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Resilience of Electric Power Distribution Networks to N-1 Contingencies: The Case of Sekondi-Takoradi Metropolis

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Abstract:*Contingency situation is an abnormal conditionthat do occur in an electric power distribution networks. It puts whole system or a part of the system under stress. It occurs due to sudden opening of a transmission line, generator tripping, sudden change in generation or sudden change in load value. Electric power networks are designed to withstand single contingency, thus (N-1) criterion. However, some events trigger others and cascading failures may occur. Therefore, not all contingencies are equal, and the number of components in a given system makes it prohibitive to evaluate all or a single contingency. The system is considered N-1 secure when a single contingency will not cause any system limits to be violated. Typical contingencies that can be experienced by an electric power distribution network consist of outages such as loss of feeders, distribution lines, or transformers. This study is an attempt to determine how secure the electric power distribution network within the Sekondi-Takoradi Metropolis is by modelling and simulations using PowerWorld Simulator version 19 GSO.*

Keywords:*Contingencies, Contingency Analysis, Contingency Detection, Simulations, Mega Volts Ampere, Modelling, Violations*

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I. Introduction

A core mission of an electric power distribution system is to deliver electrical energy from the supplying points to the end users without any interruption. The electric power distribution network segment has been the weakest link between the source of supply and the customer load points. The greatest problem encountered in the area of electric power distribution system operation and maintenance is how to reduce the number of interruptions experienced by customers (Venu*et al*., 2014). In the modern information society, requirements and expectations associated with the continuity of electric power supply have become increasingly important. Electricity is not a luxury commodity anymore as it was a few decades ago, but has become a necessity and a part of our everyday life. Even short interruptions can be harmful at a time that the number of computers, programmable logic controllers, *et cetera* in industries as well as households had increased rapidly. Large blackouts around the world have also aroused the consumers' interest in electricity distribution and reliability of distribution networks. The reliability of supply has gained greater interest in recent times (Kivikko, 2010).

There is always the need to analyse the performance of the electric power distribution network at aparticular operating point. However, for practical system operation, apart from ensuring the satisfactoryoperation of the distribution network at a particular operating condition, it is also equally important to makesure that the system operates with adequate level of security. Broadly, the term 'security' impliesthe ability of the electric power distribution network to operate within system constraints due to variations in bus voltage magnitudes, currentand power flow over the lines in the event of an outage (contingency) of any electric power distribution network component such as transmission line, transformer, switchgear, etc. In case the post-outage (post contingency) does not involve any violation(s) ofany operating constraint(s), the distribution network is said to be operating securely or resilient to contingencies (Prusty*et al*., 2014). Otherwise, the distribution network is not resilient to contingencies or secured.

This paper seeks to investigate the resilience of the electric power distribution network of the Sekondi-Takoradi Metropolis to N-1 contingencies. Sekondi-Takoradi metropolis is in the Western Region of Ghana which shares border with La Cote D'Ivoire.

II. Contingency Analysis and Contingency Detection

Electric power distribution networks are seldom loaded near their limits therefore, system adequacy is of less concern and reliability emphasis is on system security analysis (Okorie*et al*., 2015).All over the world, countries are expanding their power systems in order to meet the developmental challenges and this is accompanied by increased contingencies such as generator outages, transmission or distribution element outages which may always cause sudden and large changes in both configuration and the state of the system. Contingencies may result in severe violations of the operating constraints. Consequently, planning for contingencies forms an important aspect of secure operation (Onojo*et al*., 2015). The electric power distribution network is a very complex system, consisting of thousands of various components, such as conductors, insulators, posts, connectors, distribution transformers, cables, among others. Each of these components has a different life expectancy and failure distribution function. Contingency analysis is useful in understanding electric power system conditions in advance before taking preventive measures.

However, an accurate and detailed analytical method in a near real-time manner is still a great challenge due to the high nonlinearity and high dimensionality of power systems (Hu, 2010). Contingency analysis is an abnormal condition in an electric power network. It puts whole system or a part of the system under stress. It occurs due to sudden opening of a transmission line, generator tripping, sudden change in generation or sudden change in load value. Electric power networks are designed to withstand one contingency thus (N-1) criterion. However, some events trigger others and cascading failures may occur. Therefore, not all contingencies are equal, and the number of components in a given system makes it prohibitive to evaluate all or a single contingency. The system is considered N-1 secure when a single contingency will not cause any system limits to be violated (Chaitanya *et al*., 2013). Typical contingencies that can be experienced by an electric power distribution network consist of outages such as loss of feeders, distribution lines, or transformers. Contingencies can occur in the form of single equipment outages or in the form of multiple outages (Hu, 2010).

Power Flow Study for Contingency Analysis

Contingency analysis is the study of the outage of elements such as generators, transmission lines, transformers etc., and investigation of the resulting effects on line power flows and bus voltages of the remaining electric power system components. It represents an important tool in studying the effect of outages of elements in power system security during operation and planning stages. Power flow analysis is probably the most important of all network calculations. It is performed to investigate the magnitude and phase angle of the voltage at each bus and the real and reactive power flows in the electric power system components (Onojo*et al*., 2015).

Variables of Load Flow Studies

At each bus, two of the four quantities δ, $|V|$, P and Q are specified and the remaining two are determined as given in Table 1.

. **Table 1** Load Flow Variables

Bus Type	Known Variables	Unknown Variables
Slack/Swing/Reference Bus	V, δ	P, Q
PV/Generator/Voltage Control Bus	P, V	Q, δ
PQ/Load Bus	P, Q	V, δ

(Source: Hu, 2010; Onojo*et al*., 2015)

Developing a Power Relation

For the formulation of the real and reactive power entering a bus, use is made of Equation (1) through to Equation (7) according to Anthony and Chukwuma (2016) and Onojo*et al.* (2015).

