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Load flow and contingency analysis for transmission line outage

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Abstract: In recent years, power systems have been pushed to operate above their limits due to the increase in the demand for energy supply and its usage. This increase is accompanied by various kinds of obstructions in power transmission systems. A power system is said to be secured when it is free from danger or risk. Power systems security deals with the ability of the system to withstand any contingencies without any consequences. Contingencies are potentially harmful disturbances which occur during the steady state operation of a power system. Load flow constitutes the most important study in a power system for planning, operation, and expansion. Contingency selection is performed by calculating two kinds of performance indices; an active performance index (PIP) and reactive power performance index (PIV) for a single transmission line outage. In this paper, with the help of the Newton Raphson method, the PIP and PIV were calculated with DIgSILENT Power Factory simulation software and contingency ranking was performed. Based on the load flow results and performance indexes, the Ethiopian Electric Power (EEP) North-West region network is recommended for an upgrade or the reactive power or series compensators should be constructed on the riskiest lines and substations.

Key words: contingency analysis, DIgSILENT software, line outage, Newton Raphson method

1. Introduction

The number of times and the durations of the different types of transmission line outages has significant impact on the operation and reliability of industrial and commercial power systems [1, 2].

Contingency is the failure of any power system equipment on a network as a result of power system related problems [3, 4]. This failure could be caused by component failure or transmission line congestion which in turn lead to line outage. The transmission line congestion is caused by either overloading or underloading of the overall transmission network. The overloading or underloading of the transmission network therefore leads to power system component failure. In such situations, contingency analysis is introduced to enhance the effective operation of the power system and to secure the system from any unforeseen occurrence.

This security measure is implemented by obtaining and evaluating operating limits of the system in the pre-contingency and post-contingency operating states at an operation control center. The contingency analysis, therefore, helps to minimise the incidence of failure in a power system as a result of loss or failure of system components [5, 6].

The contingency calculation involves the calculation of the AC load flow as a result of outages which may occur at various generators and transmission lines. These and many more constitute the numerous cases of contingency making it a very lengthy and very tedious process. In order to mitigate against the aforementioned challenges, automatic contingency screening approaches are being adopted to identify and rank only those outages which actually cause the limit violation on power flow or voltages in the lines. The contingencies are screened according to the severity index or performance index where a higher value of these indices denotes a higher degree of severity [7].

The Ethiopian electric power transmission network is a complicated network as a result of its centralized grid interconnection system. Therefore, a loss of one transmission line from the network will gradually affect the rest of the network. This is observed especially in the North-West region of Ethiopia which has frequent security issues.

2. Modelling and analysis of transmission line contingency

Contingency modelling comprises of the analysis and simulation of each component on the existing model of a power system. Three major challenges arise from this analysis. The first is to develop an appropriate power system model [8]. The second is the appropriate choice of the contingency to be considered, and the third challenge is how to efficiently compute the line flow and bus voltages to reduce huge time consumption in the Energy Management System (EMS). Therefore, it is better to restrict and separate the on-line contingency analysis into three different stages, namely: contingency definition, selection, and evaluation [9].

2.1. Contingency analysis using sensitivity factors

Sensitivity factors for contingency analysis can be derived in a variety of ways and are basically divided into two types, namely:

a) generation shift factors,

b) line outage distribution factors.

The generation shift factor is designated as α_{Li} and has the following definition [10]:

$$\alpha_{Li} = \frac{\Delta P_L}{\Delta P_i}, \tag{1}$$

where: L is the line index, i is the bus index, ΔP_L is the change in real power flow on line L with respect to the change in real power flow on bus i, and ΔP_i is the change of real power generated at bus i.

The change in real power generated at bus i is virtually recovered by the reference bus real power change, i.e. loss in real power generated is equivalent to its change as given in (2).

$$\Delta P_i = -P_i^o . \tag{2}$$

Thus, power flow on each line in the power network can be determined by an anticipative factor α given as:

$$P_L = P_L^o + \alpha_{Li} \Delta P_i , \tag{3}$$

where: P_L is the post-real power flow on line L under a generator outage, and P_L^o is the pre-real power flow on line L.

