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Projected Load Growth Sustenance Investigations by Modelling and Simulations of Electric Power Distribution Networks: A Case Study of Sekondi-Takoradi Metropolis

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Abstract: *The reliability of electric power distribution networks has gained greater interest in recent times. One of the main causes of frequent failure of electric power distribution networks is exceeding the current carrying capacity of the conductors being used. That normally happen as a result of failure of utility companies to upgrade the conductor to a bigger size as the load increases due to lack of resources. The projected annual load growth for metropolitan areas in Ghana averages 8% per annum. For that reason, the projected load growth for the Sekondi-Takoradi metropolis for the years 2020, 2025 and 2030 was estimated using the 8% annual load growth rate. The modelling and the simulation results indicated that aluminium conductor of size 265 mm^2 is required to sustain the projected load growth beyond the year 2030 but will require switch shunt capacitor compensation.*

Keywords: *Simulations, Modelling, Distribution network, Contingency analysis, Shunt capacitor*

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I. Introduction

The role of the electric power distribution network is of prime importance within the electric energy business. Its operation is governed by physical laws. The electric power distribution network has a fixed structure consisting of different voltage levels; the higher levels are for transmission purposes whereas the lower levels are used for the distribution tasks, and each network element has a finite capacity. The electric power system consists of a generation, a transmission, a subtransmission, and a distribution systems. The generation and transmission systems are referred to as bulk power supply, and the subtransmission and distribution systems are considered to be the final means through which the electric power is transferred to the consumer. The capital investment at the distribution sector was estimated to be roughly equal in capital investment to the generation sector on a national average, and together they represent over 80% of the total power system investment. However, these figures have somewhat changed. The major investment has been in the generation sector, with distribution a close second. The economic importance of the distribution system cannot be overemphasised, and the amount of investment involved dictates careful planning, design, construction, and operation (Gonen, 2008; Zhang *et al*., 2006).

A core mission of an electric power distribution network 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). 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). One of the main causes of frequent failure of electric power distribution networks is exceeding the current carrying capacity of the conductors being used. That normally happen as a result of failure of utility companies to upgrade the conductor to a bigger size as the load increases. The study is based on the premise that the electric power distribution network of the Sekondi-Takoradi Metropolis is All Aluminium Conductor (AAC) of size 150 mm^2. The study is to determine whether the 150 mm^2 conductor size can sustain the load growth into the year 2020 and beyond. The projected annual load growth for metropolitan areas in Ghana averages 8% per annum (Anon., 2013). For that reason, the projected load growth for the Sekondi-Takoradi metropolis for the years 2020, 2025 and 2030 was estimated using the 8% annual load growth rate. The Sekondi-Takoradi metropolis is in the Western Region of Ghana which shares border with La Cote D'Ivoire to the west and the Gulf of Guinea to the south.

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

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

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).

$$V_i = |V_i|\angle\delta_i = |V_i|(\cos\delta_i + j\sin\delta_i) \tag{1}$$

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

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

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

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

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

$$I_i = Y_{i1}V_1 + Y_{i2}V_2 + \dots\dots\dots\dots + Y_{in}V_n = \sum_{k=1}^{n} Y_{ik}V_k \tag{4}$$

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).

$$\begin{aligned} P_i - jQ_i &= V_i^{*} I_i \\ &= V_i^{*} \sum_{k=1}^{n} Y_{ik}V_k \\ &= |V_i|(\cos\delta_i - j\sin\delta_i) \sum_{k=1}^{n} |Y_{ik}V_k|(\cos\theta_{ik} + j\sin\theta_{ik})(\cos\delta_k + j\sin\delta_k) \\ &= \sum_{k=1}^{n} |Y_{ik}V_iV_k|(\cos\delta_i - j\sin\delta_i)(\cos\theta_{ik} + j\sin\theta_{ik})(\cos\delta_k + j\sin\delta_k) \end{aligned} \tag{5}$$

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

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

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

where, V_i = voltage at bus *i*
V_k = voltage at bus *k*
δi = angle of deviation at bus *i*
δk = 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*
Ii = 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*

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).

Switch Shunt Capacitor Size Determination

Reactive power compensation technique is often the most effective way to improve both power transfer capability and voltage stability of a power system. The control of voltage levels is accomplished by controlling the production, absorption and flow of reactive power. To control the voltage throughout the system, use must be made of additional devices to compensate reactive power (Akwukwaegbu and Okwe, 2013). The primary purposes of distribution system shunt compensation near load centres are voltage control and load stabilisation. Shunt compensation technique in practical applications is often used to regulate the voltage at a given busbar against load variations, or to provide voltage support for the load when, due to generation or line outages, the capacity of the sending-end system becomes impaired (Anon., 2008). When there is any occurrence of voltage violation during simulation, thus if the p.u. voltage falls below the specified 0.95 p.u. or goes above 1.05 p.u. range, that violation must be corrected by using switch shunt capacitors (shunt compensation). The switch shunt capacitor size must be determined by taking into consideration the original power factor (Cos θ1) of electric power distribution network before simulation and the power factor after simulation (Cos θ2). The required switched shunt capacity is given by Equation (8) (Chandra1 and Agarwal, 2014; Mon, 2014).

$$MVAr = P (\tan \theta 1 - \tan \theta 2) \qquad (8)$$

where, P = real power at the bus for which power factor has to be improved

Cos θ_1 = initial power factor of the distribution network before simulation

Cos θ_2 = final power factor of the distribution network after simulation

The Electric Power Distribution Network of Sekondi-Takoradi Metropolis

The main source of electric power supply within the Sekondi-Takoradi Metropolis is from three primary substations designated as Station ‘A’, Station ‘B’, and Station ‘C’ respectively. Primary substation ‘A’ is a 33/11 kV line with two power transformers rated at 10 MVA each. Primary substation ‘B’ is also a 33/11 kV line with two power transformers with a rating of 20 MVA and 10 MVA respectively. Substation ‘C’ is also a 33/11 kV line with two power transformers rated at 10 MVA each. Work is currently on going for two more additional substations designated as Station ‘D’ and Station ‘E’ respectively. The medium voltage being used within the metropolis is 11 kV. The 33 kV medium voltage is being used to serve adjoining towns and communities that are far away from the metropolis (Anon., 2013).

The electric power distribution network comprises various sizes of distribution transformers. The transformer sizes range from 25 kVA to 2 MVA. The smaller size up to 200 kVA are double pole mounted and those that are above 200 kVA are ground mounted. Almost all the distribution transformers are equipped with individual fuses and disconnect switches on the Medium Voltage (MV) side. Lightning arrester is provided for every transformer for protection from lightning strikes. On the low voltage side, the feeder is protected with fuses. The body of the distribution transformers and the Low Voltage (LV) network’s neutral are solidly earthed.

III. Materials and Method

Power World 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) busbars and ninety-two (92) feeders or transmission lines. For the modelling, 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 to achieve the reduced number of buses which were initially three hundred and thirty-two (332) busbars (transformer substations) and circuit feeders which were four hundred and thirty-four (434). The estimated real power requirement of the metropolis based on installed transformer capacities was 48.60 MW.

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.

Methodology of investigations was modelling and simulations of the electric power distribution network of the metropolis using the year 2020 estimated load data and that of 150 mm^2 aluminium conductors. Figure 1 gives the electric power distribution network modelled with 150 mm^2 conductor size. Figure 2 gives the snapshot of the simulated results. Forty-bus and ninety-two transmission line contingencies were inserted and simulated to ascertain whether the 150 mm^2 aluminium conductors can withstand the estimated load growth without any violation be it voltage or MVA. The snapshot of the outcome of that simulation is given in Figure 3 in the case of the 40-bus contingency simulations. The snapshot of the ninety-two transmission line contingency simulations is also given in Figure 4.

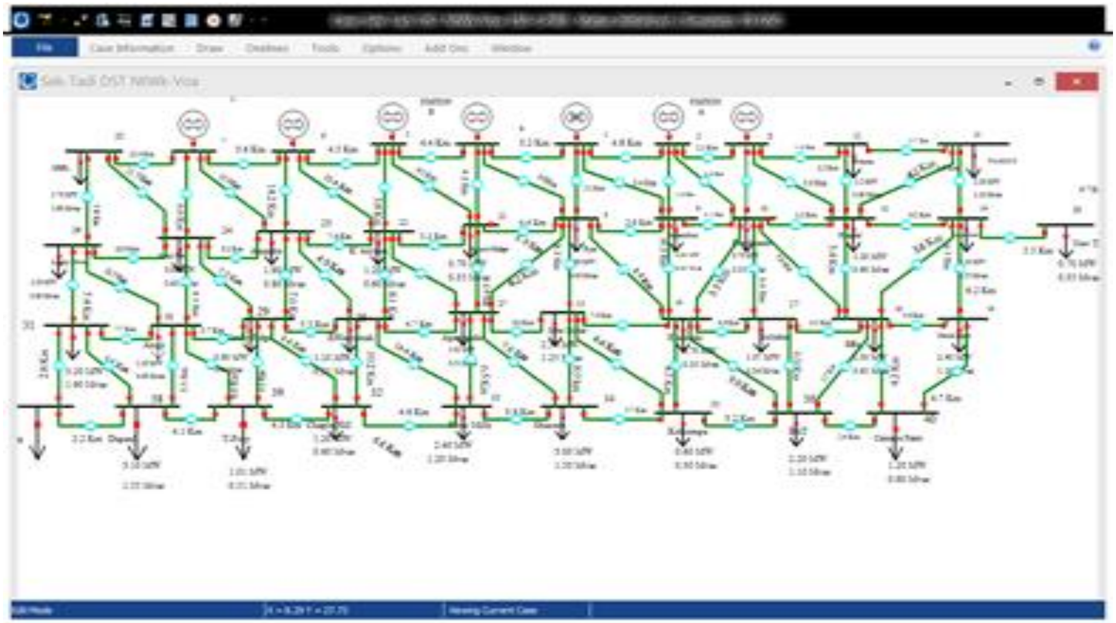


Figure 1 The Modelled Electric Power Distribution Network using 150 mm^2 Aluminium Conductors