Let the voltage at the i^{th}bus be denoted by Equation (1).

$$V_i = |V_i| \angle \delta_i = |V_i| (\cos \delta_i + j\sin \delta_i) \quad (1)$$

Also, the self-admittance at bus *i*is given by Equation (2).

$$Y_{ii} = |Y_{ii}| \angle \theta_{ii} = |Y_{ii}| (\cos \theta_{ii} + j\sin \theta_{ii}) = G_{ii} + jB_{ii} \quad (2)$$

Similarly, the mutual admittance between the buses *i*and *j* can be written as in Equation (3).

$$Y_{ij} = |Y_{ij}| \angle \theta_{ij} = |Y_{ij}| (\cos \theta_{ij} + j\sin \theta_{ij}) = G_{ij} + jB_{ij} \quad (3)$$

Let the power system contain a total number of *n* buses. The current injected at bus *i*is given by Equation (4).

$$I_i = Y_{i1}V_1 + Y_{i2}V_2 + \ldots\ldots\ldots\ldots + Y_{in}V_n = \sum_{k=1}^{n} Y_{ik}V_k \quad (4)$$

The assumption here is that the current entering a bus is positive and that leaving the bus is negative. Hence, the real power and reactive power entering a bus will also be assumed to be positive. The complex power at bus *i*is then given by Equation (5).

$$P_i - jQ_i = V_i^* I_i \quad (5)$$

$$= V_i^* \sum_{k=1}^{n} Y_{ik} V_k$$

$$= \left|V_i\right|(\cos\delta_i - j\sin\delta_i) \sum_{k=1}^{n} \left|Y_{ik} V_k\right|(\cos\theta_{ik} + j\sin\theta_{ik})(\cos\delta_k + j\sin\delta_k)$$

$$= \sum_{k=1}^{n} \left|Y_{ik} V_i V_k\right|(\cos\delta_i - j\sin\delta_i)(\cos\theta_{ik} + j\sin\theta_{ik})(\cos\delta_k + j\sin\delta_k)$$

Therefore, substituting Equation (5), real and reactive power is given respectively by Equation (6) and Equation (7).

$$P_i = \sum_{k=1}^{n} \left|Y_{ik} V_k V_i\right| \cos(\theta_{ik} + \delta_k - \delta_i) \quad (6)$$

$$Q_i = -\sum_{k=1}^{n} \left|Y_{ik} V_k V_i\right| \sin(\theta_{ik} + \delta_k - \delta_i) \quad (7)$$

where, Vi= voltage at bus i
V_k= voltage at bus k
δ_i= angle of deviation at bus i
δ_k= angle of deviation at bus k
P_i = real power at bus i
Q_i= reactive power at bus i
Y_{ii}= self-admittance at bus i
Y_{ij}= mutual admittance between buses i and j
Y_{ik}= mutual admittance between buses i and k
I_i = current injected at bus i
θ_{ii}= phase angle of self-admittance of bus i
θ_{ij}= phase angle of mutual admittance between buses i and j
θ_{ik}= phase angle of mutual admittance between buses i and k
B_{ii}= self-susceptance of the admittance matrix of bus i
B_{ij}= susceptance of the admittance matrix between buses i and j
G_{ii}= self-conductance of the admittance matrix of bus i
G_{ij}= conductance of the admittance matrix between buses i and j

Contingency Analysis Procedure

Generally, once the present working state of the power system is known, contingency analysis can be broken down into the following steps namely, contingency definition, contingency selection and contingency evaluation. Contingency definition involves preparing a list of probable contingencies. This typically includes line outages, transformer outages, circuit breaker outages or generator outages. Contingency selection process consists of selecting the set of most probable contingencies which needs to be evaluated in terms of potential risk to the electric power system. Usually, fast power flow solution techniques such as DC power flow is used to quickly evaluate the risks associated with each contingency. Finally, the selected contingencies are ranked in order of their security, till no violation of operating limits is observed (Nnonyelu and Madueme, 2013). For higher accuracy and fast convergence, Newton-Raphson load flow method is employed in this work. The algorithm for a typical N-1 contingency analysis is given in Figure 1 (Anon., 2012; Onojo*et al.*, 2015).

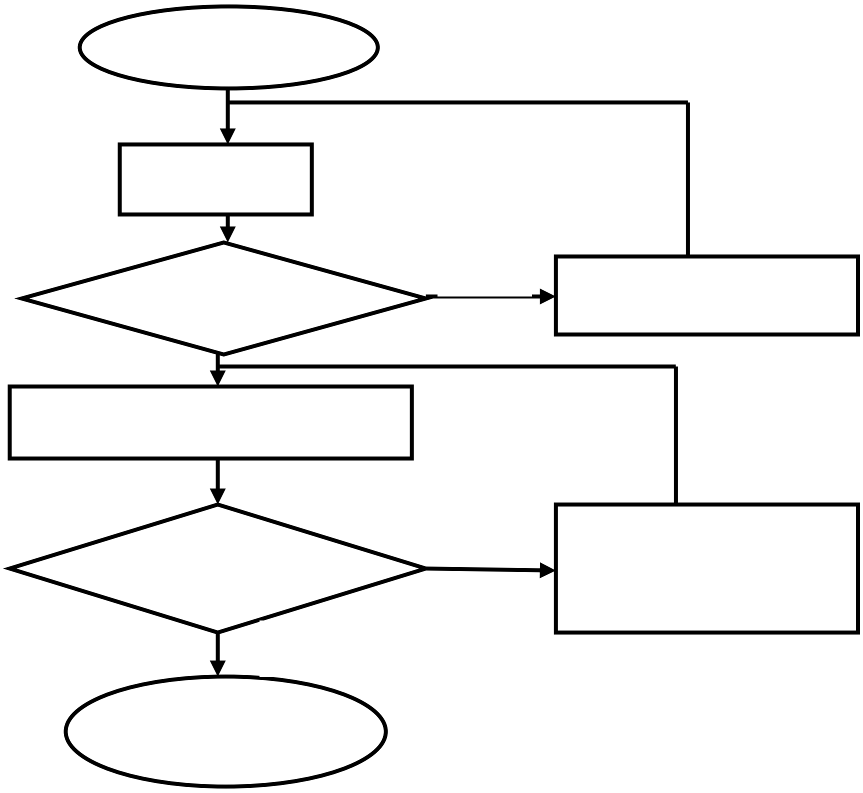


Figure 1 Procedure for N-1 Contingency Analysis

Types of Violations

Line contingency and generator contingencies are generally the most common types of contingencies. These contingencies mainly result in two types of violations namely, low voltage violations and line Mega Volts Ampere (MVA) violations. Low voltage type of violation occurs at the buses. This suggests that the voltage at the bus is less than the specified value. The operating range of voltage at any bus is generally between 0.95 - 1.05 per unit (p.u). Thus, if the voltage falls below 0.95 p.u then the bus is said to have low voltage. If the voltage rises above the 1.05 p.u then the bus is said to be experiencing high voltage problem. It is known that in the electric power network, generally, reactive power is the reason for the voltage limit violation. Hence, in the case of low voltage problems, reactive power is supplied to the bus to increase the voltage profile at the bus. In the case of the high voltage, reactive power is absorbed at the buses to maintain the system normal voltage (Chaitanya *et al*., 2013).