The line outage distribution factors are used in a similar manner as they only apply to the test for overloading when transmission circuits fail. This is achieved by defining the line outage distribution factor as:

$$d_{n,m} = \frac{\Delta P_n}{P_m^o} , \tag{4}$$

where: $d_{n,m}$ is the line outage distribution factor for monitoring line n on the outage of line m, ΔP_n is the post-change in the real power flow in line n, and P_m^o is the pre-real power flow in line m.

Consider both cases, power flow in line n and m before the outage of line m, and the post-real power flow in the line outage distribution factor as:

$$P_n = P_n^o + d_{n,m} P_m^o , \tag{5}$$

where: P_n^o and P_m^o are the pre-outage flows of line n and m, respectively, and P_n is the post-real power flow on line n under the line m outage.

2.2. Contingency selection

The process of contingency selection is needed to help stabilize power systems and for transmission expansion planning [9, 10]. Usually, the selection of contingency for specific elements in a power system is based on the power system planners and stakeholders. This process actually deals with identifying the contingencies that actually leads to the violation of the operational limits. The identification can be done by calculating the severity indices known as performance indices (PI) [11]. These indices are derived from the conventional power flow algorithm for individual contingencies in the off line mode. Based on the values obtained, ranking is done from the highest to the least. This process is continued till no severe contingencies are found.

There are two kind of PI which are of great use. These are the: active power performance index (PIP) and reactive power performance index (PIV) [12].

PIP is the violation of line active power flow which can be calculated as:

$$\mathrm{PIP} = \sum_{i=1}^{L} \left(\frac{P_i}{P_{i\,\max}} \right)^{2n} , \tag{6}$$

where: P_i is the active power flow in line L, $P_i^{\max}$ is the maximum active power flow in line L, n is the specified exponent, and L is the total number of transmission lines in the system.

The value of the maximum power flow ($P^{\max}$) in each line is calculated using the formula:

$$P_i^{\max} = \frac{V_i \cdot V_j}{X}, \tag{7}$$

where: V_i is the voltage of bus i, V_j is the voltage at bus j, and X is the reactance of the line connecting bus i and bus j.

Another performance index parameter, which is used, is the reactive power performance index corresponding to bus voltage magnitude violations, $\mathrm{P_{IV}}$. This is mathematically given as:

$$\mathrm{P_{IV}} = \sum_{i=1}^{Npq} \left[\frac{2\left(V_i - V_{i\mathrm{nom}}\right)}{V_{i\max} - V_{i\min}} \right]^2, \tag{8}$$

where: V_i is the voltage of bus i, $V_{i\max}$ and $V_{i\min}$ are the maximum and minimum voltage limits, $V_{i\mathrm{nom}}$ is the average of voltages $V_{i\max}$ and $V_{i\min}$, and N_{pq} is the total number of load buses in the system.

2.3. Newton-Raphson method

The Newton-Raphson (NR) method is one of the most widely used efficient methods for solving power flow and large power system problems [13]. This iterative method has proven to be fast in terms of computation speed and the size of the problem doesn't determine the number of iterations required to obtain a solution.

2.3.1. DigSILENT power factory simulation software

DIgSILENT power factory simulation software is a digital simulator used for the analysis of electrical power networks [14, 15]. DigSILENT power factory software uses the NR method to solve non-linear equations. In the software, the selection of the method used to formulate the nodal equations are user-defined based on the type of network to be analyzed. The NR method is used in this work because of its fast convergence when the power equations are used for large transmission systems.

In this software, the nodal equations represent the analyzed networks and are implemented using two different ways:

1) NR (current equations),
2) NR (power equations, classical).

In both ways, the resulting equations from the non-linear systems must be solved by an iterative method.

The flowchart for contingency selection for the transmission line is shown in Fig. 1. The designed algorithm was implemented with the DIgSILENT software.

2.4. Contingency analysis algorithm

The developed algorithm used for contingency analysis is given with the following steps:

1. Draw the proposed one-line diagram in a new case window of the power factory simulator (DIgSILENT).
2. Select the run mode icon.
3. Select the one-line diagram or load flow analysis in the tool menu.