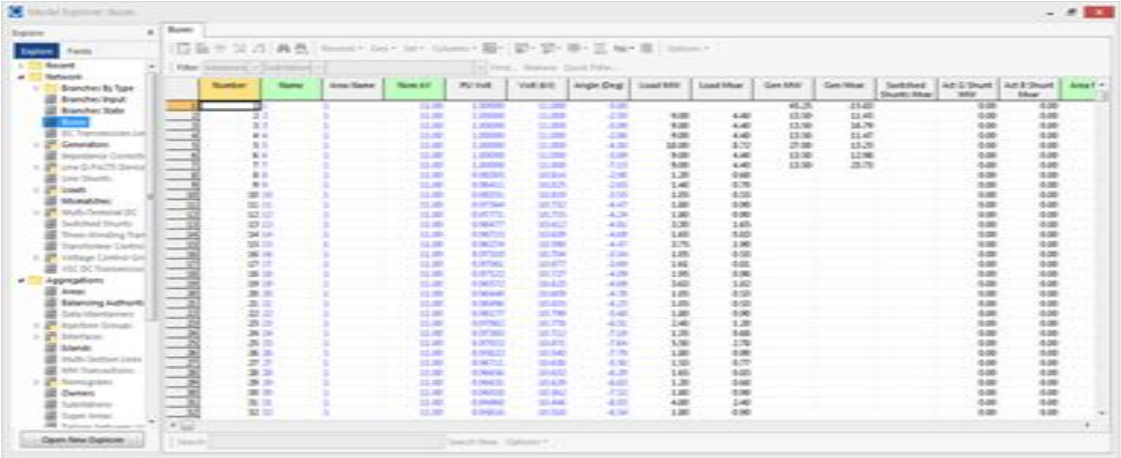
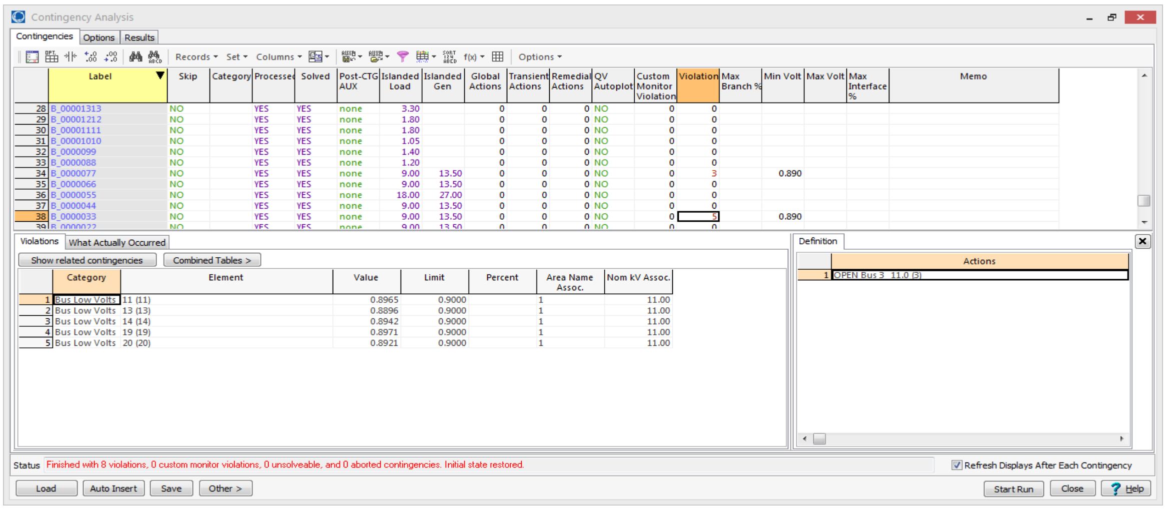


Figure 2 A Snapshot of the Simulated Results of the Year 2020 Estimated Load Growth Data using 150 mm^2 Conductors



	Label	Skip	Category	Processed	Solved	Post-CTG AUX	Islanded Load	Islanded Gen	Global Actions	Transient Actions	Remedial Actions	QV Autoplot	Custom Monitor Violation	Violation	Max Branch %	Min Volt	Max Volt	Max Interface %	Memo
28	B_00001313	NO		YES	YES	none	3.30		0	0	0	NO	0	0					
29	B_00001212	NO		YES	YES	none	1.80		0	0	0	NO	0	0					
30	B_00001111	NO		YES	YES	none	1.80		0	0	0	NO	0	0					
31	B_00001010	NO		YES	YES	none	1.05		0	0	0	NO	0	0					
32	B_0000099	NO		YES	YES	none	1.40		0	0	0	NO	0	0					
33	B_0000088	NO		YES	YES	none	1.20		0	0	0	NO	0	0					
34	B_0000077	NO		YES	YES	none	9.00	13.50	0	0	0	NO	0	3		0.890			
35	B_0000066	NO		YES	YES	none	9.00	13.50	0	0	0	NO	0	0					
36	B_0000055	NO		YES	YES	none	18.00	27.00	0	0	0	NO	0	0					
37	B_0000044	NO		YES	YES	none	9.00	13.50	0	0	0	NO	0	0					
38	B_0000033	NO		YES	YES	none	9.00	13.50	0	0	0	NO	0	5		0.890			
39	B_0000022	NO		YES	YES	none	9.00	13.50	0	0	0	NO	0	0					

	Category	Element	Value	Limit	Percent	Area Name Assoc.	Nom kV Assoc.
1	Bus Low Volts	11 (11)	0.8965	0.9000		1	11.00
2	Bus Low Volts	13 (13)	0.8896	0.9000		1	11.00
3	Bus Low Volts	14 (14)	0.8942	0.9000		1	11.00
4	Bus Low Volts	19 (19)	0.8971	0.9000		1	11.00
5	Bus Low Volts	20 (20)	0.8921	0.9000		1	11.00

	Actions
1	OPEN Bus 3 11.0 (3)

Status Finished with 8 violations, 0 custom monitor violations, 0 unsolveable, and 0 aborted contingencies. Initial state restored.

☑ Refresh Displays After Each Contingency

Figure 3 A Snapshot of the Forty-bus Contingency Simulations based on the Year 2020 Load Growth Data using 150 mm^2 Conductors

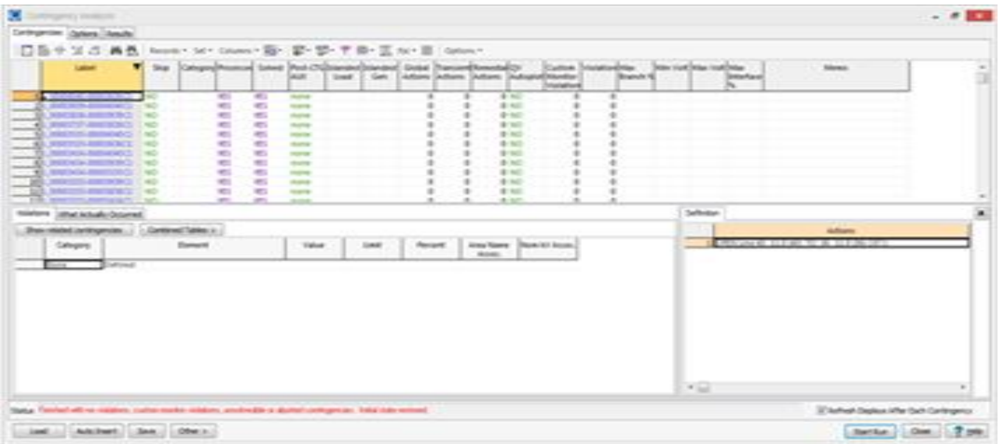


Figure 4 A Snapshot of the Results of the Ninety-two Transmission Line Contingencies using 150 mm^2 Conductors

Due to the voltage violations that occurred when the year 2020 projected load growth data was used as the input data with 150 mm^2 aluminium conductor size transmission lines, further investigations were carried out to determine the appropriate aluminium conductor size that can at least sustain the load growth up to the year 2030. During the simulations, it was noted that aluminium conductors of size 265 mm^2 can sustain the load growth beyond the year 2030 with installed switch shunt capacitors since the violations mainly encountered were those of voltage. The projected load growth data for the year 2020 served as the first input data for the modelling and simulations in PowerWorld Simulator version 19 GSO software. The modelled network using 265 mm^2 conductors only is as given in Figure 5, and Figure 6 shows the evidence of its simulations.

