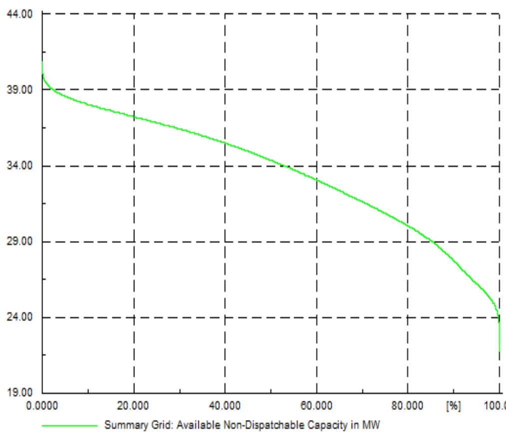


Figure 8. *Distribution plot of fixed demand for available non-dispatchable capacity (MW).*

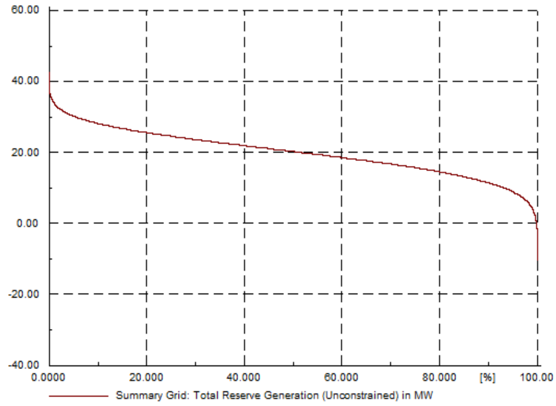


Figure 9. *Distribution plot of fixed demand for total reserve generation (MW).*

For time characteristics, any time characteristics assigned to loads was automatically considered in the calculation, therefore, the total demand varied at each iteration. In Fig. 10, LOLP index can be obtained by inspection – read from the intersection of total demand and available disputable capacity, while in Fig. 11, the intersection of residual demand with x-axis gives the LOLP index.

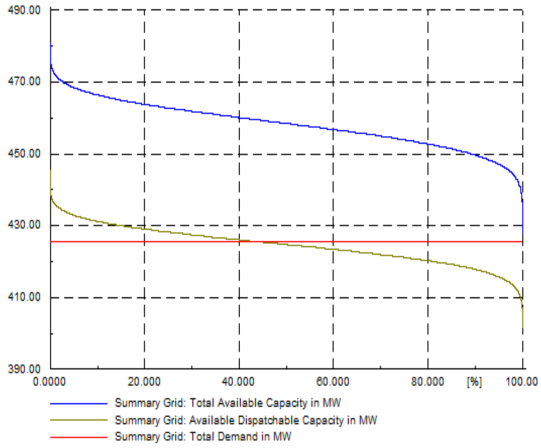


Figure 10. *Distribution plot of fixed demand for available dispatchable capacity/total demand (MW).*

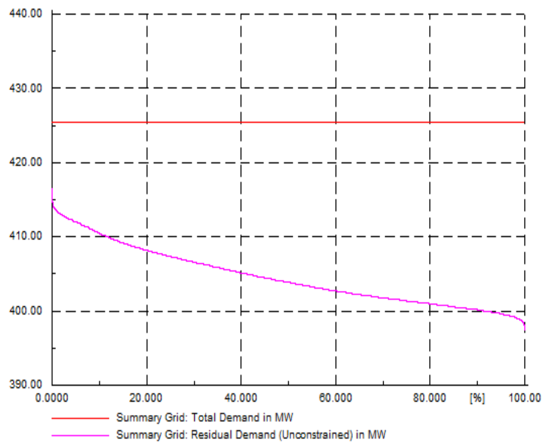


Figure 11. *Distribution plot of fixed demand for total demand/residual demand (MW).*

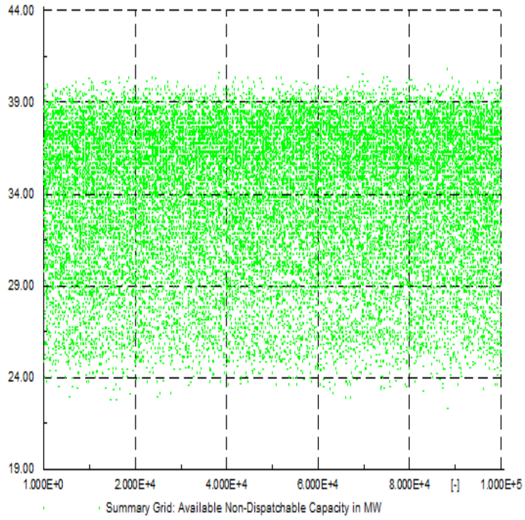


Figure 12. *Monte-Carlo draw plots of fixed demand for: available dispatchable capacity (MW).*

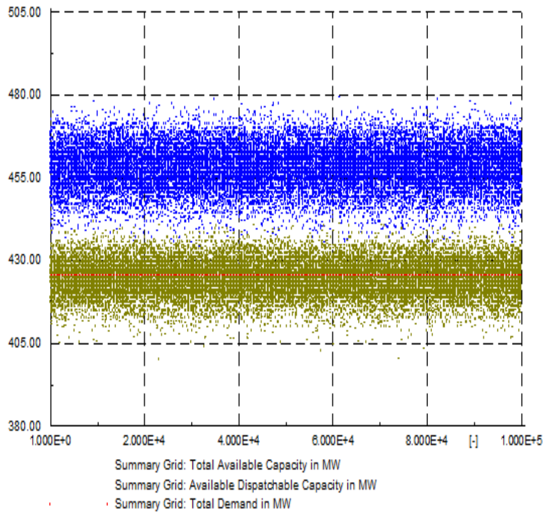


Figure 13. *Monte-Carlo draw plots of fixed demand for total demand/ available dispatchable capacity (MW)/total available capacity.*