Line MVA limit contingency violations occur in the system when the MVA rating of the line exceeds a given rating. This is mainly due to the increase in the amplitude of the current flowing in that line. The lines are designed in such a way that they should be able to withstand 125% of their MVA limit. Based on utility practices, if the current crosses the 80-90% of the limit, it is declared as an alarm situation (Chaitanya *et al*., 2013).

III. Materials and Method

PowerWorld Simulator version 19 GSO was used in modelling and simulating the electric power distribution network of Sekondi-Takoradi metropolis. The secondary substations within the metropolis are many. In modelling the network, the major suburbs within the metropolis were considered as the load points whilst the load points of the minor suburbs were absorbed into the major ones. The estimated real power requirement of the metropolis based on installed transformer capacities was 48.60 MW. For the modelling, the network of the metropolis was reduced to forty (40) buses and ninety-two (92) feeders or transmission lines. The modelling was done based on the following assumptions:

1. Base voltage = 11 kV.
2. System base MVA = 100 MVA.
3. Supply frequency = 50 Hz.
4. Static load power factor = 0.9.

5. Conductor type = AAC.
6. Resistance = Ohm/km.
7. Reactance = Ohm/km.

The electric power distribution network within the Sekondi-Takoradi metropolis consists of 120 mm^2 and 150 mm^2 conductor sizes. Ninety-five percent (95%) being 120 mm^2 conductor size. The modelling was carried out using two different conductor sizes, thus 120 mm^2 and 150 mm^2 All Aluminium Conductor (AAC). The load and transformer data as well as estimated feeder lengths were used for the modelling in the PowerWorld Simulator version 19 GSO software after which simulations were carried out. Figure 2 shows the simulated electric power distribution network. The snapshot of the simulation results is also given in Figure 3. To be sure of the ability of the modelled network to withstand N-1 contingency, forty-bus and ninety-two transmission line contingencies were inserted to determine where exactly low or high voltages would be experienced within the network of the metropolis. Thus, the ninety-two transmission lines were taken off one by one in the case of transmission line contingency, and the forty-buses were also taken off one by one in the case of the bus contingency. For the voltage to be declared as low, the per unit (p.u.) value must fall below 0.95, and for high voltage, it must be above 1.05 p.u for a feeder and the branch circuits. The limits were set at ± 5% to ensure optimum efficiency for the feeder and the branch circuits. Forty-bus contingencies were inserted after which contingency simulations were carried out resulting in a total of 154 violations as shown by the snapshot given in Figure 4.

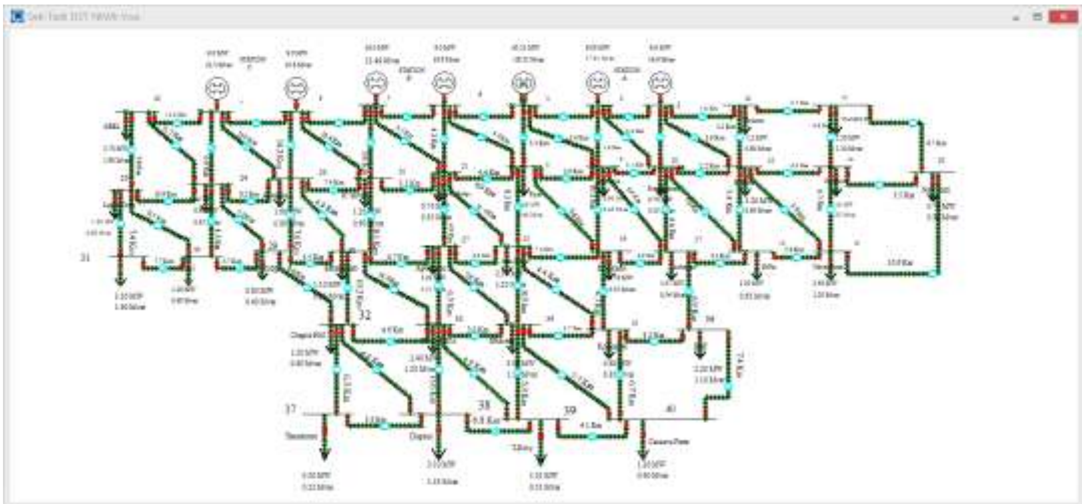


Figure 2 TheSimulated Electric Power Distribution Network of Sekondi-TakoradiMetropolis

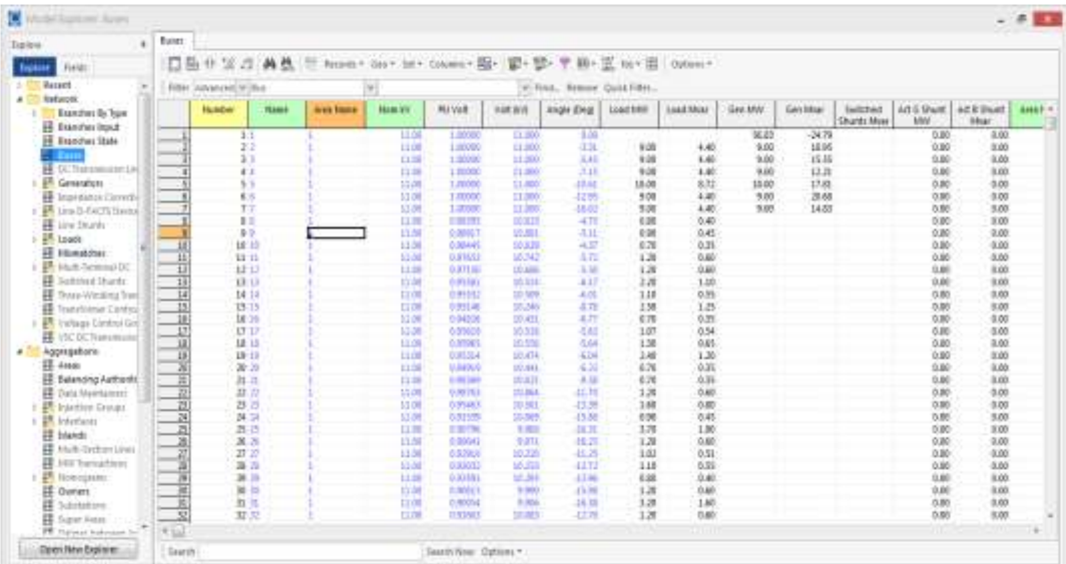


Figure 3 A Snapshot of Simulated Results of the Electric Power Distribution Network ofSekondi-Takoradi Metropolis using 120 mm2 and 150 mm2 Conductors