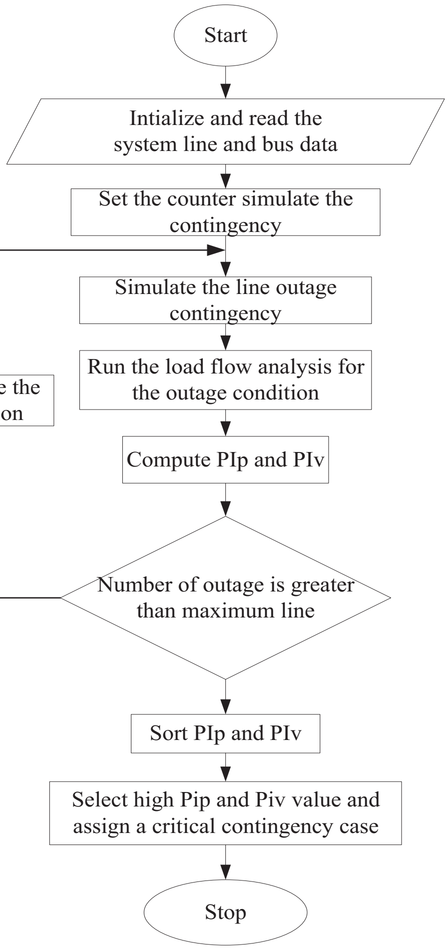

Fig. 1. Flowchart of the contingency selection procedure

4. Select contingency analysis in the tool menu, then open the contingency analysis dialogue box.
5. Use the insert special options menu to auto-insert contingencies.
6. Verify that a single transmission line or transformer is selected.
7. Limit the contingencies inserted to only those meeting a defined filter.
8. Apply overloading or a line outage.
9. Check filter zones to verify.
10. Click the insert contingencies button to accept all contingencies.
11. Click YES to get the contingencies.
12. Now the contingency analysis dialog shows contingencies.
    a) Right click on the list display on the contingency tap and select insert special and click auto-insert to the local menu.
    b) Select a single generating unit then click the do insert contingencies button. Click YES to complete.

13. The auto-insert tool will not insert a contingency for the generator connected to the slack bus.
14. Click "start run" on the contingencies tab and click start on the summary tab or run contingency.
15. Select the maximum violation of contingency analysis to be taken into account in the secured dispatch for the deregulation of power market.

3. Results and discussion

In this section, we propose a single line power system network for the Ethiopian North-West region network. This is shown in Fig. 2.

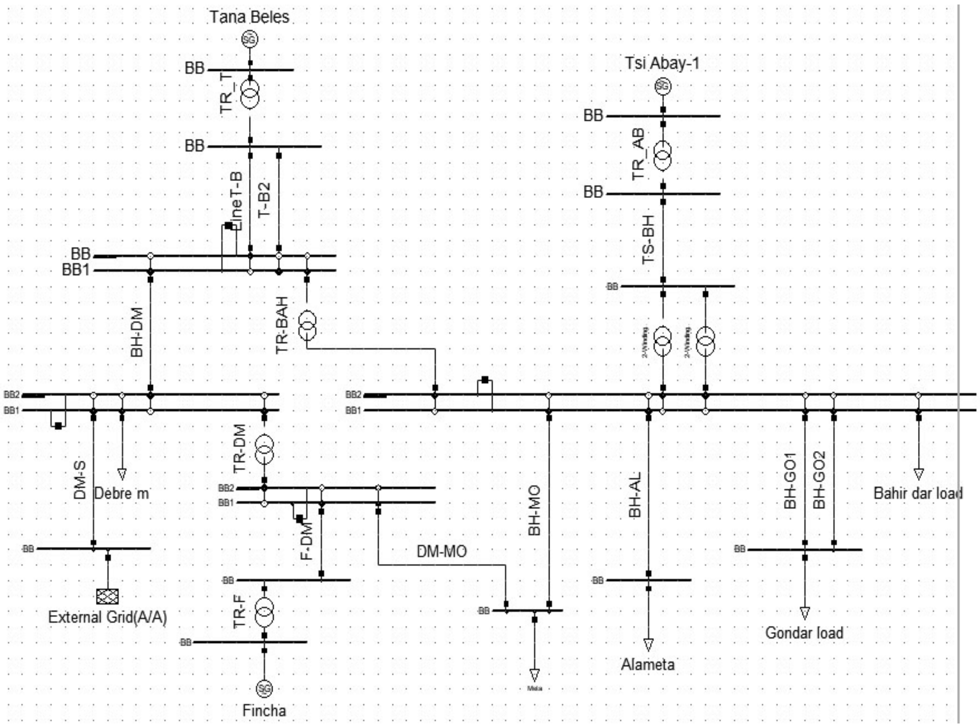

Fig. 2. Proposed single line network diagram

The external grid shown in Fig. 2 is an equivalent model of the entire power system which was proposed (single line network diagram).