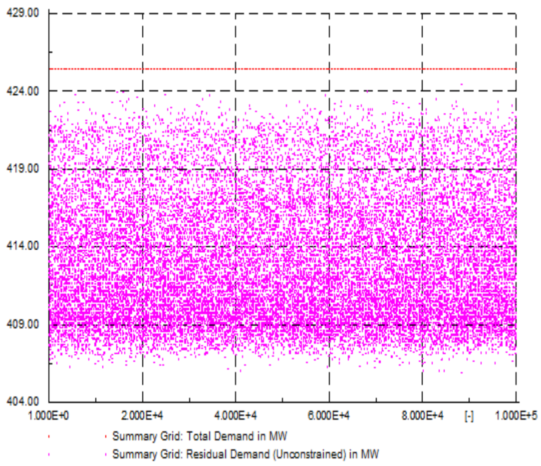


Figure 14. *Monte-Carlo draw plots total demand/residual demand (MW).*

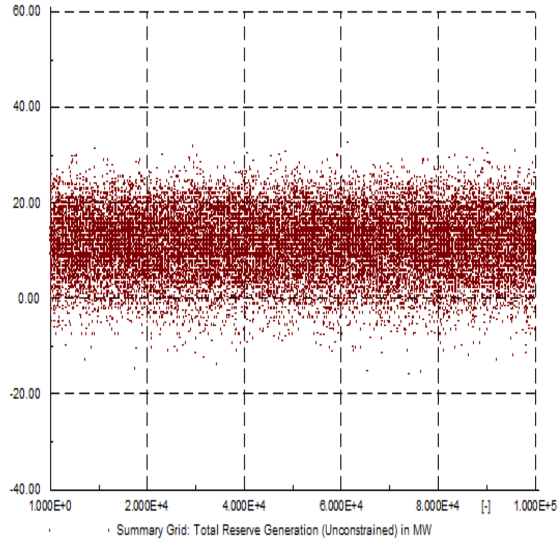


Figure 15. *Monte-Carlo draw plots total reserved generation (MW).*

For reliability assessment, failure models were made for the following PowerFactory objects:

• busbars and

• lines – the objects defined for stochastic failure and repairs model are: line 28 line 42 line 43 and double earth faults defined on: lines 28 and 29. Also, outages and maintenance period each assigned to the following lines: line 1, 2, 28 and 35 as shown in figure 16.0;

• synchronous generators – receive active and reactive powers limits;

• loads – the following loads are defined for shedding: while numbers of Customers were entered into all loads and creating load states for each load.

All failure models define how often a component will suffer an active failure. All active failures must be cleared by protection. When a failure cannot be separated from all generators or external networks by protection, a warning message will be issued. Repair of the faulted component is assumed to start directly after the fault has been cleared. The repair duration (which is also defined in the failure models) is the time needed to restore the functionality of the component. The time needed to begin the repair (that is, if spare parts need to be ordered first) and all other delays are therefore to be included in the total repair time.

There are two methods used for this analysis: connectivity analysis (without considering constraints) and load flow analysis (considers constraints by completing load-flows for each contingency). The calculation period for the year 2010 (specified). The results are shown in Tables 2-5.

Lastly contingency analysis was carried out which include single- and multiple-time phases. In the former, A.C. load flow calculation was used to calculate the power flow and voltages per contingencies cases. Bauchi wind farm (BauchiW), Benue conventional station (Benue), Edo solar farm (EdoS), transmission line linking Niger and F.C.T. generating stations (line 28) were defined as contingency cases for the single-time phase over a time sweep as shown in Figure 17. The time sweep must be enabled to define a post contingency time. This value defines the time phase under consideration for the update of contingencies. This means that all switch-open events with an event time less than or equal to this are considered in the update. The contingency load flow is calculated at the post contingency time. The buses reports are the same for the two methods.