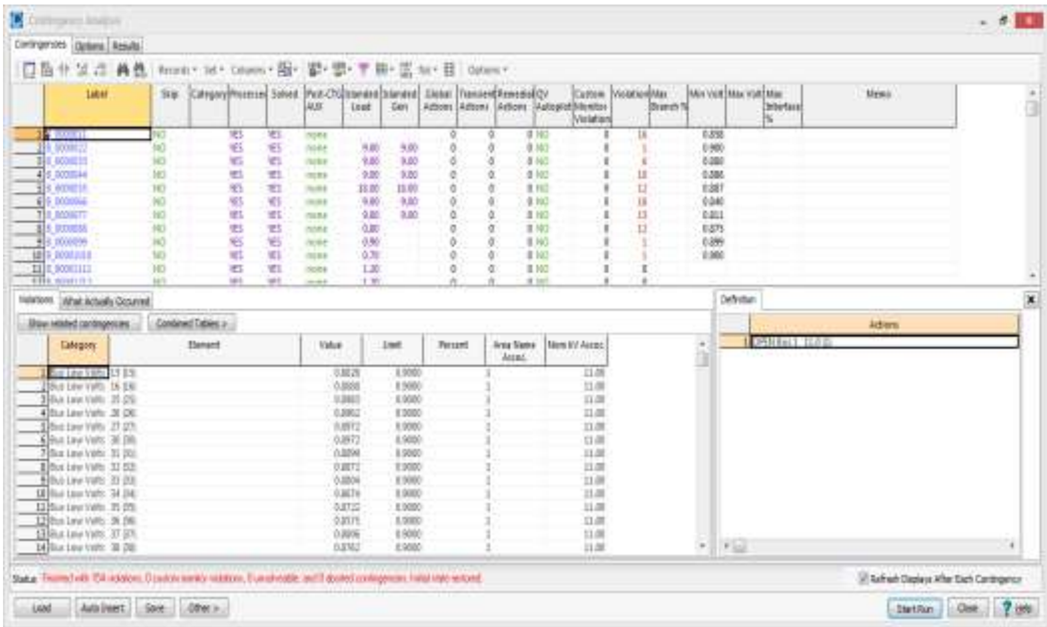


Figure 4A Snapshot of Results of Simulated Forty-bus Contingencies of Electric Power Distribution Network of the Sekondi -Takoradi Metropolis Comprising 120 mm^2 and 150 mm^2 Conductors

Again, ninety-two transmission line contingencies were inserted as shown by the snapshot of results given in Figure 5 resulting in a total of 81 violations.

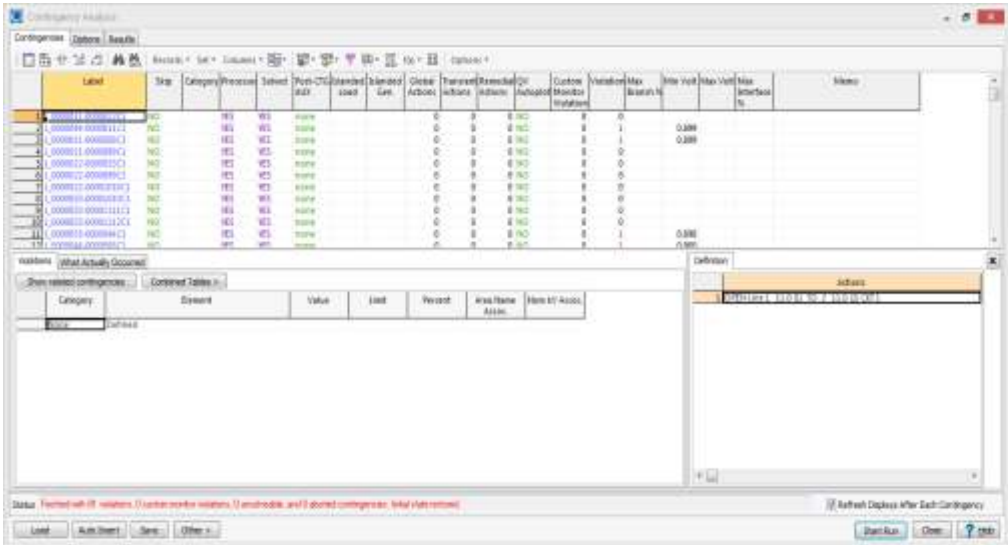


Figure 5A Snapshot of Results of Simulated Ninety-two Transmission Line Contingencies of Electric Power Distribution Network of the Sekondi-Takoradi Metropolis Comprising 120 mm^2 and 150 mm^2 Conductors

Due to the numerous violations observed during the simulations of the electric power distribution network which comprised 120 mm^2 and 150 mm^2 conductor sizes, all the 120 mm^2 conductors were replaced with those of 150 mm^2 AAC. The snapshot of the network modelled with only 150 mm^2 conductors is given in Figure 6. The snapshot of the results of the simulated electric power distribution network modelled with only 150 mm^2 conductor size is given in Figure 7. Forty (40) bus contingencies were inserted into the electric power distribution network modelled with only 150 mm^2 conductors. A snapshot of the simulated results is shown in Figure 8 with no violation. To further investigate the voltage stability of the electric power distribution network modelled using 150 mm^2 conductors, ninety-two transmission line contingencies were inserted. A snapshot of the ninety-two transmission line contingencies is given in Figure 9.