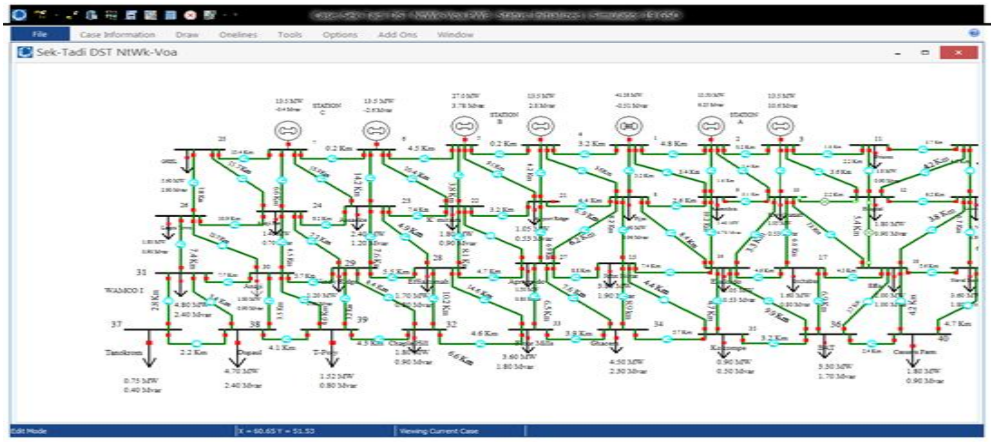
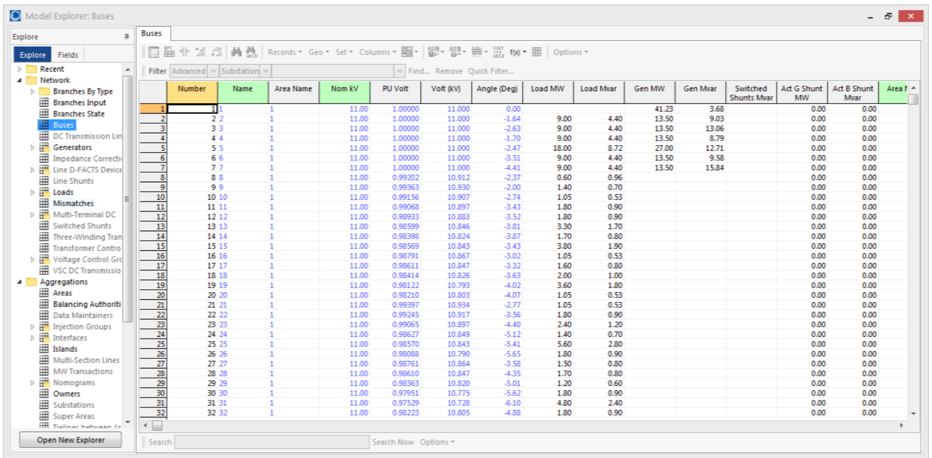


Figure 5 The Modelled Electric Power Distribution Network using 265 mm^2 Aluminium Conductors



	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 N
1	1	1	1	11.00	1.00000	11.000	0.00			41.23	3.68		0.00	0.00	
2	2	2	1	11.00	1.00000	11.000	-1.64	9.00	4.40	13.50	9.03		0.00	0.00	
3	3	3	1	11.00	1.00000	11.000	-2.63	9.00	4.40	13.50	13.06		0.00	0.00	
4	4	4	1	11.00	1.00000	11.000	-1.70	9.00	4.40	13.50	8.79		0.00	0.00	
5	5	5	1	11.00	1.00000	11.000	-2.47	18.00	8.72	27.00	12.71		0.00	0.00	
6	6	6	1	11.00	1.00000	11.000	-3.51	9.00	4.40	13.50	9.58		0.00	0.00	
7	7	7	1	11.00	1.00000	11.000	-4.41	9.00	4.40	13.50	15.84		0.00	0.00	
8	8	8	1	11.00	0.99202	10.912	-2.37	0.60	0.96				0.00	0.00	
9	9	9	1	11.00	0.99363	10.930	-2.00	1.40	0.70				0.00	0.00	
10	10	10	1	11.00	0.99156	10.907	-2.74	1.05	0.53				0.00	0.00	
11	11	11	1	11.00	0.99068	10.897	-3.43	1.80	0.90				0.00	0.00	
12	12	12	1	11.00	0.98933	10.883	-3.52	1.80	0.90				0.00	0.00	
13	13	13	1	11.00	0.98599	10.846	-3.81	3.30	1.70				0.00	0.00	
14	14	14	1	11.00	0.98398	10.824	-3.87	1.70	0.80				0.00	0.00	
15	15	15	1	11.00	0.98569	10.843	-3.43	3.80	1.90				0.00	0.00	
16	16	16	1	11.00	0.98791	10.867	-3.02	1.05	0.53				0.00	0.00	
17	17	17	1	11.00	0.98611	10.847	-3.32	1.60	0.80				0.00	0.00	
18	18	18	1	11.00	0.98414	10.826	-3.63	2.00	1.00				0.00	0.00	
19	19	19	1	11.00	0.98122	10.793	-4.02	3.60	1.80				0.00	0.00	
20	20	20	1	11.00	0.98210	10.803	-4.07	1.05	0.53				0.00	0.00	
21	21	21	1	11.00	0.99397	10.934	-2.77	1.05	0.53				0.00	0.00	
22	22	22	1	11.00	0.99245	10.917	-3.56	1.80	0.90				0.00	0.00	
23	23	23	1	11.00	0.99065	10.897	-4.40	2.40	1.20				0.00	0.00	
24	24	24	1	11.00	0.98627	10.849	-5.12	1.40	0.70				0.00	0.00	
25	25	25	1	11.00	0.98570	10.843	-5.41	5.60	2.80				0.00	0.00	
26	26	26	1	11.00	0.98088	10.790	-5.65	1.80	0.90				0.00	0.00	
27	27	27	1	11.00	0.98761	10.864	-3.58	1.50	0.80				0.00	0.00	
28	28	28	1	11.00	0.98610	10.847	-4.35	1.70	0.80				0.00	0.00	
29	29	29	1	11.00	0.98363	10.820	-5.01	1.20	0.60				0.00	0.00	
30	30	30	1	11.00	0.97951	10.775	-5.62	1.80	0.90				0.00	0.00	
31	31	31	1	11.00	0.97529	10.728	-6.10	4.80	2.40				0.00	0.00	
32	32	32	1	11.00	0.98223	10.805	-4.88	1.80	0.90				0.00	0.00	

Figure 6 A Snapshot of Simulation Results based on the Year 2020 Projected Load Growth Data using 265 mm^2 Aluminium Conductors

Forty-bus and ninety-two transmission line contingencies were inserted. The evidence of such contingency simulations are also given in Figure 7 and Figure 8 respectively. The projected load growth data for the year 2025 served as the input for the next modelling and simulations using 265 mm^2 aluminium conductors. The snapshot of simulations is given in Figure 9. The evidences of the forty-bus and ninety-two transmission line contingencies are also given in Figure 10 and Figure 11 respectively.

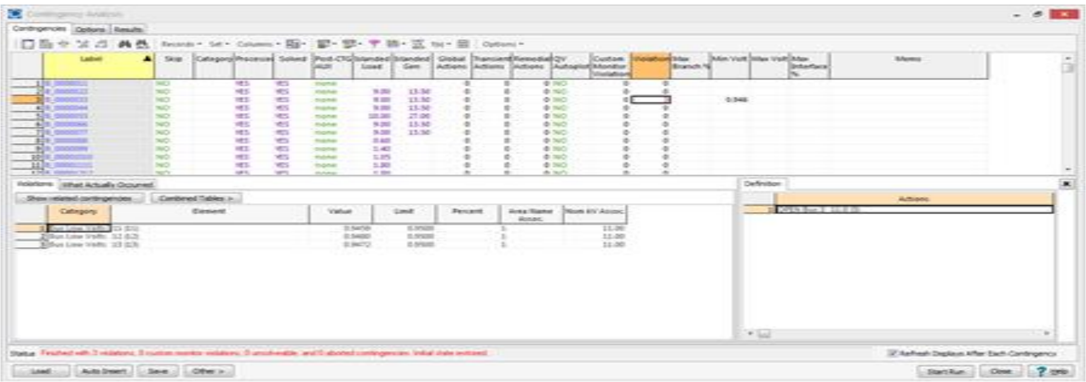


Figure 7 A Snapshot of the Forty-bus Contingency Simulation Results Based on the Year 2020 Projected Load Growth Data using 265 mm^2 Aluminium Conductors