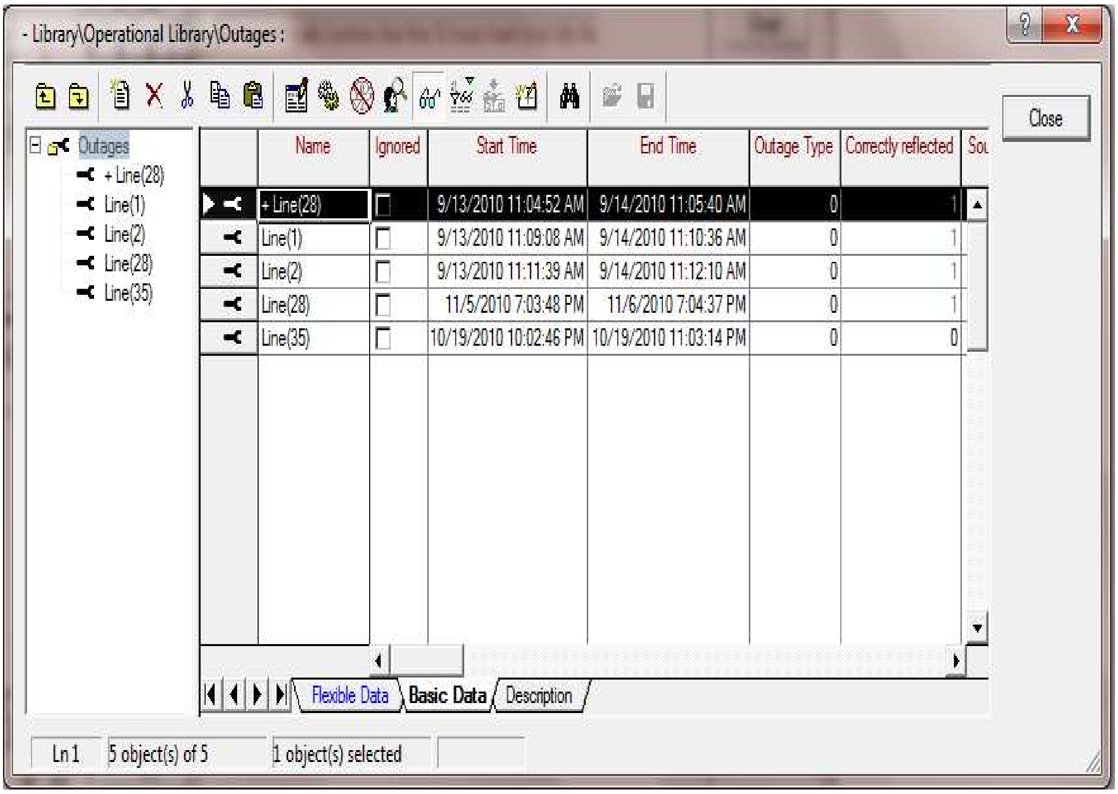


Figure 16. *Command dialogue for outages.*

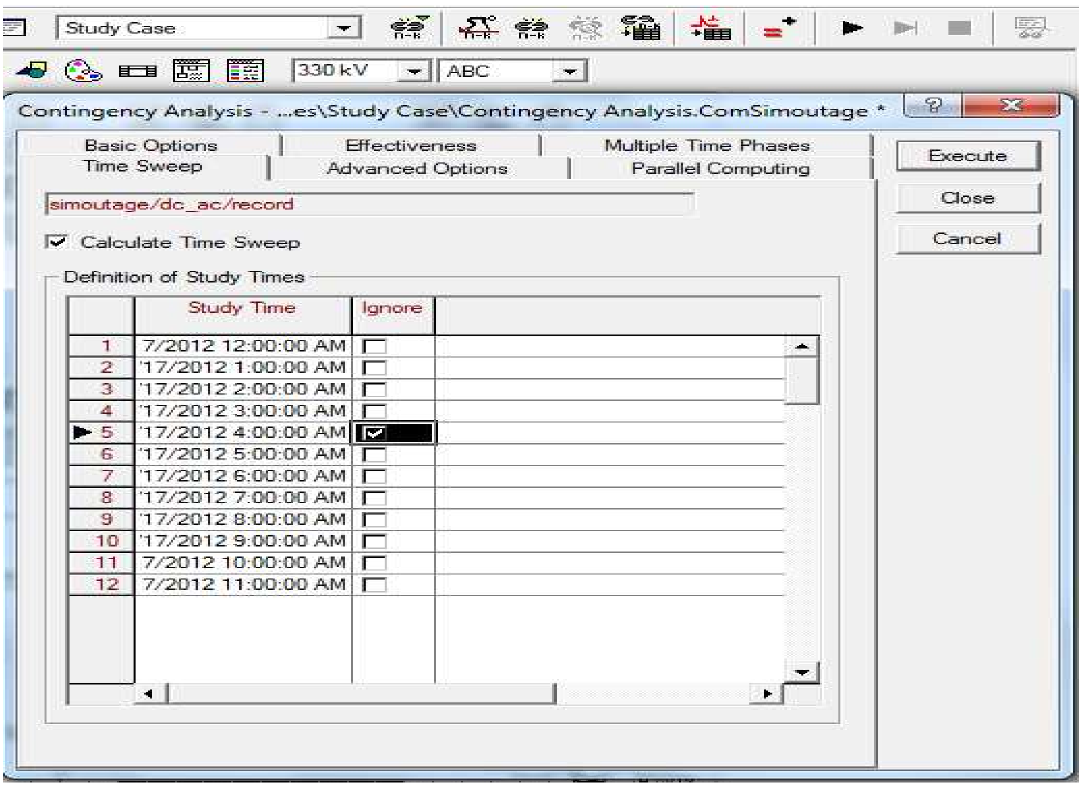


Figure 17. *Contingency analysis command dialogue showing time sweep.*

In multiple-time phase contingency analysis, contingency analysis for multiple time phases was performed, allowing the definition of post-fault actions. Line 2 (Sokoto – Kebbi), line 1 (Katsina – Kano), line 10 (Osun – Ondo), line 12 (Ogun – Oyo), line 16 (Delta – Edo), line 19 (Bauchi – Gombe), line 2 (Kano – Jigawa), line 21 (Gombe – Borno), line 3 (Zamfara – Kebbi), line 31 (F.C.T. – Niger), line 32 (Akwa – Cross River), line 39 (Imo – Ebonyi), N2 (Zamfara), N16 (Bayelsa), L22 (Ebonyi load) and L30 (Yobe load) were defined as contingency cases.

Table 2. *Single-point-in-time period analysis (connectivity method).*

Fault Clearance Breakers use all circuit breakers	
Time to open remote controlled switches	1.00 minutes
Consider Maintenance	Yes
Protection/switching failures	Yes
Double earth faults	Yes
Independent second failures	Yes
SAIFI	0.034831 1/Ca
CAIFI	0.041377 1/Ca
SAIDI	0.348 h/Ca
CAIDI	10.002 h
ASAI	0.999960231
ASUI	3.97693E-05
ENS	149.400 MWh/a
AENS	0.011 MWh/Ca
ACCI	0.033 MWh/Ca
EIC	4.264 M$/a
IEAR	28.538 $/kWh
SES	0.000 MWh/a
ASIFI	0.035112 1/a
ASIDI	0.351190 h/a
MAIFI	0.000000 1/Ca