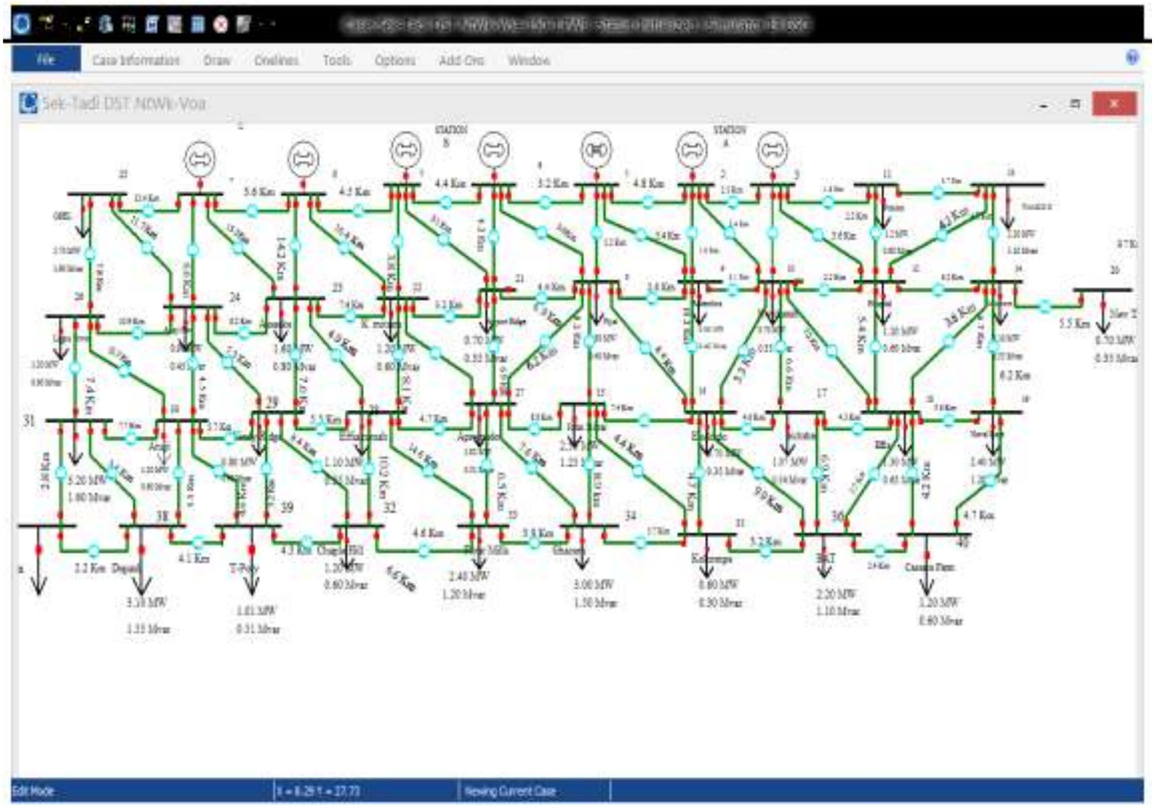
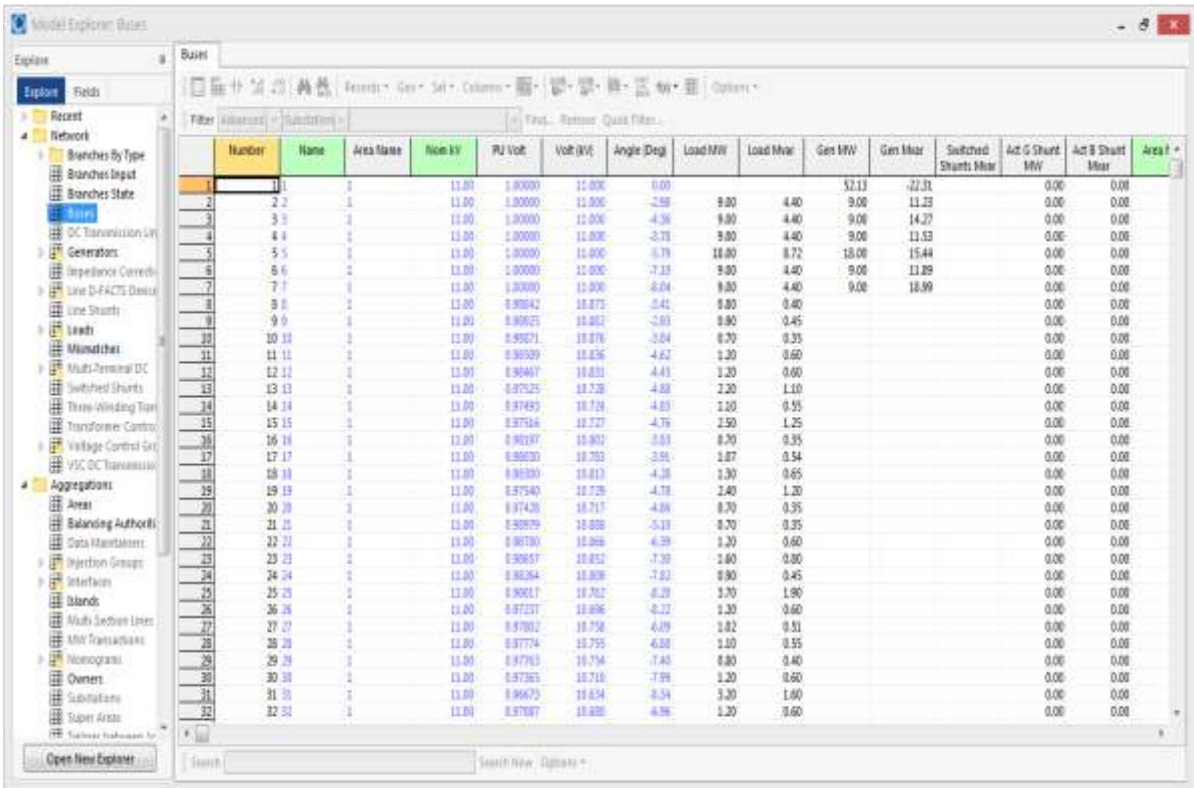


Figure 6 The Modelled Electric Power Distribution Network using 150 mm^2 AluminiumConductors Only