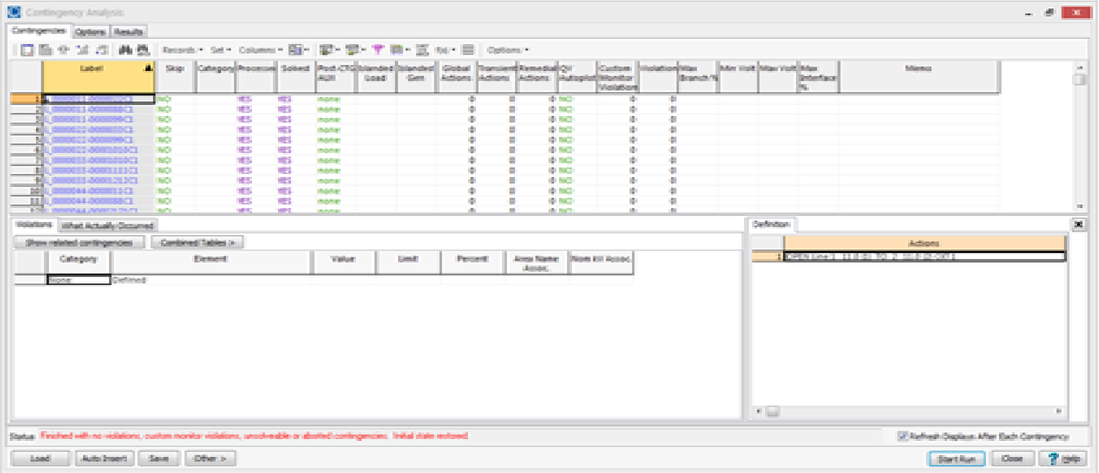
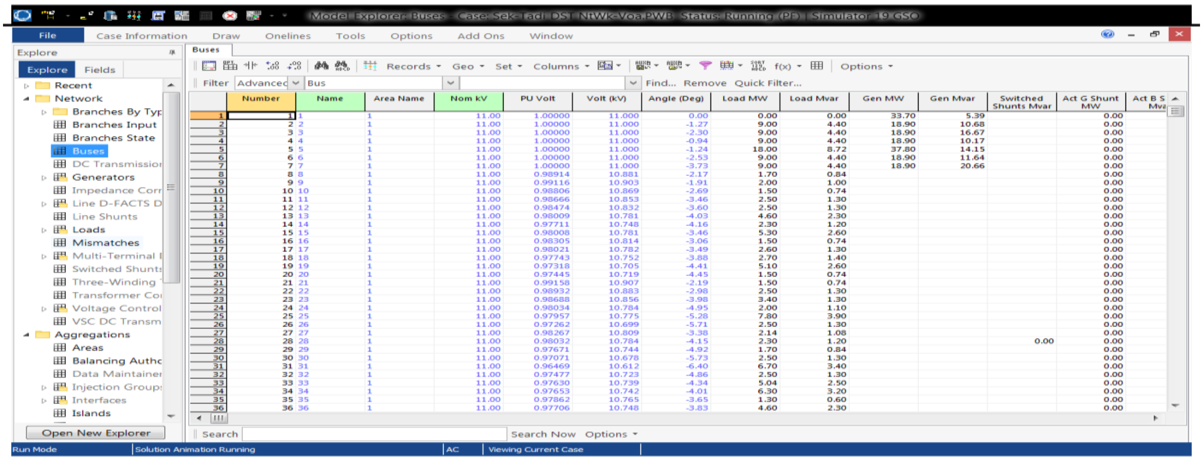
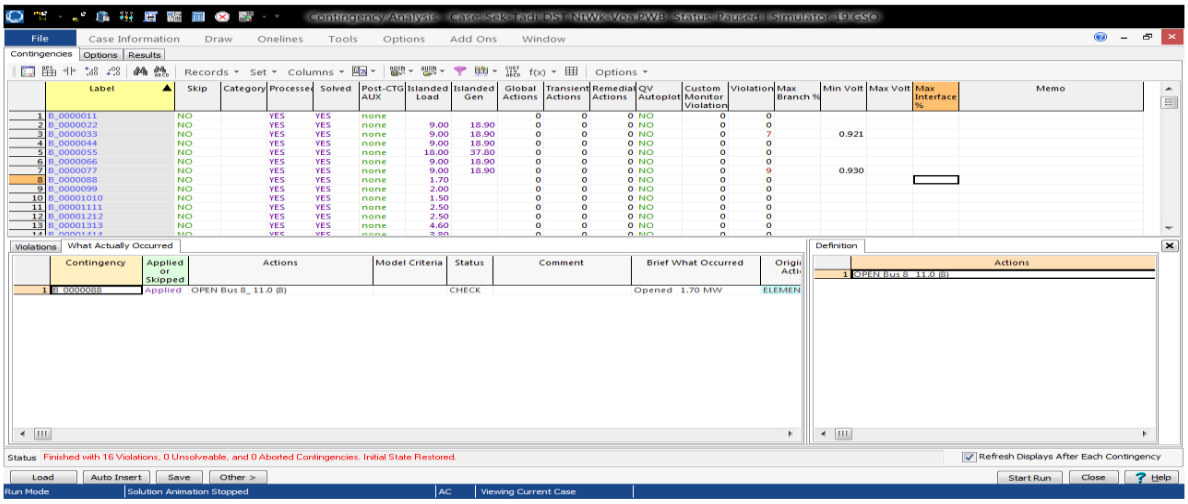


Figure 8 A Snapshot of the Ninety-two Transmission Line Contingency Simulation Results Based on the Year 2020 Projected Load Growth Data using 265 mm^2 Aluminium Conductors



	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 S Mva
1	1	1	1	11.00	1.00000	11.000	0.00	0.00	0.00	33.70	5.39		0.00	
2	2	2	1	11.00	1.00000	11.000	-1.27	9.00	4.40	18.90	10.68		0.00	
3	3	3	1	11.00	1.00000	11.000	-2.30	9.00	4.40	18.90	16.67		0.00	
4	4	4	1	11.00	1.00000	11.000	-0.94	9.00	4.40	18.90	10.17		0.00	
5	5	5	1	11.00	1.00000	11.000	-1.24	18.00	8.72	37.80	14.15		0.00	
6	6	6	1	11.00	1.00000	11.000	-2.53	9.00	4.40	18.90	11.64		0.00	
7	7	7	1	11.00	1.00000	11.000	-3.73	9.00	4.40	18.90	20.66		0.00	
8	8	8	1	11.00	0.98914	10.881	-2.17	1.70	0.84				0.00	
9	9	9	1	11.00	0.99116	10.903	-1.91	2.00	1.00				0.00	
10	10	10	1	11.00	0.98806	10.869	-2.69	1.50	0.74				0.00	
11	11	11	1	11.00	0.98666	10.853	-3.46	2.50	1.30				0.00	
12	12	12	1	11.00	0.98474	10.832	-3.60	2.50	1.30				0.00	
13	13	13	1	11.00	0.98009	10.781	-4.03	4.60	2.30				0.00	
14	14	14	1	11.00	0.97711	10.748	-4.16	2.30	1.20				0.00	
15	15	15	1	11.00	0.98008	10.781	-3.46	5.30	2.60				0.00	
16	16	16	1	11.00	0.98305	10.814	-3.06	1.50	0.74				0.00	
17	17	17	1	11.00	0.98021	10.782	-3.49	2.60	1.30				0.00	
18	18	18	1	11.00	0.97743	10.752	-3.88	2.70	1.40				0.00	
19	19	19	1	11.00	0.97318	10.705	-4.41	5.10	2.60				0.00	
20	20	20	1	11.00	0.97445	10.719	-4.45	1.50	0.74				0.00	
21	21	21	1	11.00	0.99158	10.907	-2.19	1.50	0.74				0.00	
22	22	22	1	11.00	0.98932	10.883	-2.98	2.50	1.30				0.00	
23	23	23	1	11.00	0.98688	10.856	-3.98	3.40	1.30				0.00	
24	24	24	1	11.00	0.98034	10.784	-4.95	2.00	1.10				0.00	
25	25	25	1	11.00	0.97957	10.775	-5.28	7.80	3.90				0.00	
26	26	26	1	11.00	0.97262	10.699	-5.71	2.50	1.30				0.00	
27	27	27	1	11.00	0.98267	10.809	-3.38	2.14	1.08				0.00	
28	28	28	1	11.00	0.98032	10.784	-4.15	2.30	1.20			0.00	0.00	
29	29	29	1	11.00	0.97671	10.744	-4.92	1.70	0.84				0.00	
30	30	30	1	11.00	0.97071	10.678	-5.73	2.50	1.30				0.00	
31	31	31	1	11.00	0.96469	10.612	-6.40	6.70	3.40				0.00	
32	32	32	1	11.00	0.97477	10.723	-4.86	2.50	1.30				0.00	
33	33	33	1	11.00	0.97630	10.739	-4.34	5.04	2.50				0.00	
34	34	34	1	11.00	0.97653	10.742	-4.01	6.30	3.20				0.00	
35	35	35	1	11.00	0.97862	10.765	-3.65	1.30	0.60				0.00	
36	36	36	1	11.00	0.97706	10.748	-3.83	4.60	2.30				0.00	

Figure 9 A Snapshot of Simulation Results based on the Year 2025 Projected Load Growth Data using 265 mm^2 Aluminium Conductors



	Label	Skip	Category	Processed	Solved	Post-CTG AUX	Islanded Load	Islanded Gen	Global Actions	Transient Actions	Remedial Actions	QV Autoplot	Custom Monitor Violation	Violation	Max Branch %	Min Volt	Max Volt	Max Interface %	Memo
1	B_0000011	NO		YES	YES	none			0	0	0	NO	0	0					
2	B_0000022	NO		YES	YES	none	9.00	18.90	0	0	0	NO	0	0					
3	B_0000033	NO		YES	YES	none	9.00	18.90	0	0	0	NO	0	7		0.921			
4	B_0000044	NO		YES	YES	none	9.00	18.90	0	0	0	NO	0	0					
5	B_0000055	NO		YES	YES	none	18.00	37.80	0	0	0	NO	0	0					
6	B_0000066	NO		YES	YES	none	9.00	18.90	0	0	0	NO	0	0					
7	B_0000077	NO		YES	YES	none	9.00	18.90	0	0	0	NO	0	9		0.930			
8	B_0000088	NO		YES	YES	none	1.70		0	0	0	NO	0	0					
9	B_0000099	NO		YES	YES	none	2.00		0	0	0	NO	0	0					
10	B_00001010	NO		YES	YES	none	1.50		0	0	0	NO	0	0					
11	B_00001111	NO		YES	YES	none	2.50		0	0	0	NO	0	0					
12	B_00001212	NO		YES	YES	none	2.50		0	0	0	NO	0	0					
13	B_00001313	NO		YES	YES	none	4.60		0	0	0	NO	0	0					

	Contingency	Applied or Skipped	Actions	Model Criteria	Status	Comment	Brief What Occurred	Origi Acti
1	B_0000088	Applied	OPEN Bus 8_ 11.0 (8)		CHECK		Opened 1.70 MW	ELEMEN

	Actions
1	OPEN Bus 8_ 11.0 (8)

Status Finished with 16 Violations, 0 Unsolveable, and 0 Aborted Contingencies. Initial State Restored.