3.1. Result of the systems power flow

The results of the power flow of the system have been obtained using the DIgSILENT base-coupled Newton Raphson method. The results obtained for the respective bus IDs are shown in

Table 1. Table 2 shows the line flow and losses, and Table 3 shows the sample power flow results at normal loading condition with voltage deviation and a tolerance of ±10%.

Table 1. Power flow results of the existing system

Bus No.	Voltage magnitude	Voltage angle	Load		Generation	
			P (MW)	Q (MVAr)	P (MW)	Q (MVAr)
1	1.0	0.0	0	0	165.20	150.70
2	0.988	−0.58	0	0	0	0
3	0.986	−0.63	0	0	0	0
4	0.991	−0.11	0	0	0	0
5	1.0	0.56	0	0	10	53.35
6	0.972	−1.49	163.53	132.53	0	0
7	0.971	−0.92	4.45	2.9	0	0
8	0.936	−1.17	117.85	57.08	0	0
9	0.927	−3.38	142.0	132.0	0	0
10	0.977	−1.17	0	0	0	0
11	0.986	−0.62	0	0	0	0
12	1.0	0.42	0	0	90.0	67.40
13	0.993	0.30	16.70	12.40	0	0
14	0.999	0.85	0	0	0	0
15	1.0	2.47	0	0	10	5.27

Table 2. Electric power flow on the transmission lines

Line		Transmission line power flow		Losses	
From	To	P (MW)	Q (MVAr)	P (MW)	Q (MVAr)
2	3	165.32	185.31	0.33	−13.64
3	4	−140.88	−72.69	0.05	−19
5	4	100	6.1	0.26	−3.37
6	7	−32.74	13.99	0.09	−0.82
6	8	120.38	61.89	2.51	4.81
6	9	144.66	126.86	2.34	6.3
7	13	−37.28	11.91	1	−1.04
13	14	−99.47	−4.73	0.53	1.37
10	11	−89.76	−60.99	0.24	1.38
Total losses				7.35	−24.13

Table 3. Base case power flow result at normal loading condition

Grid: BORNR	**System Stage: BORNR**								
Bus name	**Rated voltage**	**Bus voltage**			**Voltage deviation (%)**				
	kV	p.u.	kV	Degree	−10	−5	0	5	10
Alamata 230 kV									
BB	230	0.936	215.32	−3.47	−6				
Bahir Dar 132 kV									
BB	132	0.977	128.93	−1.17		−2.0			
Bahir Dar 230 kV									
BB1	230	0.973	223.73	−1.50		−3.0			
BB2	230	0.973	223.73	−1.50		−3.0			
Bahir Dar 400 kV									
BB1	400	0.987	394.62	−0.63		−1.5			
BB	400	0.987	394.62	−0.63		−1.5			
Debre Markos 230 kV									
BB2	230	0.992	228.17	0.18		−1.0			
BB1	230	0.992	228.17	0.18		−1.0			
Debre Markos 400 kV									
BB1	400	0.991	396.56	−0.10		−1.0			
BB2	400	0.991	396.56	−0.10		−1.0			
External grid bus									
BB	400	1.000	400.00	0.57		−0.5			
Fincha 230 kV									
BB	230	0.999	229.80	1.73		−0.5			

3.2. Contingency analysis of the proposed system at 50% load increment

The contingency line voltage violation simulation result is shown in Fig. 3. The results show that Bahir Dar, Mota, Alamata, and Gondar have base voltages of 0.87, 0.88, 0.77, and 0.76 p.u., respectively. This implies their line p.u. voltage margin is below the permissible standard voltage limit when the network is exposed to 50% demand increment. Especially, the Gondar line has a severe security issue and its voltage is violated highly as shown in the screenshot of Fig. 3.