	Number	Name	Area Name	Nom kV	PU Volt	Volt (kV)	Angle (Deg)	Load MW	Load Mvar	Gen MW	Gen Mvar	Switched Shunts Mvar	Act G Shunt MW	Act B Shunt Mvar	Area I
1	1	1	1	11.00	1.00000	11.000	0.00			52.13	-22.31		0.00	0.00	
2	2	2	1	11.00	1.00000	11.000	-2.58	9.00	4.40	9.00	11.23		0.00	0.00	
3	3	3	1	11.00	1.00000	11.000	-4.36	9.00	4.40	9.00	14.27		0.00	0.00	
4	4	4	1	11.00	1.00000	11.000	-3.71	9.00	4.40	9.00	11.53		0.00	0.00	
5	5	5	1	11.00	1.00000	11.000	-5.79	18.00	8.72	18.00	15.44		0.00	0.00	
6	6	6	1	11.00	1.00000	11.000	-7.13	9.00	4.40	9.00	11.89		0.00	0.00	
7	7	7	1	11.00	1.00000	11.000	-8.04	9.00	4.40	9.00	18.99		0.00	0.00	
8	8	8	1	11.00	0.98842	10.873	-2.41	0.80	0.40				0.00	0.00	
9	9	9	1	11.00	0.98925	10.882	-2.83	0.80	0.45				0.00	0.00	
10	10	10	1	11.00	0.98871	10.876	-3.04	0.70	0.35				0.00	0.00	
11	11	11	1	11.00	0.98509	10.836	-4.62	1.20	0.60				0.00	0.00	
12	12	12	1	11.00	0.98467	10.831	-4.41	1.20	0.60				0.00	0.00	
13	13	13	1	11.00	0.97525	10.728	-4.88	2.20	1.10				0.00	0.00	
14	14	14	1	11.00	0.97493	10.724	-4.83	1.10	0.55				0.00	0.00	
15	15	15	1	11.00	0.97516	10.727	-4.76	2.50	1.25				0.00	0.00	
16	16	16	1	11.00	0.98197	10.802	-3.83	0.70	0.35				0.00	0.00	
17	17	17	1	11.00	0.98030	10.783	-3.91	1.07	0.54				0.00	0.00	
18	18	18	1	11.00	0.98300	10.813	-4.28	1.30	0.65				0.00	0.00	
19	19	19	1	11.00	0.97540	10.729	-4.78	2.40	1.20				0.00	0.00	
20	20	20	1	11.00	0.97428	10.717	-4.86	0.70	0.35				0.00	0.00	
21	21	21	1	11.00	0.98979	10.888	-5.13	0.70	0.35				0.00	0.00	
22	22	22	1	11.00	0.98780	10.866	-6.39	1.20	0.60				0.00	0.00	
23	23	23	1	11.00	0.98657	10.852	-7.30	1.60	0.80				0.00	0.00	
24	24	24	1	11.00	0.98264	10.809	-7.82	0.90	0.45				0.00	0.00	
25	25	25	1	11.00	0.98017	10.782	-8.28	3.70	1.90				0.00	0.00	
26	26	26	1	11.00	0.97237	10.696	-8.22	1.20	0.60				0.00	0.00	
27	27	27	1	11.00	0.97802	10.758	-6.09	1.02	0.51				0.00	0.00	
28	28	28	1	11.00	0.97774	10.755	-6.88	1.10	0.55				0.00	0.00	
29	29	29	1	11.00	0.97763	10.754	-7.40	0.80	0.40				0.00	0.00	
30	30	30	1	11.00	0.97365	10.710	-7.99	1.20	0.60				0.00	0.00	
31	31	31	1	11.00	0.98673	10.854	-8.34	3.20	1.60				0.00	0.00	
32	32	32	1	11.00	0.97087	10.680	-6.96	1.20	0.60				0.00	0.00	

Figure 7A Snapshot of Simulated Results of the Electric Power Distribution Network Comprising 150 mm^2 Aluminium Conductors Only

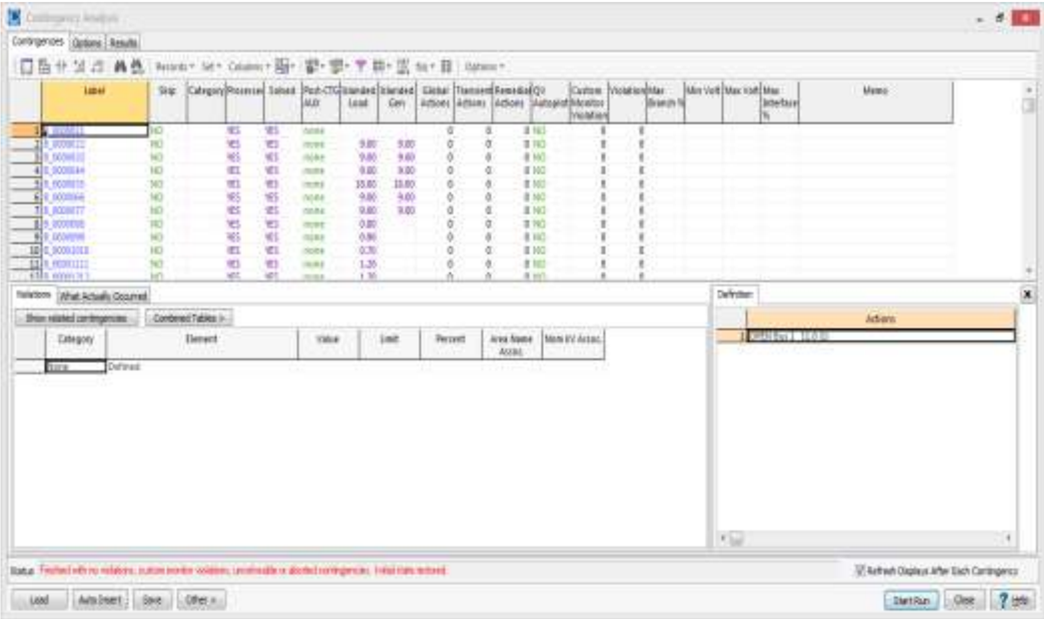


Figure 8A Snapshot of Results of Simulated Forty-bus Contingencies of Electric Power Distribution Network Comprising 150 mm^2 Conductors Only

