Power Flow Analysis and Steady State Contingency of IEEE 9-bus System Using DigSilent

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Abstract – *Power flow analysis and contingency states of a power system are fundamental tests of finding the real performance of an electrical network during power system planning and operation. Maintaining the system's security is a challenging issue facing power system engineers. The system will be secure if it can run within system restrictions, such as limits of bus voltage magnitudes, current and power flow through the lines. in the case of a component failure, such as a generator or transmission line, contingency analysis is useful for increasing the power system's resilience by examining the system's vulnerability in case of components failure. Using an IEEE 9-bus system as benchmark, the analysis of power flow through contingency analysis is performed to identify the most critical component affected by voltage violation and critical loading condition. Using the one-by-one and two-by-two outages of generators and lines using DIgSILENT Power Factory software. The results of the contingency analysis demonstrate how voltage on busbars can be critically affected when the power system is subject to some sort of unconditional phenomena during the operation of the electrical network.*

***Keywords**: contingency analysis, multiple contingencies, power flow analysis, security performances indices, voltage stability*

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I. Introduction

Load flow analysis is the terminology used to emphasise the study of power system operation. Power flows from one or more sources to the loads through transmission lines [1]. Using important tools such as DigSilent power factory, which involve stability analysis applied to an IEEE-9 Bus system. The results of such analysis provide a clear picture of the electrical structure that plays a huge role in any electrical system's daily operation for its control and stability. The power flow analysis is also required during power system design phases, well as future planning growth, and development of stability control strategies [2]. The main purpose of the load or power flow analysis is to collect accurate steady-state voltages magnitudes and angles of all involved buses of the 9 bus power systems, for specified components such as generator real power, loading profile and voltage situations. Once the related data from the power flow analysis are known, a steady operation of the power system that prevents the grid from power instability can be made possible. This data also helps to reduce the risk of voltage collapse in power systems. Due to the importance of safety in operation of the power systems, numerical methods are put in place to assist in obtaining a solution that is within an acceptable tolerance. Hence, contingency analysis is important in power systems. Contingency analysis is a mathematical method for predicting power systems equipment failure and undertaking preventative and corrective action before the system collapse or enters an unstable operational state[3]. Addition or exclusion of one or more electrical components in the power system can be considered as one of the contingencies. Considering the results of these adjustments can lead the power system to an unsafe operating condition that can lead the power system to voltage collapse. It is advisable to put in place corrective action that can be determined through contingency analysis, which is considered as a successful method of providing a power system safety assessment to regulate the steady-state operation of the power system[4]-[5]. This paper presents an investigation field of power flow study and contingency analysis to show how to retrieve different performance indicators and group them based on their severity. The IEEE- 9 buses have been simulated to test for various scenarios of emergencies. The simulation proves that for each contingency an appropriate counteraction was available to reduce the impact of such conditions on the safe operation of the power system. Thus, most of the parameters were within the permitted voltage profile that allow the steady state operation of the electrical network.

II. Research methodology

The load flow analysis on the network model in Fig. 1 is performed using Dig SILENT Power Factory software to examine the system's steady state performance. Such analysis is required throughout transmission network planning, control and operation.

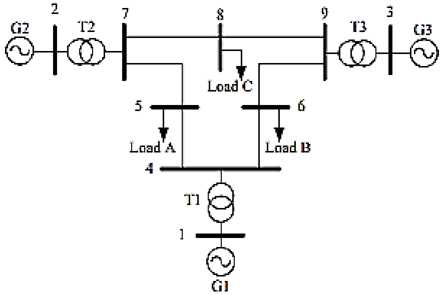


Fig. 1. IEEE-9 bus power System

This load flow calculation focuses on finding the magnitude voltage (V) of the node, and voltage angle, as well as the active (P) and reactive (Q) power flow on all branches [6]. The method used to perform these load flow calculations in a balanced network is the Newton-Raphson method. Based on this method, the incoming current to a specific bus of the power system can be expressed as follows:

$$I_i = \sum_i^n Y_{ij} V_j \text{ for } i = 1,2,3\ldots...,n \qquad (1)$$

The above equation can be expressed in polar form as follows:

$$I_i = \sum_j^n Y_{IJ} V_j < \theta_{ij} + \delta_j \qquad (2)$$

The complex power needed to be delivered to bus i is then given by below equation:

$$P_I - jQI = Vi^* I_i \qquad (3)$$

Both the real and reactive power are respectively expressed by:

$$P_i = \sum_{j=1}^n |V_i||V_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \qquad (4)$$

$$Q_i = \sum_{j=1}^n |V_i||V_j||Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) \qquad (5)$$

Because of its focus in calculating power flow and voltage magnitudes of the power system at the nodes or branches. Authors in [2], have stated that for the power flow to be deemed successful it must meet the following requirements:

1. Adequate power flow from generator to the load and network losses are to be considered.
2. Voltage magnitudes of buses to remain close to rated values.
3. Operation of generators should stay within specified power limits.
4. No overloading of transformers, transmission lines, and cables.