When 50% load increment is applied to the base case network, lines and transformers get overloaded with the base case and continuous loading conditions. The contingency analysis reports show that transformers at Tis Abay, Tana Beles, and Bahir Dar II have a loading percentage of 105%, 139.9%, and 168%, respectively.

Hence, even if the system has no fault or there is no line outage, it shows that it is overloaded and it violates up to 168% of the system's loading due to 50% increase in demand at the customer premises as presented in Table 4.

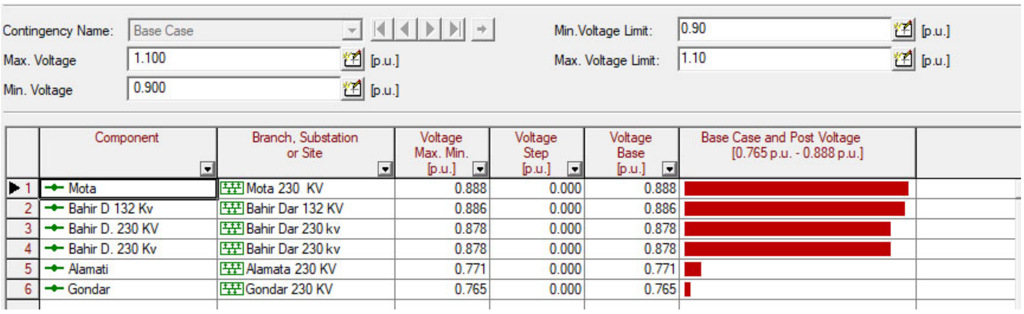

Fig. 3. Screenshot of the DIgSILENT software interface showing the voltage violation at 50% load increment

Table 4. Loading violations per case

Component	Continuous loading	Short-term loading	Base case loading
2-Winding Trafo @BDR	168	168	168
2-Winding Trafo @Tana	139.9	139.9	139.9
2-Winding Trafo @Tis Abay	105.1	105.1	105.1
Line BDR-Alamata	85.5	85.5	85.5

a. Network contingency analysis for N-1 line outage

When there is a line outage at the Bahir Dar–Debre Markos network, the voltage profile is observed to be lower than the minimum voltage margin limit. In this instance, the voltage profiles of all the entire lines are reduced due to the outage propagation effect of the Bahir Dar – Debre Markos line. Bahir Dar-Gondar, Bahir Dar-Alamata, and Bahir Dar-Mota lines are the

Table 5. Voltage violation of line outage Bahir Dar–Debre Markos

Component	Branch substation	Voltage max (p.u.)	Voltage step (p.u.)	Voltage base (p.u.)
Tis Abay G-side	Tis Abay 1	0.827	0	0.827
Tana 1	Tana	0.811	0	0.811
Tisa 132 kV	Tis Abay 2	0.799	0	0.799
Tana 2	Tana 2	0.79	0	0.79
Bahir D 400 kV	Bahir D 400 kV	0.788	0	0.788
Bahir D 400 kV	Bahir D 400 kV	0.788	0	0.788
Bahir D 132 kV	Bahir D 132 kV	0.782	0	0.782
Bahir D 230 kV	Bahir D 230 kV	0.774	0	0.774
Bahir D 230 kV	Bahir D 230 kV	0.774	0	0.774
Mota 230 kV	Mota 230 kV	0.755	0	0.755
Alamata 230 kV	Alamata 230 kV	0.726	0	0.726
Gondar 230 kV	Gondar 230 kV	0.717	0	0.717

most affected lines with respective voltage levels of 0.717, 0.26, and 0.55 p.u., respectively, as presented in Table 5.

b. Network performance indices at line outages

Table 6 shows the network performance indices at line outages of all respective lines. This table also clearly displays the PIP and PIV values with security/contingency severity ranking based on the PIV values of the lines. From Table 6, one can conclude that in the event of a line outage from Bahir Dar to Debre Markos, then the entire system will be down, resulting in a high load violation percentage.