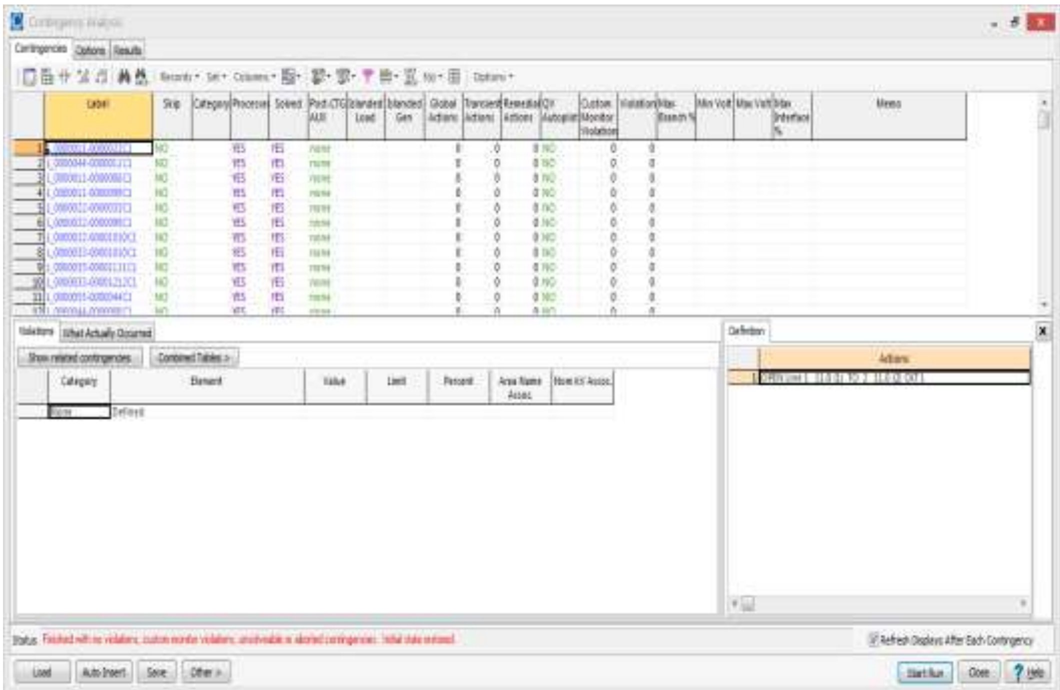


Figure 9A Snapshot of Results of Simulated Ninety-two Transmission Line Contingencies of Electric Power Distribution Network Comprising 150 mm^2 Conductors Only

IV. Results and Discussions

Presented in this section are the results obtained after modelling and simulations of the electric power distribution network of Sekondi-Takoradi metropolis. Computer simulations were done after modelling the electric power distribution network with forty-buses and ninety-two feeders or transmission lines in the PowerWorld Simulator version 19 GSO. Cases considered were the simulations of the normal network comprising 120 mm^2 and 150 mm^{2}aluminium conductors, insertion of forty-bus contingencies as well as insertion of ninety-two transmission line contingencies. Also, the simulations of the modelled electric power distribution network were done with only 150 mm^2 conductors in circuit, followed by insertion of forty-bus contingencies as well as insertion of ninety-two transmission line contingencies.The results are presented in Figure 10, Figure 11, Figure 12 and Figure 13 respectively.

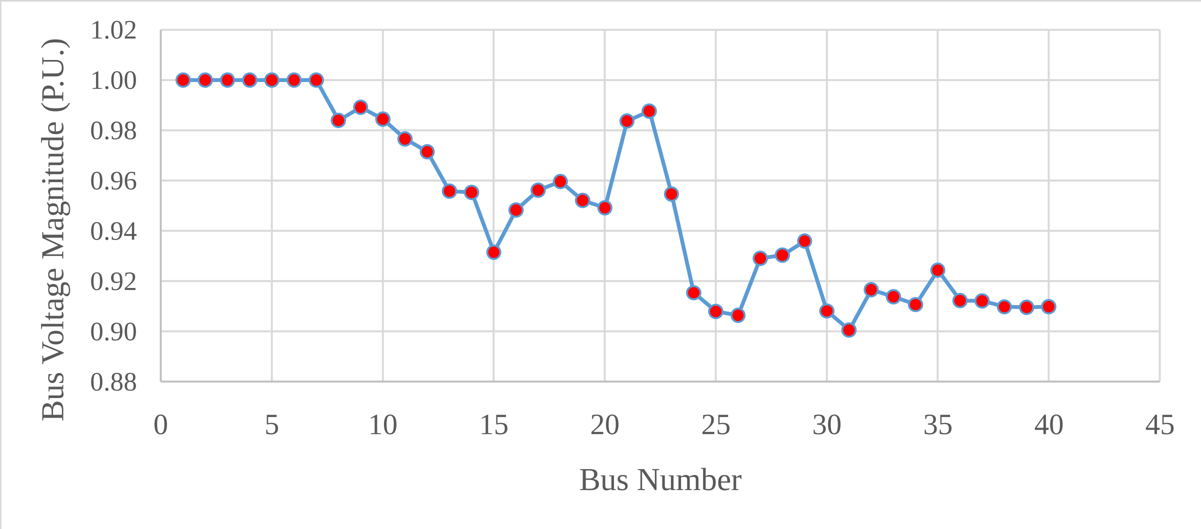


Figure 10 Simulated Bus Voltages of the Network with 120 mm^2 and 150 mm^2Conductors

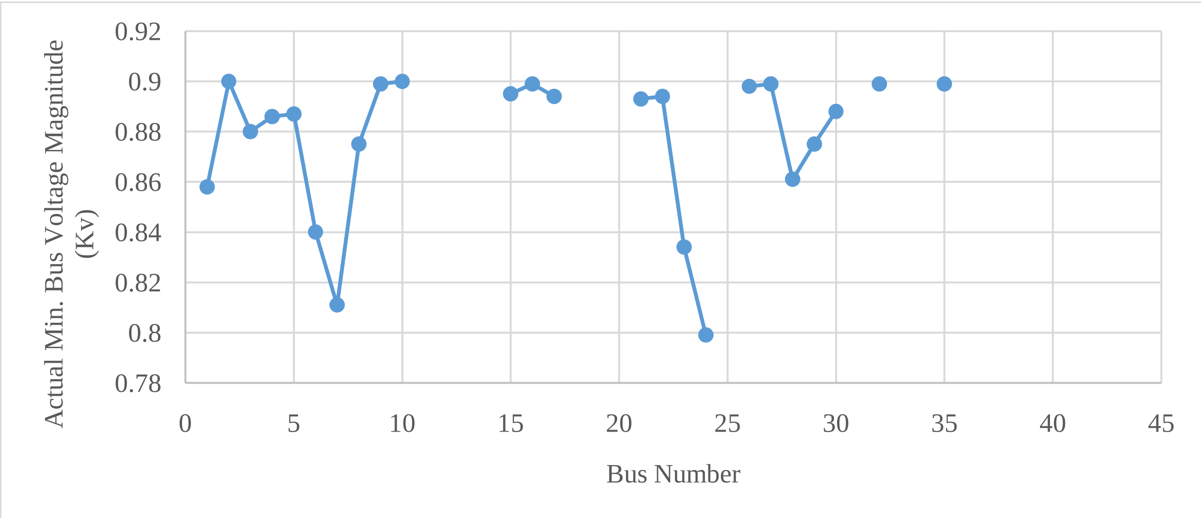


Figure 11 Simulated Minimum Bus Voltages of the Network with 120 mm^2 and 150 mm^2 Conductors during Forty-bus Contingencies