☑ Refresh Displays After Each Contingency

Figure 10 A Snapshot of the Forty-bus Contingency Simulation Results based on the Year 2025 Projected Load Growth Data using 265 mm^2 Conductors

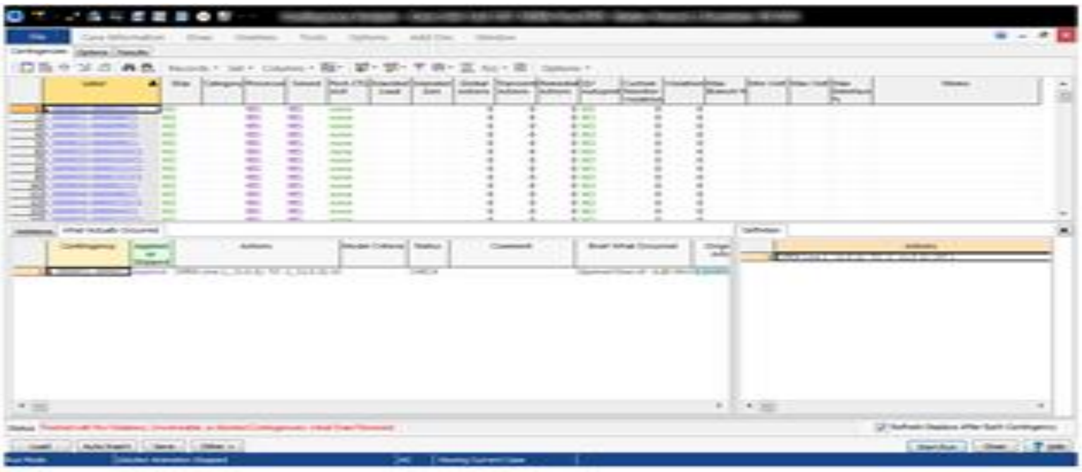
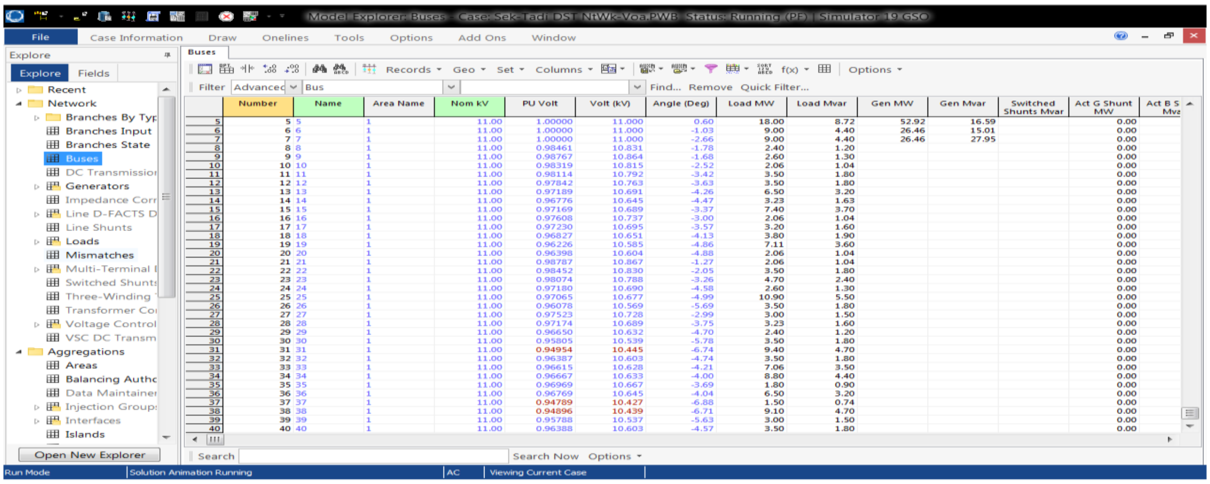


Figure 11 A Snapshot of the Ninety-two Transmission Line Contingency Simulation Results based on the Year 2025 Projected Load Growth Data

The projected load growth data for the year 2030 was also modelled in the PowerWorld Simulator version 19 GSO using the 265 mm2 conductor size. The evidence of that simulation is given in Figure 12.



	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 S Mva
5	5	5	1	11.00	1.00000	11.000	0.60	18.00	8.72	52.92	16.59		0.00	
6	6	6	1	11.00	1.00000	11.000	-1.03	9.00	4.40	26.46	15.01		0.00	
7	7	7	1	11.00	1.00000	11.000	-2.66	9.00	4.40	26.46	27.95		0.00	
8	8	8	1	11.00	0.98461	10.831	-1.78	2.40	1.20				0.00	
9	9	9	1	11.00	0.98767	10.864	-1.68	2.60	1.30				0.00	
10	10	10	1	11.00	0.98319	10.815	-2.52	2.06	1.04				0.00	
11	11	11	1	11.00	0.98114	10.792	-3.42	3.50	1.80				0.00	
12	12	12	1	11.00	0.97842	10.763	-3.63	3.50	1.80				0.00	
13	13	13	1	11.00	0.97189	10.691	-4.26	6.50	3.20				0.00	
14	14	14	1	11.00	0.96776	10.645	-4.47	3.23	1.63				0.00	
15	15	15	1	11.00	0.97169	10.689	-3.37	7.40	3.70				0.00	
16	16	16	1	11.00	0.97608	10.737	-3.00	2.06	1.04				0.00	
17	17	17	1	11.00	0.97230	10.695	-3.57	3.20	1.60				0.00	
18	18	18	1	11.00	0.96827	10.651	-4.13	3.80	1.90				0.00	
19	19	19	1	11.00	0.96226	10.585	-4.86	7.11	3.60				0.00	
20	20	20	1	11.00	0.96398	10.604	-4.88	2.06	1.04				0.00	
21	21	21	1	11.00	0.98787	10.867	-1.27	2.06	1.04				0.00	
22	22	22	1	11.00	0.98452	10.830	-2.05	3.50	1.80				0.00	
23	23	23	1	11.00	0.98074	10.788	-3.26	4.70	2.40				0.00	
24	24	24	1	11.00	0.97180	10.690	-4.58	2.60	1.30				0.00	
25	25	25	1	11.00	0.97065	10.677	-4.99	10.90	5.50				0.00	
26	26	26	1	11.00	0.96078	10.569	-5.69	3.50	1.80				0.00	
27	27	27	1	11.00	0.97523	10.728	-2.99	3.00	1.50				0.00	
28	28	28	1	11.00	0.97174	10.689	-3.75	3.23	1.60				0.00	
29	29	29	1	11.00	0.96650	10.632	-4.70	2.40	1.20				0.00	
30	30	30	1	11.00	0.95805	10.539	-5.78	3.50	1.80				0.00	
31	31	31	1	11.00	0.94954	10.445	-6.74	9.40	4.70				0.00	
32	32	32	1	11.00	0.96387	10.603	-4.74	3.50	1.80				0.00	
33	33	33	1	11.00	0.96615	10.628	-4.21	7.06	3.50				0.00	
34	34	34	1	11.00	0.96667	10.633	-4.00	8.80	4.40				0.00	
35	35	35	1	11.00	0.96969	10.667	-3.69	1.80	0.90				0.00	
36	36	36	1	11.00	0.96769	10.645	-4.04	6.50	3.20				0.00	
37	37	37	1	11.00	0.94789	10.427	-6.88	1.50	0.74				0.00	
38	38	38	1	11.00	0.94896	10.439	-6.71	9.10	4.70				0.00	
39	39	39	1	11.00	0.95788	10.537	-5.63	3.00	1.50				0.00	
40	40	40	1	11.00	0.96388	10.603	-4.57	3.50	1.80				0.00	

Figure 12 A Snapshot of Simulation Results based on the Year 2030 Load Growth Data using 265 mm^2 Conductors

After the simulations, it was noted that three (3) of the buses had their per unit voltages below the 0.95 p.u. minimum threshold. The following buses had that problem: 31, 37 and 38. Under this condition, any attempt to insert any contingency would result in a lot of violations. A switch shunt compensation is required. The sizes of the various switch shunt capacitors required at each of the three buses were determined using Equation (8) i.e.:

$$\text{MVAr} = P\,(\tan\theta 1 - \tan\theta 2)$$

The results are as given in Table 2.

Table 2 MVAr Capacity Determination for Voltage Improvement

Bus Number	Angle (Deg.)	MVAr Calculation	MVAr Size
31	– 6.74	9.4 [(0.4843) – (– 0.1182)]	5.7
37	– 6.88	1.5 [(0.4843) – (– 0.1207)]	0.91
38	– 6.71	9.10 [(0.4843)–(– 0.1177)]	5.5
	Total		**12.11**

The calculated MVAr of approximate size of 12 was placed at bus number 31 as given in Figure 13. The simulation was carried out to ascertain the level of voltages after the compensation at the buses experiencing low voltages. The evidence of the simulation is given in Figure 14. Based on the encouraging results, a forty-bus and ninety-two transmission line contingencies were inserted. The snapshots of the contingency simulations are given in Figure 15 and Figure 16, respectively.