Table 6. Performance indices and severity rank of each line outage

	Line outages		**Performance indices**		**Severity rank**
Bus No.	**From**	**To**	**PIP**	**PIV**	
1	Tana Beles	Bahir Dar	0.01866	2.241	4
2	Bahir Dar	Debre Markos	0.00874	4.07	1
3	External Grid	Debre Markos	0.00598	1.14	6
4	Fincha	Debre Markos	0.00568	0.95	7
5	Bahir Dar	Alamata	0.00392	0.41	9
6	Bahir Dar	Mota	0.01939	3.37	2
7	Bahir Dar	Gondar 1	0.00647	2.46	3
8	Bahir Dar	Gondar 2	0.0067	1.23	5
9	Tis Abay	Bahir Dar	0.0568	0.95	8

Figs. 4 and 5 show the performance index curves of the network at the considered line outages. These graphs show the plot of performance index (PIP) against a bus number. Results in Fig. 5

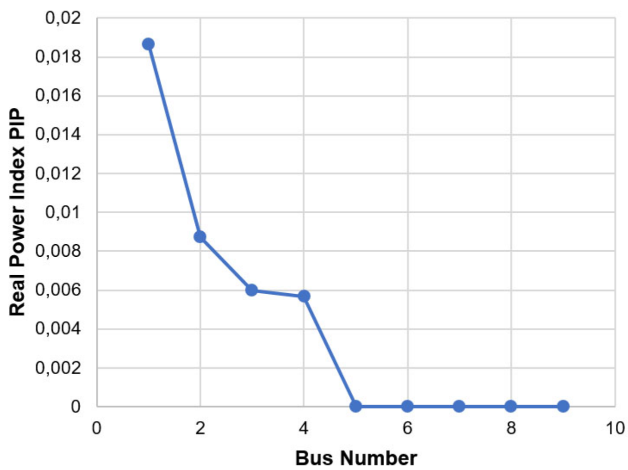

Fig. 4. Real power, PIP index at line outage

suggest that the severity rank is directly proportional to the PIV value of the line. Lines like Bahir Dar – Debre Markos, Bahir Dar – Motta, Bahir Dar – Gondar I, and Tan Beles – Bahir Dar are the most affected lines on the network.

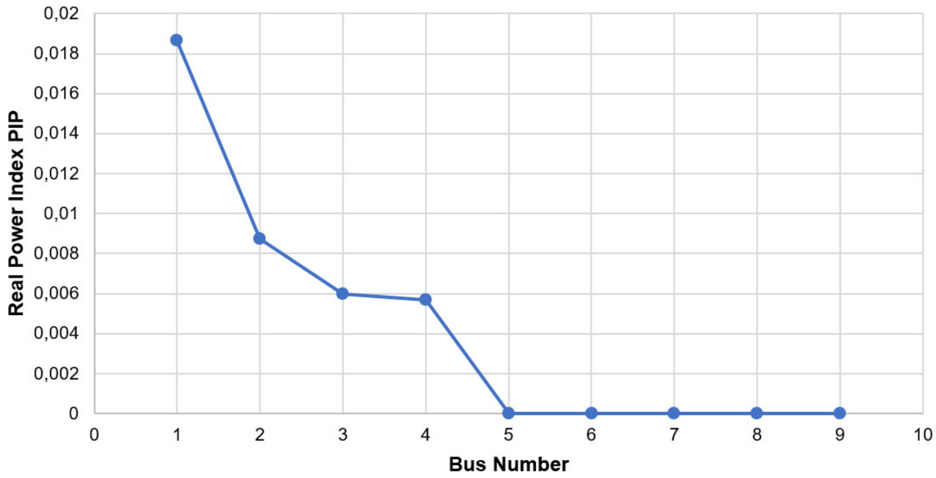

Fig. 5. Reactive power, PIV index at line outage

c. Bus voltage profile at loading scenarios

Table 7 shows the normal voltage profile and that of the 50% load increment. When the systems load is increased, the voltage profile will be decreased.

Fig. 6 shows the voltage profile of the baseline system with normal loading conditions for the simulation result of pre-contingency and post-contingency analysis. From this figure, it is observed that the pre-contingency voltage series is somewhat better than the post-contingency voltage level, because the post-contingency voltage level is violated due to lack of surplus/reserve system power.