Table 3. *Complete year period analysis – (connectivity method).*

Fault Clearance Breakers Use all circuit breakers			
Switching procedures Sequential			
Calculation time period	2010		
Consider Maintenance	Yes		
Independent second failure	Yes		
Double earth faults	Yes		
Protection/switching failure	Yes		
Buses name	AIT (h/a)	AIF (1/a)	AID (h)
SingleBusbar(25) /N36	0.96	0.1	10
SingleBusbar(24) /N37	0.69	0.07	10
SingleBusbar(26) /N35	0.69	0.07	10
SingleBusbar(9) /N23	0.69	0.07	10
SingleBusbar(22) /N18	0.64	0.06	10
SingleBusbar(5) /N7	0.54	0.05	10
SingleBusbar /N2	0.32	0.03	10
SingleBusbar(1) /N4	0.32	0.03	10
SingleBusbar(10) /N22	0.32	0.03	10
SingleBusbar(11) /N12	0.32	0.03	10
SingleBusbar(12) /N16	0.32	0.03	10
SingleBusbar(13) /N1	0.32	0.03	10
SingleBusbar(14) /N9	0.32	0.03	10
SingleBusbar(15) /N10	0.32	0.03	10
SingleBusbar(16) /N11	0.32	0.03	10
SingleBusbar(17) /N14	0.32	0.03	10
SingleBusbar(2) /N3	0.32	0.03	10
SingleBusbar(20) /N19	0.32	0.03	10
SingleBusbar(21) /N20	0.32	0.03	10
SingleBusbar(23) /N15	0.32	0.03	10
SingleBusbar(28) /N21	0.32	0.03	10
SingleBusbar(29) /N17	0.32	0.03	10
SingleBusbar(3) /N5	0.32	0.03	10
SingleBusbar(34) /N26	0.32	0.03	10

Fault Clearance Breakers Use all circuit breakers			
SingleBusbar(35) /N34	0.32	0.03	10
SingleBusbar(36) /N25	0.32	0.03	10
SingleBusbar(4) /N6	0.32	0.03	10
SingleBusbar(6) /N8	0.32	0.03	10
SingleBusbar(7) /N13	0.32	0.03	10
SingleBusbar(8) /N24	0.32	0.03	10
SingleBusbar(18) /N30	0.32	0.03	10
SingleBusbar(19) /N28	0.32	0.03	10
SingleBusbar(27) /N27	0.32	0.03	10
SingleBusbar(30) /N31	0.32	0.03	10
SingleBusbar(31) /N29	0.32	0.03	10
SingleBusbar(32) /N33	0.32	0.03	10
SingleBusbar(33) /N32	0.32	0.03	10

Table 4. *Single-point-in-time period analysis - (load-flow method).*

Fault Clearance Breakers Use all circuit breakers	
Time to open remote controlled switches	1.00 minutes
Consider Maintenance	Yes
Protection/switching failures	Yes
Double earth faults	Yes
Independent second failures	Yes
SAIFI	0.362857 1/Ca
CAIFI	0.362857 1/Ca
SAIDI	3.603 h/Ca
CAIDI	9.931 h
ASAI	0.999588657
ASUI	0.000411343
ENS	1653.312 MWh/a
AENS	0.118 MWh/Ca
ACCI	0.000 MWh/Ca
EIC	4.264 M$/a
IEAR	26.229 $/kWh
SES	206.746 MWh/a
ASIFI	0.391121 1/a
ASIDI	3.886384 h/a
MAIFI	0.004643 1/Ca

Table 5. *Complete year period analysis – (load-flow method).*

Fault Clearance Breakers Use all circuit breakers			
Switching procedures Sequential			
Calculation time period	2010		
Consider Maintenance	Yes		
Independent second failure	Yes		
Double earth faults	Yes		
Protection/switching failure	Yes		
Buses name	AIT (h/a)	AIF (1/a)	AID (h)
SingleBusbar(25) /N36	0.96	0.1	10
SingleBusbar(24) /N37	0.69	0.07	10
SingleBusbar(26) /N35	0.69	0.07	10
SingleBusbar(9) /N23	0.69	0.07	10
SingleBusbar(22) /N18	0.64	0.06	10
SingleBusbar(5) /N7	0.54	0.05	10
SingleBusbar /N2	0.32	0.03	10
SingleBusbar(1) /N4	0.32	0.03	10
SingleBusbar(10) /N22	0.32	0.03	10
SingleBusbar(11) /N12	0.32	0.03	10
SingleBusbar(12) /N16	0.32	0.03	10
SingleBusbar(13) /N1	0.32	0.03	10
SingleBusbar(14) /N9	0.32	0.03	10
SingleBusbar(15) /N10	0.32	0.03	10
SingleBusbar(16) /N11	0.32	0.03	10
SingleBusbar(17) /N14	0.32	0.03	10
SingleBusbar(2) /N3	0.32	0.03	10
SingleBusbar(20) /N19	0.32	0.03	10
SingleBusbar(21) /N20	0.32	0.03	10
SingleBusbar(23) /N15	0.32	0.03	10
SingleBusbar(28) /N21	0.32	0.03	10
SingleBusbar(29) /N17	0.32	0.03	10
SingleBusbar(3) /N5	0.32	0.03	10
SingleBusbar(34) /N26	0.32	0.03	10
SingleBusbar(35) /N34	0.32	0.03	10
SingleBusbar(36) /N25	0.32	0.03	10
SingleBusbar(4) /N6	0.32	0.03	10
SingleBusbar(6) /N8	0.32	0.03	10
SingleBusbar(7) /N13	0.32	0.03	10
SingleBusbar(8) /N24	0.32	0.03	10
SingleBusbar(18) /N30	0.32	0.03	10
SingleBusbar(19) /N28	0.32	0.03	10
SingleBusbar(27) /N27	0.32	0.03	10
SingleBusbar(30) /N31	0.32	0.03	10
SingleBusbar(31) /N29	0.32	0.03	10
SingleBusbar(32) /N33	0.32	0.03	10
SingleBusbar(33) /N32	0.32	0.03	10

The time phases of a contingency analysis are defined in the calculation settings section of the Basic Data tab of the contingency analysis command dialogue, by specifying a ‘post contingency time’ for each defined time phase. A specified post contingency time defines the end of a time phase and is used to determine which events (actions) from the analyzed contingency are considered. If the time of occurrence of an event from a contingency occurs earlier than or equal to the post contingency time, the event will be considered in the corresponding load flow calculation.

Figure 18 shows the stated study case, while Figures 19 and 20 show minimum voltage violations and maximum voltage violations ASCII report respectively. Figures 21 and 22 ASCII report depicts minimum voltages and voltage steps respectively.