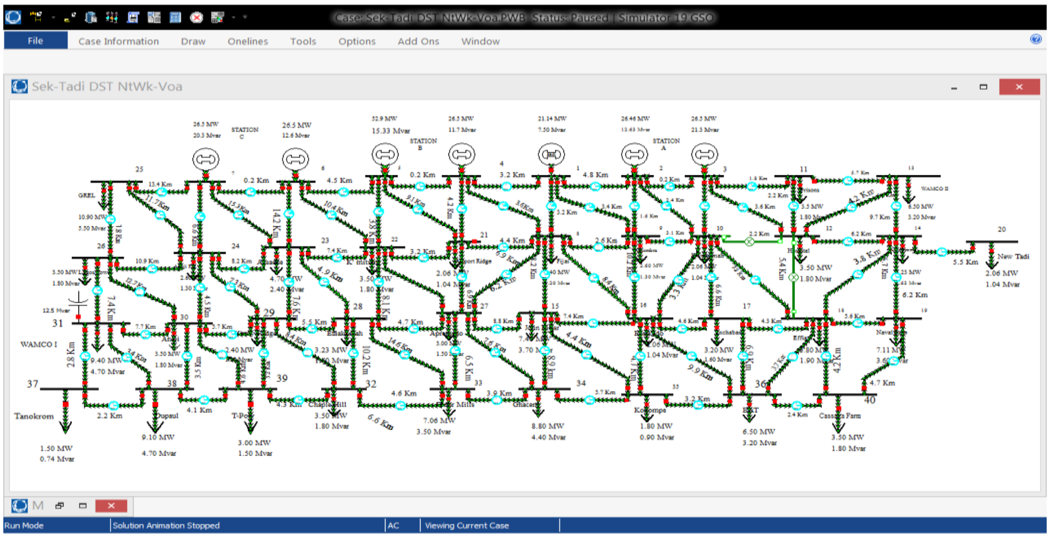
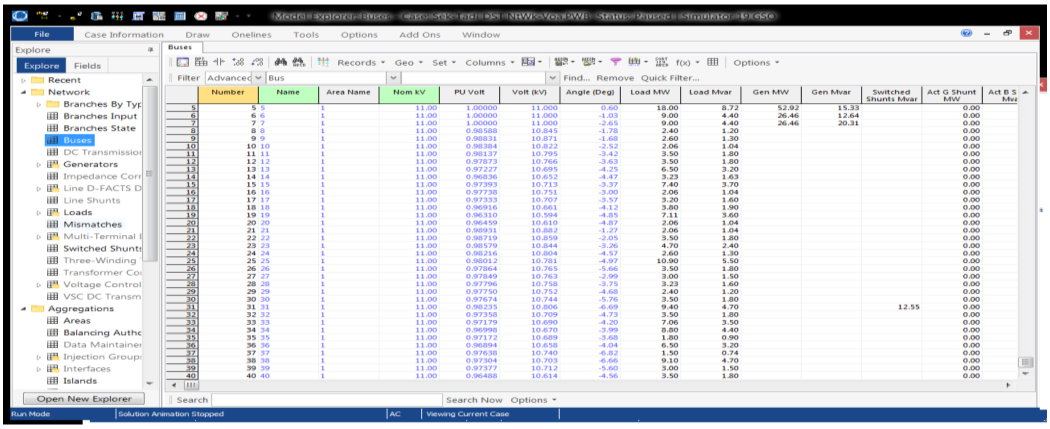
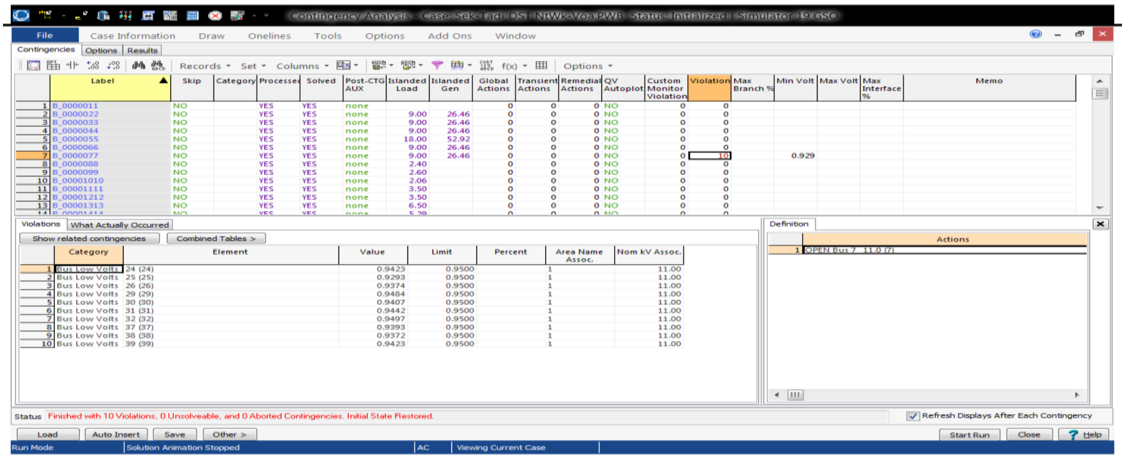


Figure 13 The Compensated Distribution Network with Switch Shunt Capacitors Placed at Busbar Number Thirty-one



	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 S Mva
5	5	5	1	11.00	1.00000	11.000	0.60	18.00	8.72	52.92	15.33		0.00	
6	6	6	1	11.00	1.00000	11.000	-1.03	9.00	4.40	26.46	12.64		0.00	
7	7	7	1	11.00	1.00000	11.000	-2.65	9.00	4.40	26.46	20.31		0.00	
8	8	8	1	11.00	0.98588	10.845	-1.78	2.40	1.20				0.00	
9	9	9	1	11.00	0.98831	10.871	-1.68	2.60	1.30				0.00	
10	10	10	1	11.00	0.98384	10.822	-2.52	2.06	1.04				0.00	
11	11	11	1	11.00	0.98137	10.795	-3.42	3.50	1.80				0.00	
12	12	12	1	11.00	0.97873	10.766	-3.63	3.50	1.80				0.00	
13	13	13	1	11.00	0.97227	10.695	-4.25	6.50	3.20				0.00	
14	14	14	1	11.00	0.96836	10.652	-4.47	3.23	1.63				0.00	
15	15	15	1	11.00	0.97393	10.713	-3.37	7.40	3.70				0.00	
16	16	16	1	11.00	0.97738	10.751	-3.00	2.06	1.04				0.00	
17	17	17	1	11.00	0.97333	10.707	-3.57	3.20	1.60				0.00	
18	18	18	1	11.00	0.96916	10.661	-4.12	3.80	1.90				0.00	
19	19	19	1	11.00	0.96310	10.594	-4.85	7.11	3.60				0.00	
20	20	20	1	11.00	0.96459	10.610	-4.87	2.06	1.04				0.00	
21	21	21	1	11.00	0.98931	10.882	-1.27	2.06	1.04				0.00	
22	22	22	1	11.00	0.98719	10.859	-2.05	3.50	1.80				0.00	
23	23	23	1	11.00	0.98579	10.844	-3.26	4.70	2.40				0.00	
24	24	24	1	11.00	0.98216	10.804	-4.57	2.60	1.30				0.00	
25	25	25	1	11.00	0.98012	10.781	-4.97	10.90	5.50				0.00	
26	26	26	1	11.00	0.97864	10.765	-5.66	3.50	1.80				0.00	
27	27	27	1	11.00	0.97849	10.763	-2.99	3.00	1.50				0.00	
28	28	28	1	11.00	0.97796	10.758	-3.75	3.23	1.60				0.00	
29	29	29	1	11.00	0.97750	10.752	-4.68	2.40	1.20				0.00	
30	30	30	1	11.00	0.97674	10.744	-5.76	3.50	1.80				0.00	
31	31	31	1	11.00	0.98235	10.806	-6.69	9.40	4.70			12.55	0.00	
32	32	32	1	11.00	0.97358	10.709	-4.73	3.50	1.80				0.00	
33	33	33	1	11.00	0.97179	10.690	-4.20	7.06	3.50				0.00	
34	34	34	1	11.00	0.96998	10.670	-3.99	8.80	4.40				0.00	
35	35	35	1	11.00	0.97172	10.689	-3.68	1.80	0.90				0.00	
36	36	36	1	11.00	0.96894	10.658	-4.04	6.50	3.20				0.00	
37	37	37	1	11.00	0.97638	10.740	-6.82	1.50	0.74				0.00	
38	38	38	1	11.00	0.97304	10.703	-6.66	9.10	4.70				0.00	
39	39	39	1	11.00	0.97377	10.712	-5.60	3.00	1.50				0.00	
40	40	40	1	11.00	0.96488	10.614	-4.56	3.50	1.80				0.00	

Figure 14 A Snapshot of the Simulated Results with Switched Shunt Capacitors based on Year 2030 Projected Load Growth Data