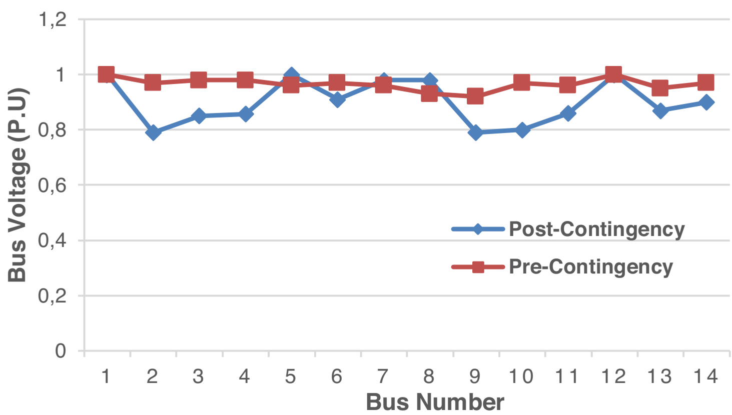

Fig. 6. Voltage profile at normal loading condition

Table 7. Voltage profile at different scenarios

Bus no.	**Voltage profile at normal loading condition**		**Voltage profile at 50% loading increment condition**	
	Pre-contingency	**Post-contingency**	**Pre-contingency**	**Post-contingency**
1	1.00	1.00	1.00	0.77
2	0.988	0.79	0.988	0.88
3	0.986	0.851	0.986	0.88
4	0.991	0.857	0.991	0.86
5	1.00	1.00	1.00	0.88
6	0.972	0.91	0.972	0.91
7	0.971	0.98	0.971	0.91
8	0.936	0.98	0.936	0.76
9	0.927	0.79	0.927	0.88
10	0.977	0.80	0.977	0.90
11	0.986	0.86	0.986	0.91
12	1.00	1.00	1.00	0.77
13	0.993	0.87	0.993	0.90
14	0.999	0.90	0.999	0.91
15	1.00	1.00	1.00	0.91

Fig. 7 shows the voltage profile of the network when it is overloaded by 50%. It is clear from Fig. 7 that the pre-contingency voltage profile of some buses are below the permissible limit due to

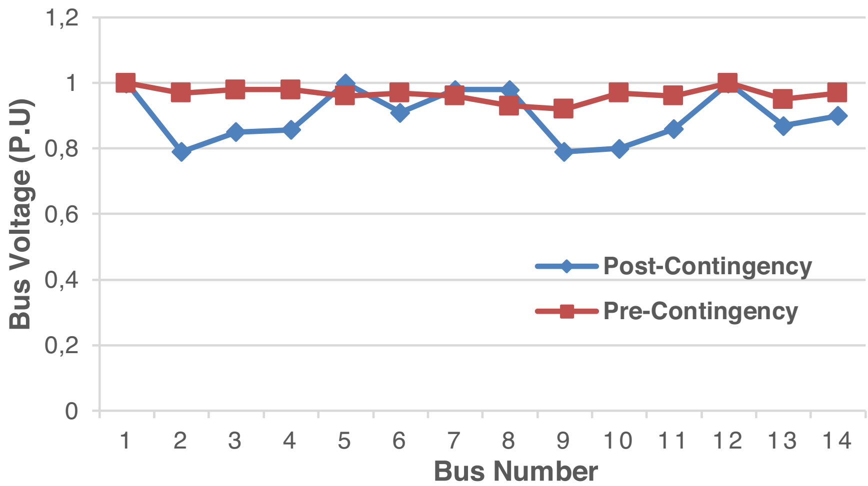

Fig. 7. Voltage profile at 50% load increment

their performance and poor capacity to withstand the challenges faced by the power system. When the network is exposed to a demand increment of 50% and analyzed with contingency analysis, the result of the voltage profile is shown in Fig. 7. The results show that the post-contingency voltage level is violated to a large extent due to the 50% increase in demand.

4. Conclusion

This work analyzed the critical line outages that violate the prescribed and acceptable system limits in terms of thermal ratings of transmission lines and voltage boundaries on the system buses. From the simulation results, it can be concluded that there is a need to expand the EEP North-West region transmission network in order to put in place enough redundancy to maintain the systems security against instability caused by overloading and overheating. The results further show that there are weak transmission lines in the system. Therefore, for the implementation of future power generation projects, the system planner should recognize the faults that exist in the present power network so as to be able to accommodate the power generated from the new system. This is, therefore, a principal factor that can greatly help to execute the implementation of the planned electricity generation projects and maintain the genuineness of the present operational power network in relation to meeting the future power growth demand.

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