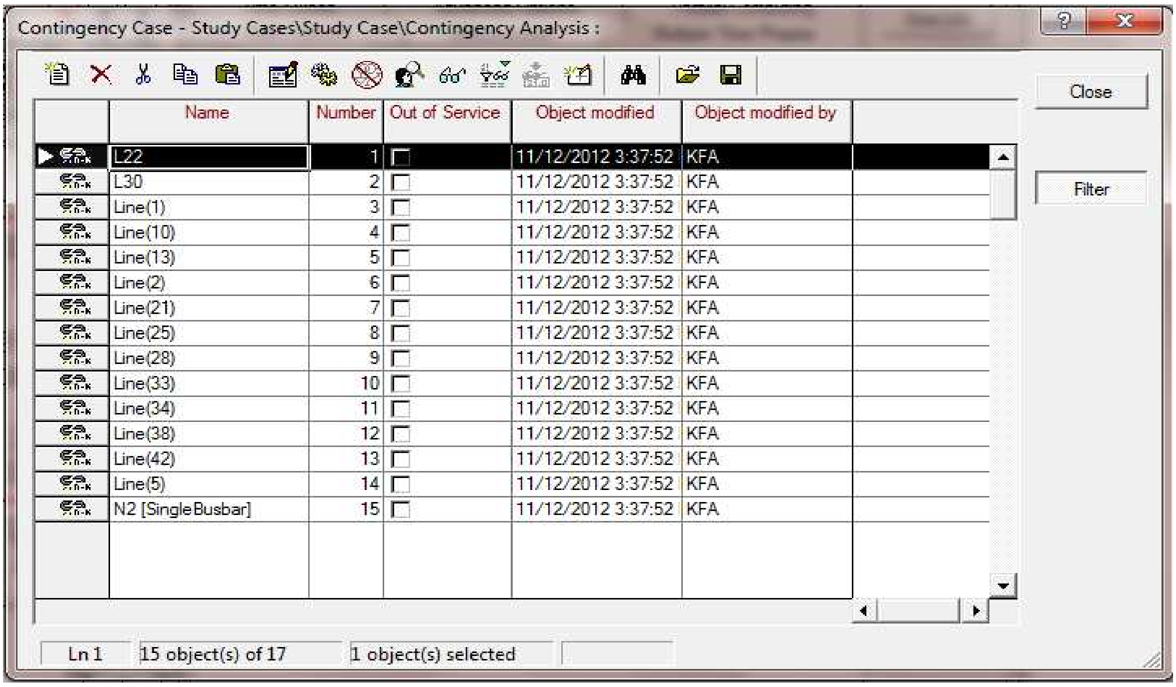


Figure 18. *Contingency analysis – study case*

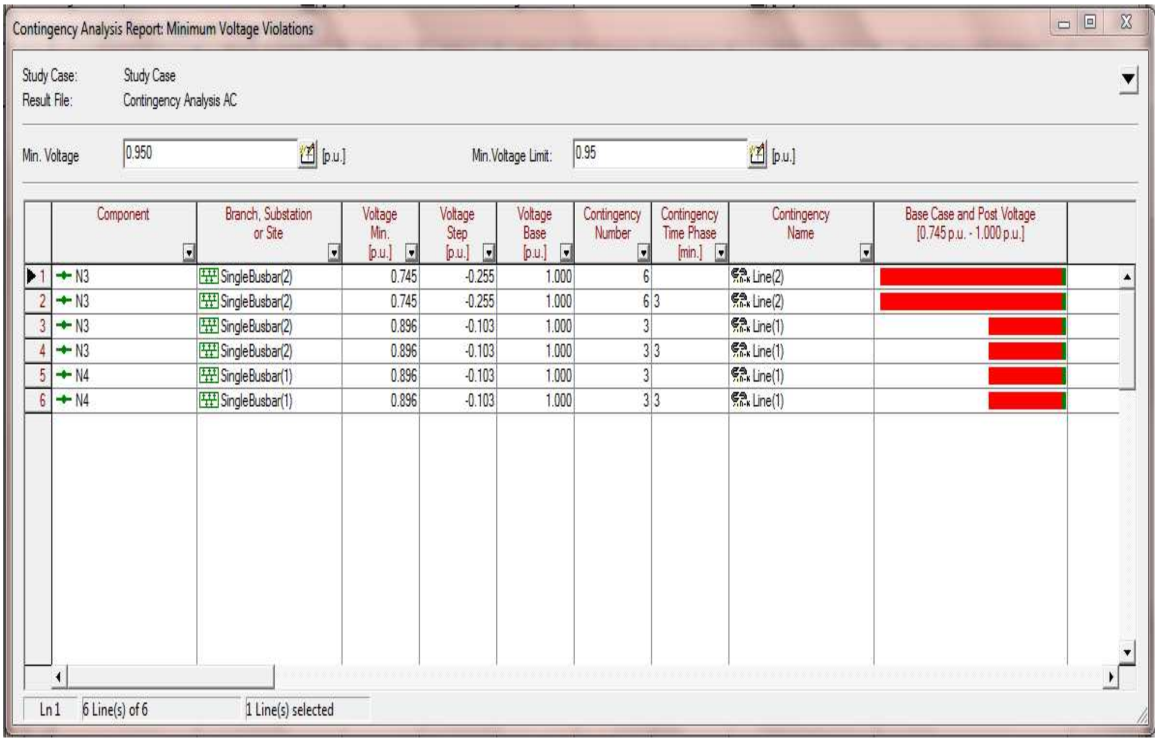
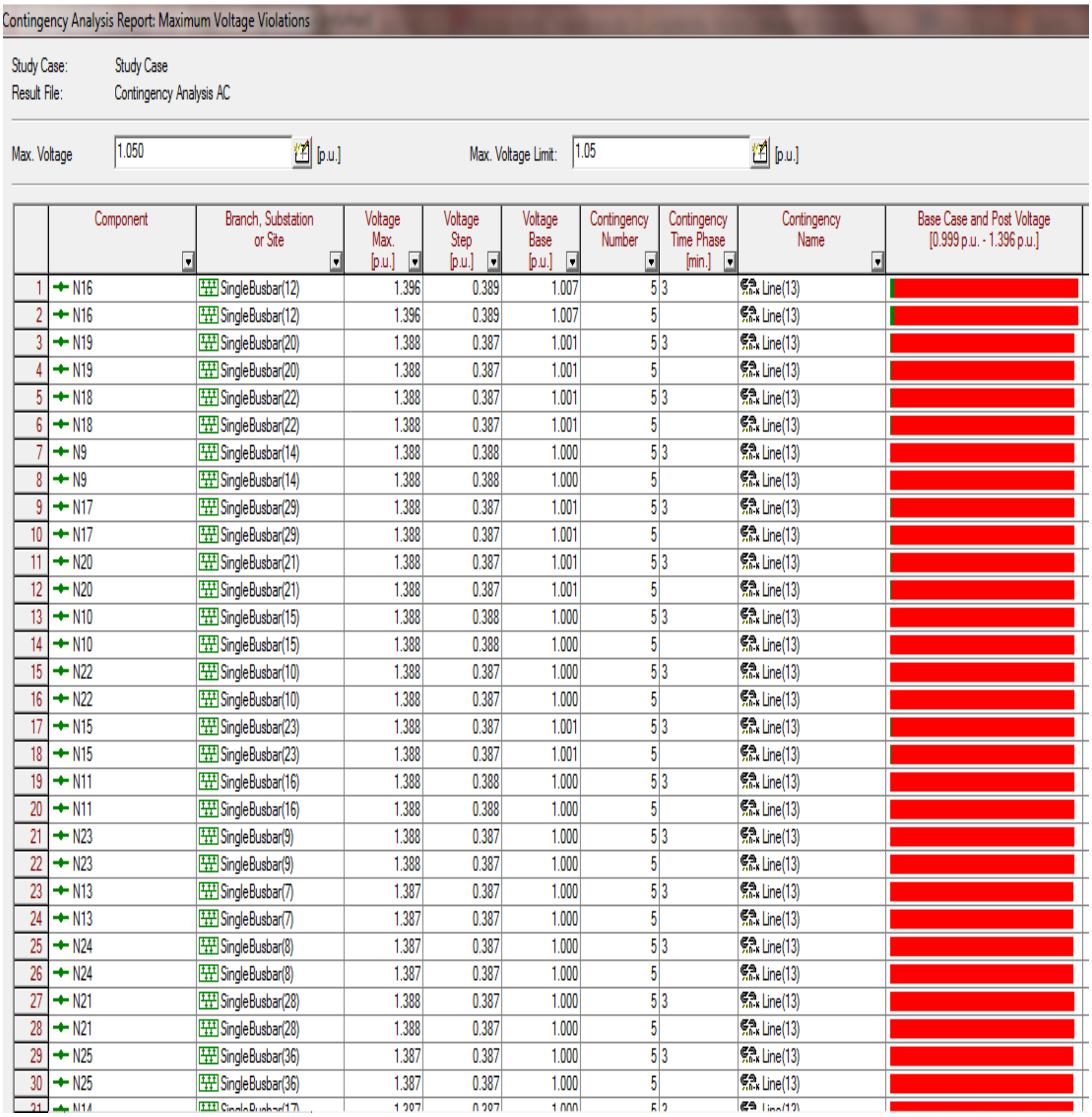


Figure 19. *ASCII report minimum voltage violations.*