	Label	Skip	Category	Processe	Solved	Post-CTG AUX	Islanded Load	Islanded Gen	Global Actions	Transient Actions	Remedial Actions	QV Autoplot	Custom Monitor Violation	Violation	Max Branch %	Min Volt	Max Volt	Max Interface %	Memo
1	B_0000011	NO		YES	YES	none			0	0	0	NO	0	0					
2	B_0000022	NO		YES	YES	none	9.00	26.46	0	0	0	NO	0	0					
3	B_0000033	NO		YES	YES	none	9.00	26.46	0	0	0	NO	0	0					
4	B_0000044	NO		YES	YES	none	9.00	26.46	0	0	0	NO	0	0					
5	B_0000055	NO		YES	YES	none	18.00	52.92	0	0	0	NO	0	0					
6	B_0000066	NO		YES	YES	none	9.00	26.46	0	0	0	NO	0	0					
7	B_0000077	NO		YES	YES	none	9.00	26.46	0	0	0	NO	0	10		0.929			
8	B_0000088	NO		YES	YES	none	2.40		0	0	0	NO	0	0					
9	B_0000099	NO		YES	YES	none	2.60		0	0	0	NO	0	0					
10	B_00001010	NO		YES	YES	none	2.06		0	0	0	NO	0	0					
11	B_00001111	NO		YES	YES	none	3.50		0	0	0	NO	0	0					
12	B_00001212	NO		YES	YES	none	3.50		0	0	0	NO	0	0					
13	B_00001313	NO		YES	YES	none	6.50		0	0	0	NO	0	0					

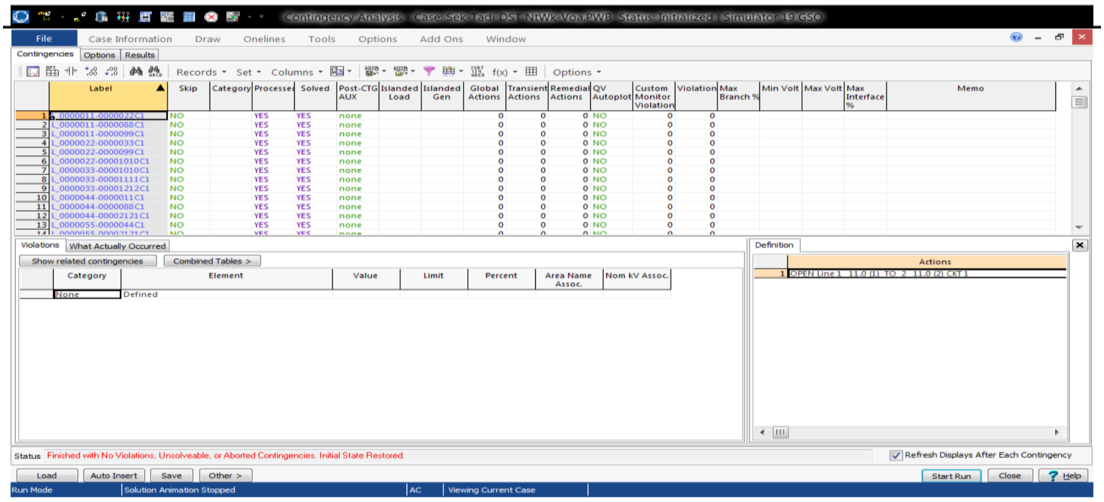
	Category	Element	Value	Limit	Percent	Area Name Assoc.	Nom kV Assoc.
1	Bus Low Volts	24 (24)	0.9423	0.9500		1	11.00
2	Bus Low Volts	25 (25)	0.9293	0.9500		1	11.00
3	Bus Low Volts	26 (26)	0.9374	0.9500		1	11.00
4	Bus Low Volts	29 (29)	0.9484	0.9500		1	11.00
5	Bus Low Volts	30 (30)	0.9407	0.9500		1	11.00
6	Bus Low Volts	31 (31)	0.9442	0.9500		1	11.00
7	Bus Low Volts	32 (32)	0.9497	0.9500		1	11.00
8	Bus Low Volts	37 (37)	0.9393	0.9500		1	11.00
9	Bus Low Volts	38 (38)	0.9372	0.9500		1	11.00
10	Bus Low Volts	39 (39)	0.9423	0.9500		1	11.00

	Actions
1	OPEN Bus 7 11.0 (7)

Status Finished with 10 Violations, 0 Unsolveable, and 0 Aborted Contingencies. Initial State Restored.

☑ Refresh Displays After Each Contingency

Figure 15 A Snapshot of Forty-bus Contingency Simulation Results with Switched Shunt Capacitors based on the Year 2030 Load Growth Data



	Label	Skip	Category	Processe	Solved	Post-CTG AUX	Islanded Load	Islanded Gen	Global Actions	Transient Actions	Remedial Actions	QV Autoplot	Custom Monitor Violation	Violation	Max Branch %	Min Volt	Max Volt	Max Interface %	Memo
1	L_0000011-0000022C1	NO		YES	YES	none			0	0	0	NO	0	0					
2	L_0000011-0000088C1	NO		YES	YES	none			0	0	0	NO	0	0					
3	L_0000011-0000099C1	NO		YES	YES	none			0	0	0	NO	0	0					
4	L_0000022-0000033C1	NO		YES	YES	none			0	0	0	NO	0	0					
5	L_0000022-0000099C1	NO		YES	YES	none			0	0	0	NO	0	0					
6	L_0000022-00001010C1	NO		YES	YES	none			0	0	0	NO	0	0					
7	L_0000033-00001010C1	NO		YES	YES	none			0	0	0	NO	0	0					
8	L_0000033-00001111C1	NO		YES	YES	none			0	0	0	NO	0	0					
9	L_0000033-00001212C1	NO		YES	YES	none			0	0	0	NO	0	0					
10	L_0000044-0000011C1	NO		YES	YES	none			0	0	0	NO	0	0					
11	L_0000044-0000088C1	NO		YES	YES	none			0	0	0	NO	0	0					
12	L_0000044-00002121C1	NO		YES	YES	none			0	0	0	NO	0	0					
13	L_0000055-0000044C1	NO		YES	YES	none			0	0	0	NO	0	0					

	Category	Element	Value	Limit	Percent	Area Name Assoc.	Nom kV Assoc.
	None	Defined					

	Actions
1	OPEN Line 1 11.0 (1) TO 2 11.0 (2) CKT 1

Status Finished with No Violations, Unsolveable, or Aborted Contingencies. Initial State Restored.

☑ Refresh Displays After Each Contingency

Figure 16 A Snapshot of Ninety-two Transmission Line Contingency Simulation Results with Switched Shunt Capacitors based on the Year 2030 Load Growth Data

Based on the phasor diagram of Figure 6, the reduced voltage drops, V_D along a series compensated transmission line is given by Equation (6) according to (Kranti and Laxmi, 2011).

IV. Results And Discussions

Presented in this section are the results emanating from the investigation into the ability of conductor size upgrading to sustain the load growth beyond the year 2030 which were obtained through modelling and simulations of the network. The results are presented in Figure 17, Figure 18 and Figure 19 for the years 2020 and 2025. Two simulations were performed for the year 2030. The first simulation was without switched shunt compensation and the second simulation was after switched shunt compensation was effected. Figure 20 and Figure 21 represent these results. From Figure 17, for the year 2020 using 150 mm^2 conductors, no p.u. voltage at the buses fell below the 0.95 minimum. The results of the forty-bus contingency simulations however, gave a total of eight (8) low voltage violations during the contingency simulations. This gives an indication that conductor upgrading or switched shunt compensation is required. There was not any violation noted when the ninety-two transmission line contingencies were inserted. For the year 2020 using 265 mm2 conductors, from Figure 18 all the p.u. voltages were within the acceptable range of 0.95 to 1.05 limits.

The forty-bus contingency results showed that there was only one low voltage violation at bus number 3. The results of the ninety-two transmission line contingencies showed no violation. This points to the fact that conductor size of 265 mm^2 can sustain the projected load growth of the year 2020 without any serious violations. Justifying from Figure 19, for the year 2025 using 265 mm^2 conductor size, the p.u. voltage magnitudes were all within the acceptable limits of 0.95 and 1.05. From the forty-bus contingency simulations, nineteen (19) low voltage violations were obtained but the results of ninety-two transmission line contingency simulations showed no single violation. These showed that the 265 mm^2 aluminium conductors can withstand the projected load growth for the year 2025. For the year 2030 using 265 mm^2 conductor size without switched shunt compensations from Figure 20, three (3) of the buses had their p.u. voltage magnitudes below the 0.95 minimum threshold. Any attempt therefore to insert any contingency would result in serious voltage violations at most of the buses. Switched shunt compensation was implemented. From Figure 21, all the p.u. voltage magnitude variations were within the acceptable limit range of 0.95 to 1.05.