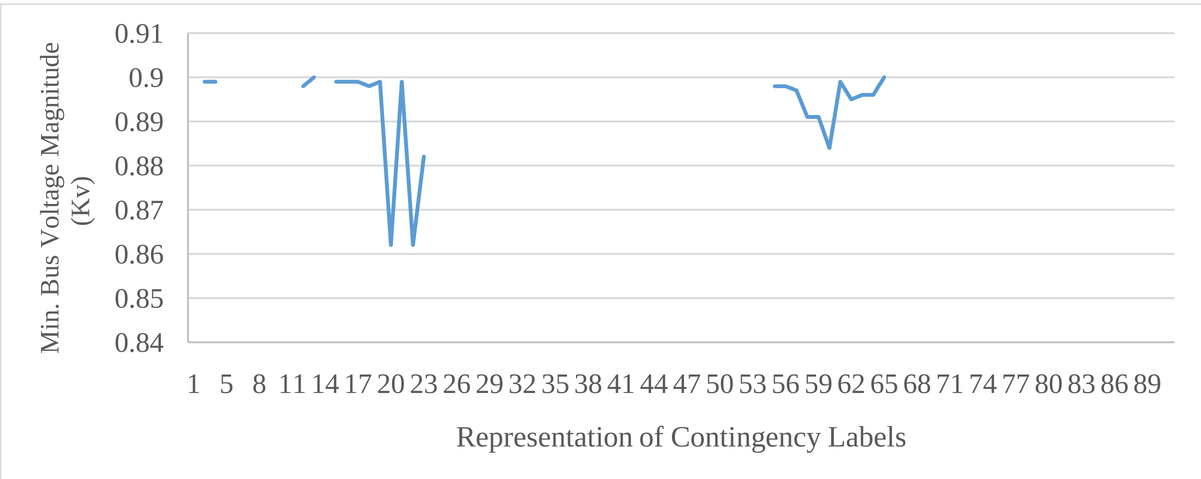


Figure 12 Simulated Minimum Bus Voltages of the Network with 120 mm^2 and 150 mm^2 Conductors during

Ninety-two Transmission Line Contingencies

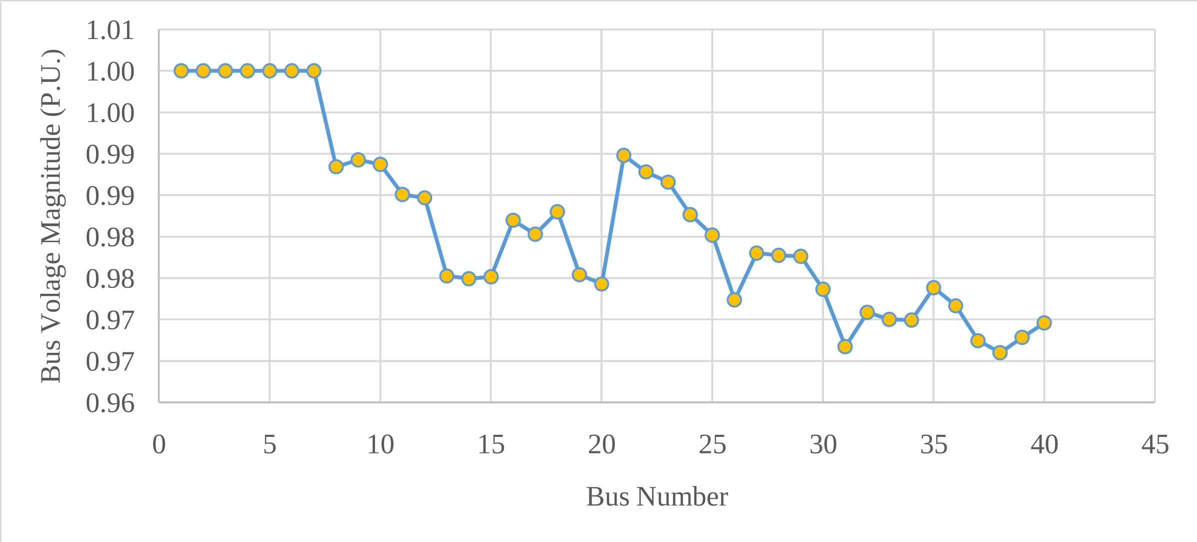


Figure 13 Simulated Bus Voltages with only 150 mm^2 Conductors

Figure 10 showed that not all the p.u. voltage variations at the various buses are within the specified range i.e. a minimum of 0.95 p.u. and maximum of 1.05 p.u. Twenty-five (25) buses violated the minimum limit value. The minimum p.u. voltage of 0.95 was violated at bus numbers fifteen (15) through to bus number forty (40). An indication that customers connected to those buses will be experiencing low voltages some of the time. No bus experienced a voltage violation exceeding the maximum p.u. voltage of 1.05. From Figure 11, twenty-four (24) of the buses experienced low voltages at their ends for a forty-bus contingency simulations resulting in a total of one-hundred and fifty-four (154) violations. The low voltages experienced ranged between 0.799 to 0.90 p.u. which fell below the recommended minimum of 0.95 p.u. This is an indication that the existing electric power distribution network within the metropolis is not immune to N-1 bus contingencies when both the present 120 mm^2 and 150 mm^2 conductors continue to be used.

In Figure 12, ninety-two transmission line contingencies were processed successfully resulting in a total of eighty-one (81) violations with the p.u. minimum voltages ranging between 0.862 to 0.90 p.u. This is also an indication that the existing electric power distribution network within the metropolis is not immune to N-1 transmission line contingencies.

Figure 13 revealed that all the bus voltages are within the stipulated voltage range of 0.95 p.u. minimum and the 1.05 p.u. maximum for the network having only 150 mm^2 conductor sizes in circuit. When the forty-bus and ninety-two transmission line contingencies were inserted, there was not a single voltage or MVA limit violation occurred. These are indications that the electric power distribution network modelled with 150 mm^2 conductor sizes only in circuit is immune to N-1 bus and transmission line contingencies.

V. Conclusion

The present use of 120 mm^2 and 150 mm^2 conductor sizes results in voltage violations giving an indication that the electric power distribution network is not immune to N-1 contingencies. The electric power distribution network of the Sekondi-Takoradi Metropolis shall be secured and reliable when all existing 120 mm^{2}aluminium conductors are replaced with 150 mm^{2}aluminium conductors.

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