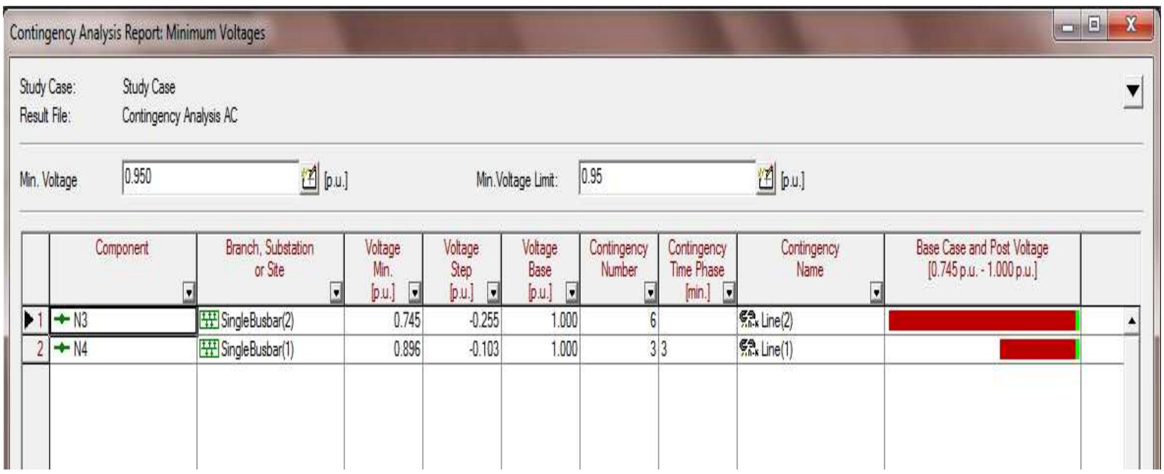
Contingency Analysis Report: Maximum Voltage Violations

Study Case: Study Case
Result File: Contingency Analysis AC

Max. Voltage 1.050 [p.u.] Max. Voltage Limit: 1.05 [p.u.]