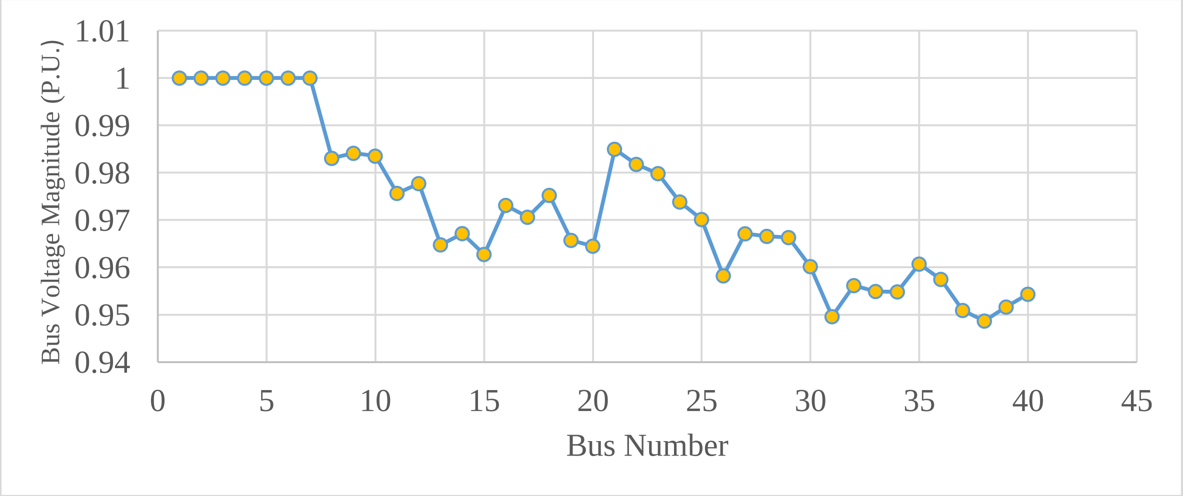


Figure 17 Simulated Bus Voltages for the Year 2020 using 150 mm^2 Conductors

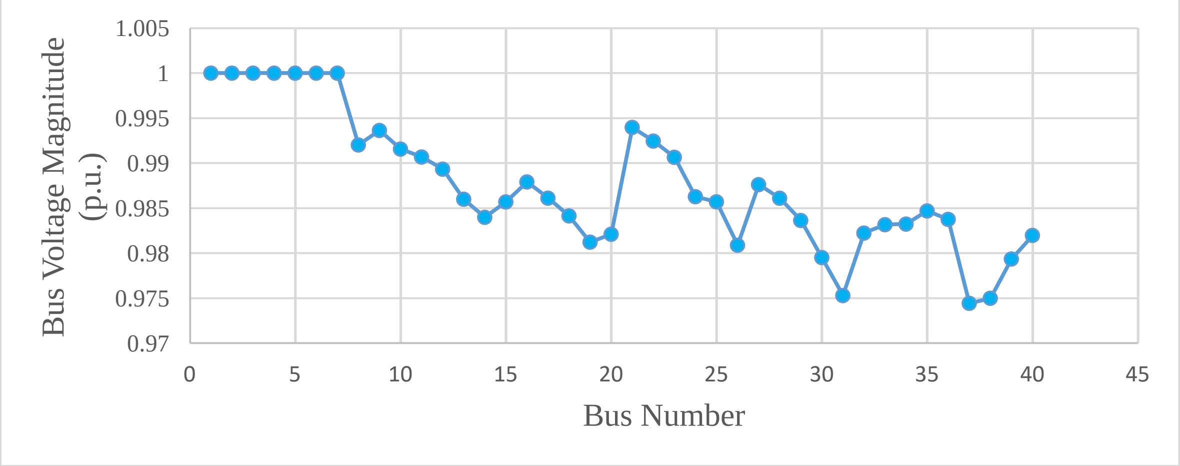


Figure 18 Simulated Bus Voltages for the Year 2020 using 265 mm^2 Conductors

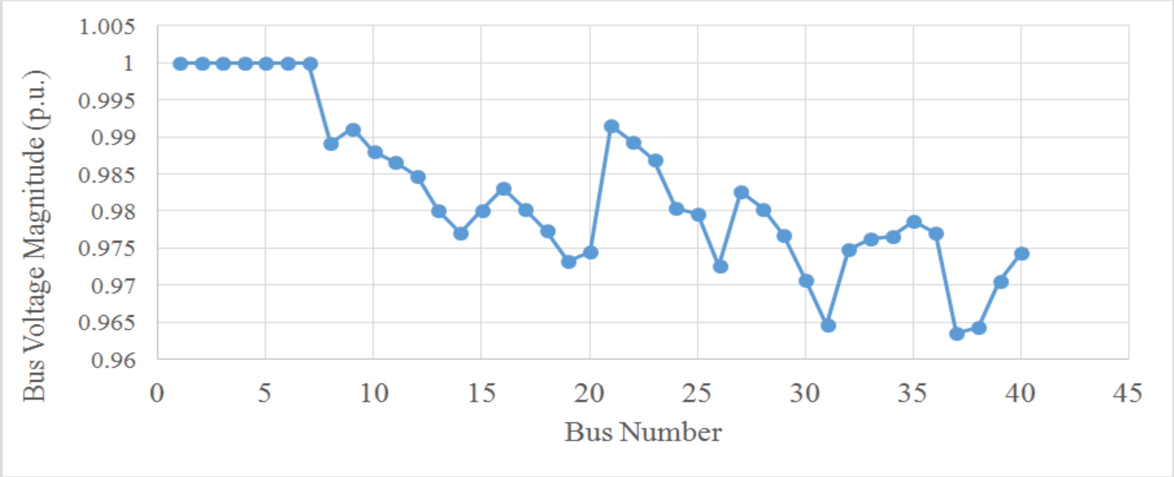


Figure 19 Simulated Bus Voltages for the Year 2025 using 265 mm^2 Conductors

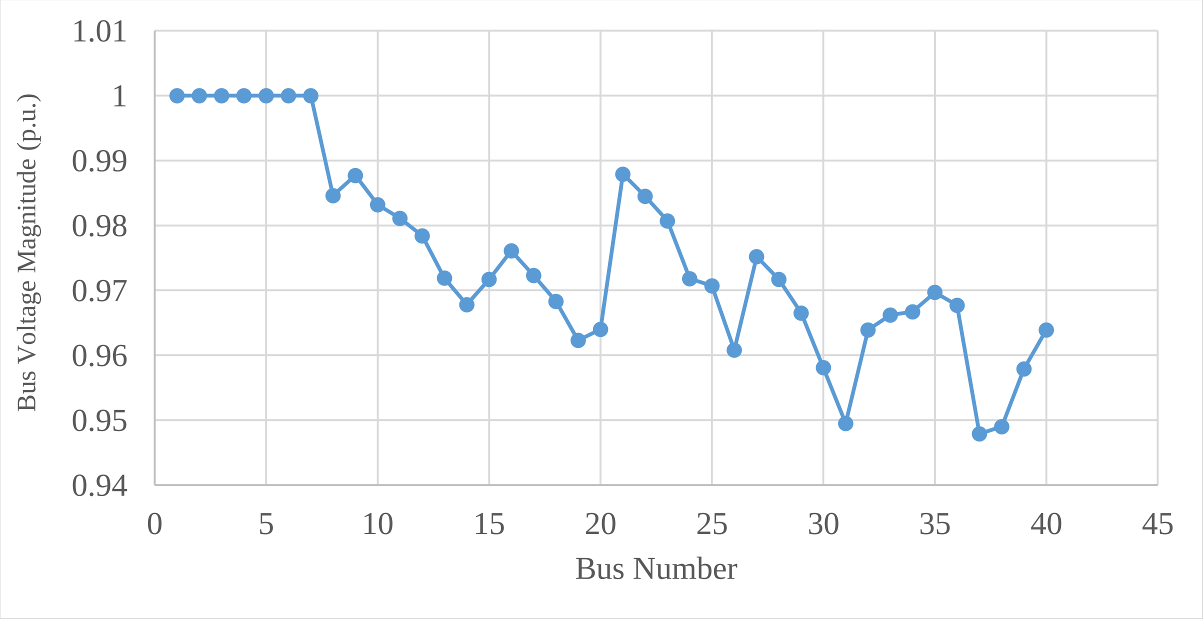


Figure 20 Simulated Bus Voltages for the Year 2030 using 265 mm^2 Conductors without Switched Shunt Capacitor Compensation

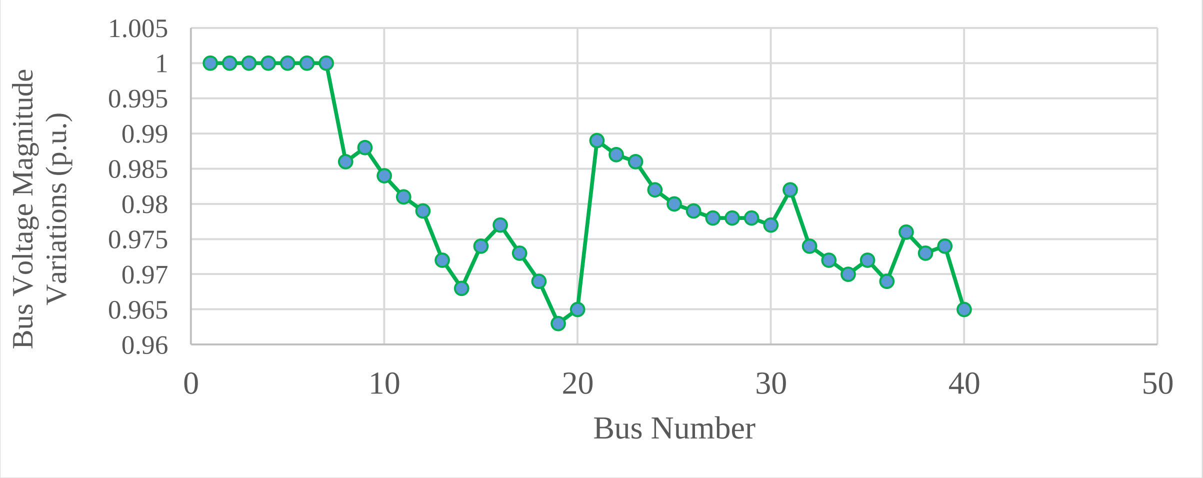


Figure 21 Simulated Bus Voltages for the Year 2030 using 265 mm^2 Conductors with Switched Shunt Capacitor Compensation

V. Conclusion

The present use of 150 mm^2 conductor size result in voltage violations giving an indication that the network is not immune to N-1 contingency. Use of 265 mm^2 aluminium conductor size will enable the distribution network sustain the projected annual load growth up to the year 2030. Beyond the year 2030, switch shunt compensation will be required to enable the 265 mm^2 aluminium conductors sustain further load growth.

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