	Component	Branch, Substation or Site	Voltage Max. [p.u.]	Voltage Step [p.u.]	Voltage Base [p.u.]	Contingency Number	Contingency Time Phase [min.]	Contingency Name	Base Case and Post Voltage [0.999 p.u. - 1.396 p.u.]
1	N16	SingleBusbar(12)	1.396	0.389	1.007	5	3	Line(13)	
2	N16	SingleBusbar(12)	1.396	0.389	1.007	5		Line(13)	
3	N19	SingleBusbar(20)	1.388	0.387	1.001	5	3	Line(13)	
4	N19	SingleBusbar(20)	1.388	0.387	1.001	5		Line(13)	
5	N18	SingleBusbar(22)	1.388	0.387	1.001	5	3	Line(13)	
6	N18	SingleBusbar(22)	1.388	0.387	1.001	5		Line(13)	
7	N9	SingleBusbar(14)	1.388	0.388	1.000	5	3	Line(13)	
8	N9	SingleBusbar(14)	1.388	0.388	1.000	5		Line(13)	
9	N17	SingleBusbar(29)	1.388	0.387	1.001	5	3	Line(13)	
10	N17	SingleBusbar(29)	1.388	0.387	1.001	5		Line(13)	
11	N20	SingleBusbar(21)	1.388	0.387	1.001	5	3	Line(13)	
12	N20	SingleBusbar(21)	1.388	0.387	1.001	5		Line(13)	
13	N10	SingleBusbar(15)	1.388	0.388	1.000	5	3	Line(13)	
14	N10	SingleBusbar(15)	1.388	0.388	1.000	5		Line(13)	
15	N22	SingleBusbar(10)	1.388	0.387	1.000	5	3	Line(13)	
16	N22	SingleBusbar(10)	1.388	0.387	1.000	5		Line(13)	
17	N15	SingleBusbar(23)	1.388	0.387	1.001	5	3	Line(13)	
18	N15	SingleBusbar(23)	1.388	0.387	1.001	5		Line(13)	
19	N11	SingleBusbar(16)	1.388	0.388	1.000	5	3	Line(13)	
20	N11	SingleBusbar(16)	1.388	0.388	1.000	5		Line(13)	
21	N23	SingleBusbar(9)	1.388	0.387	1.000	5	3	Line(13)	
22	N23	SingleBusbar(9)	1.388	0.387	1.000	5		Line(13)	
23	N13	SingleBusbar(7)	1.387	0.387	1.000	5	3	Line(13)	
24	N13	SingleBusbar(7)	1.387	0.387	1.000	5		Line(13)	
25	N24	SingleBusbar(8)	1.387	0.387	1.000	5	3	Line(13)	
26	N24	SingleBusbar(8)	1.387	0.387	1.000	5		Line(13)	
27	N21	SingleBusbar(28)	1.388	0.387	1.000	5	3	Line(13)	
28	N21	SingleBusbar(28)	1.388	0.387	1.000	5		Line(13)	
29	N25	SingleBusbar(36)	1.387	0.387	1.000	5	3	Line(13)	
30	N25	SingleBusbar(36)	1.387	0.387	1.000	5		Line(13)	
31	N14	SingleBusbar(17)	1.387	0.387	1.000	5	3	Line(13)	

Figure 20. *ASCII report maximum voltage violations.*



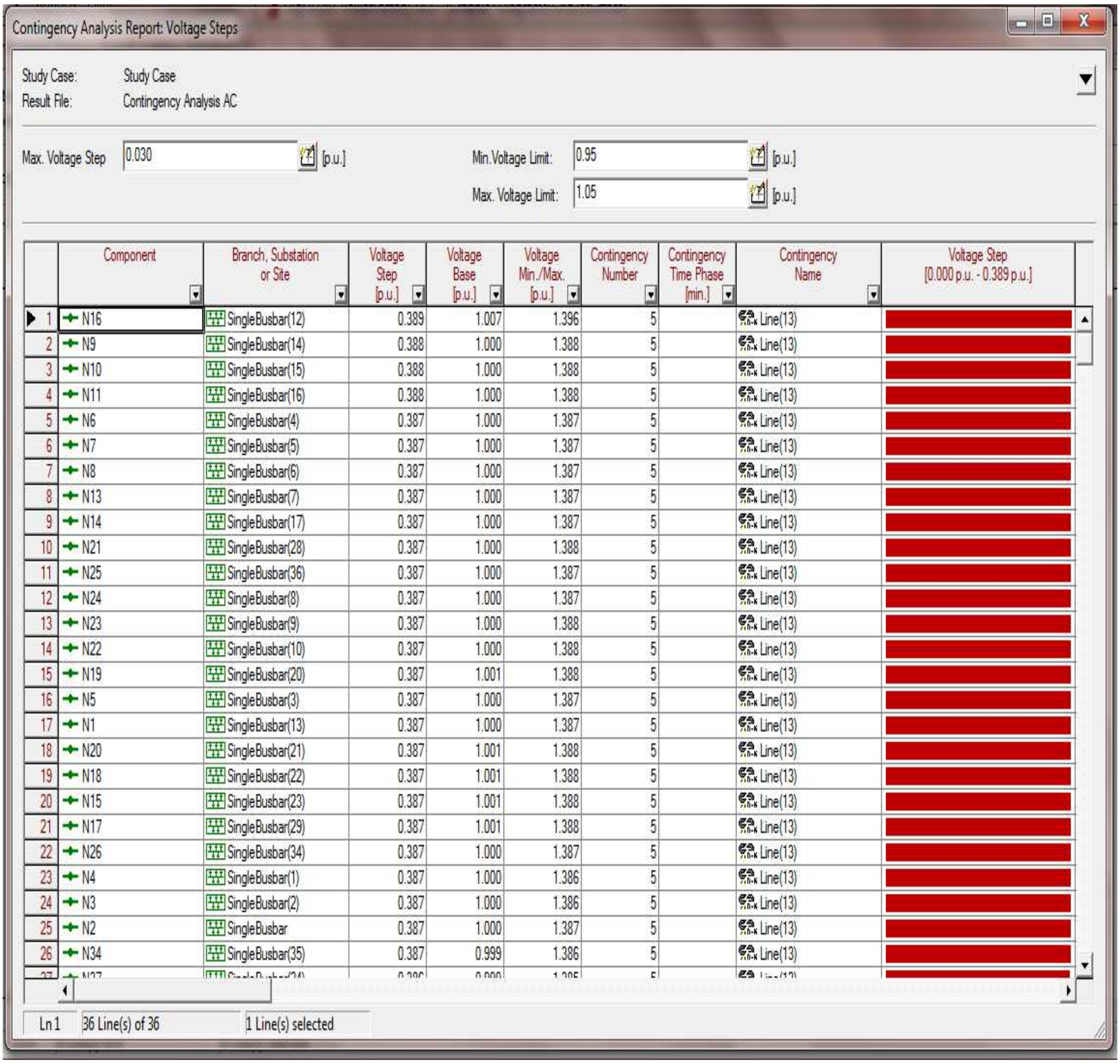
Contingency Analysis Report: Minimum Voltages

Study Case: Study Case
Result File: Contingency Analysis AC

Min. Voltage 0.950 [p.u.] Min.Voltage Limit: 0.95 [p.u.]

	Component	Branch, Substation or Site	Voltage Min. [p.u.]	Voltage Step [p.u.]	Voltage Base [p.u.]	Contingency Number	Contingency Time Phase [min.]	Contingency Name	Base Case and Post Voltage [0.745 p.u. - 1.000 p.u.]
1	N3	SingleBusbar(2)	0.745	-0.255	1.000	6		Line(2)	
2	N4	SingleBusbar(1)	0.896	-0.103	1.000	3	3	Line(1)	

Figure 21. *ASCII report – minimum voltages.*


Contingency Analysis Report: Voltage Steps

Study Case: Study Case
Result File: Contingency Analysis AC

Max. Voltage Step 0.030 [p.u.]
Min.Voltage Limit: 0.95 [p.u.]
Max. Voltage Limit: 1.05 [p.u.]

	Component	Branch, Substation or Site	Voltage Step [p.u.]	Voltage Base [p.u.]	Voltage Min./Max. [p.u.]	Contingency Number	Contingency Time Phase [min.]	Contingency Name	Voltage Step [0.000 p.u. - 0.389 p.u.]
1	N16	SingleBusbar(12)	0.389	1.007	1.396	5		Line(13)	
2	N9	SingleBusbar(14)	0.388	1.000	1.388	5		Line(13)	
3	N10	SingleBusbar(15)	0.388	1.000	1.388	5		Line(13)	
4	N11	SingleBusbar(16)	0.388	1.000	1.388	5		Line(13)	
5	N6	SingleBusbar(4)	0.387	1.000	1.387	5		Line(13)	
6	N7	SingleBusbar(5)	0.387	1.000	1.387	5		Line(13)	
7	N8	SingleBusbar(6)	0.387	1.000	1.387	5		Line(13)	
8	N13	SingleBusbar(7)	0.387	1.000	1.387	5		Line(13)	
9	N14	SingleBusbar(17)	0.387	1.000	1.387	5		Line(13)	
10	N21	SingleBusbar(28)	0.387	1.000	1.388	5		Line(13)	
11	N25	SingleBusbar(36)	0.387	1.000	1.387	5		Line(13)	
12	N24	SingleBusbar(8)	0.387	1.000	1.387	5		Line(13)	
13	N23	SingleBusbar(9)	0.387	1.000	1.388	5		Line(13)	
14	N22	SingleBusbar(10)	0.387	1.000	1.388	5		Line(13)	
15	N19	SingleBusbar(20)	0.387	1.001	1.388	5		Line(13)	
16	N5	SingleBusbar(3)	0.387	1.000	1.387	5		Line(13)	
17	N1	SingleBusbar(13)	0.387	1.000	1.387	5		Line(13)	
18	N20	SingleBusbar(21)	0.387	1.001	1.388	5		Line(13)	
19	N18	SingleBusbar(22)	0.387	1.001	1.388	5		Line(13)	
20	N15	SingleBusbar(23)	0.387	1.001	1.388	5		Line(13)	
21	N17	SingleBusbar(29)	0.387	1.001	1.388	5		Line(13)	
22	N26	SingleBusbar(34)	0.387	1.000	1.387	5		Line(13)	
23	N4	SingleBusbar(1)	0.387	1.000	1.386	5		Line(13)	
24	N3	SingleBusbar(2)	0.387	1.000	1.386	5		Line(13)	
25	N2	SingleBusbar	0.387	1.000	1.387	5		Line(13)	
26	N34	SingleBusbar(35)	0.387	0.999	1.386	5		Line(13)	

Ln 1 36 Line(s) of 36 1 Line(s) selected

Figure 22. *ASCII report – voltage steps.*

8. Conclusion

Since objective of electric power systems is to supply electrical energy to customers at low cost, while simultaneously providing acceptable, economically and justifiable service quality, generation adequacy, voltage sag, contingencies analysis and reliability analysis are very important. Deterministic indices reflect postulated conditions. They are not directly indicative of electric system reliability and are not response to most parameters which influence system reliability performance; this is applicable to contingency analysis. Probabilistic indices directly reflect the uncertainty which is inherent in the power system reliability problem and have the capability of reflecting the various parameters which impact reliability [4].

Contingency analysis could be used for blackout prediction in power grid. It simulates and quantifies the results of problems that could occur in the power system in the immediate future. Also, reliability is a key aspect of power system design and planning; giving system interruptions during an operating period, while voltage sag assessment provides frequency and severity of voltage sag during an operation period.

Nomenclature

SAIFI - System Average Interruption Frequency Index
CAIFI - Customer Average Interruption Frequency Index
SAIDI - System Average Interruption Duration Index
CAIDI - Customer Average Interruption Duration Index
ASAI - Average Service Availability Index
ASUI - Average Service Unavailability Index
ENS - Energy Not Supplied
AENS - Average Energy Not Supplied
ACCI - Average Customer Curtailment Index

EIC - Expected Interruption Cost
IEAR - Interrupted Energy Assessment Rate
SES - System energy shed
ASIFI - Average System Interruption Frequency Index
ASIDI - Average System Interruption Duration Index
MAIFI - Momentary Average Interruption Freq. Index
F.C.T. – Federal Capital Territory

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