The purpose of load flow studies is to assess the technical capability of a power network under steady-state or fault conditions [7]-[8].

Network behavior must always be analysed for both normal and abnormal conditions. Contingency analysis is the term related to abnormal conditions of the system [8]. Contingency analysis is done to assess the security degree of an electrical power system [3]-[9]. It becomes a crucial problem for the daily operation of power system networks if the contingency cases are not investigated [10]. A commonly used criterion is evaluating the contingencies for a single outage of any equipment including generators, transformers, and transmission lines, and assessing the post-contingency state of the power system network. This is recognised as the *n*-1 contingency case [11]. Another criterion is estimating the contingencies of a double outage of any system element and evaluating the post-contingency state of the system. This is said to be the *n*-2 contingency case [12]. Both cases were analysed in this research study to evaluate the post-contingency state of the network after an outage of one or two system elements. Additionally, they were analysed to assess the most crucial busbar in the IEEE nine bus system.

To perform the steady state contingency analysis of the IEEE-9 bus systems using DigSILENT, the paper is structured as follows: Section two covers the comprehensive theorical related to the concepts of power flow and contingency analysis in power system, section three is related to case studies to be considered. The modelling of network, power flow analysis and ccontingency studies are presented in section four. Discussion of the results in section five and the conclusion is in section six.

III. Case studies

Two cases are studied in this work.

i. Case 1-IEEE-9 load flow.
ii. Case 2- IEEE-9 Contingency analysis.

The analysis steps are performed and proven using the IEEE-9 bus system. Simulations and certification of findings are executed using DigSILENT. The power systems grid portrays a transmission network of three generators, three transformers, six lines, nine buses and three loads. The electrical network in Fig.1 is an illustration of 9 bus systems to be used in this work. The network represents a radial configuration with ideal placement and sizing of power generation that are lucky to create poor power quality when one of these generations is affected by a fault. The different loading profile and their interactions during normal operation of the power system represent an ideal benchmark to carry out the importance of adequate contingency analysis [13].

IV. Simulation results

This section focuses on the investigation related to the performance of the IEEE-9 bus system. A load analysis is performed to reveal the performance of the network while the contingency analysis will focus on the vulnerability of the network leading to possible action to be taken when such vulnerability rises during the operation of the power systems.

A. Load flow investigation to evaluate the IEEE-9 bus.

Load flow calculations are performed to evaluate the steady-state operation of an electrical power system network. They are used to assess if the system voltages remain within acceptable limits of +/-5% as per IEEE standard 141-1993 under normal and contingency conditions [14]. They evaluate if generators, transformers, and transmission lines are not overloaded. Lastly, load flow calculations are necessary for the planning of an existing power network and its future growth. The waveforms shown in Fig. 2 represent 3-phase voltages after successfully executing the load flow. Where red color represents phase A, yellow represents phase B, and blue represents phase C. These waveforms were captured during the steady-state condition in the transmission network. Table 1 shows the results related to the power flow analysis executed using Dig Silent.

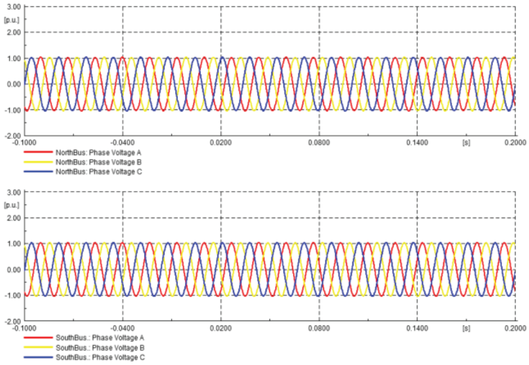


Fig 1. Simulated three-phase voltage wave form

TABLE I
LOAD FLOW RESULTS

Bus (Nbr)	Normal voltage (p.u)	Actual voltage (kV)
1	1.040	17.16
2	1.025	18.45
3	1.025	14.14
4	1.025	235.83
5	0.992	228.14
6	1.020	234.5
7	1.011	232.4
8	0.990	225.16
9	0.990	235.3

The results from the simulation prove that the voltages on busbars are operating within an acceptable range and that there is no overloading of equipment such as transformers and transmission lines. According to [15], a three-phase system is considered balanced or symmetrical if the three-phase voltages and currents have the same magnitude and are phase shifted by 120° with regard to each other; if any or both of these conditions are not met, the three-phase system is called non-balanced or asymmetrical[16]. Voltage imbalance is a recognised power quality criterion that signifies the phase voltages have different magnitudes or the phase differences between consecutive voltages are less than 120° in a three-phase system.

The next section explains the contingency analysis which is done to evaluate the vulnerability of the power system. It is also an important exercise to do in order to identify the critical busbar of the IEEE nine bus power system.

B. Process flow of contingency studies

The network behaviour is analysed for both normal and abnormal conditions. Contingency analysis is the term related to abnormal conditions of the system [7]-[8]. Contingency analysis is done to assess the security degree of an electrical power system [4]-[17]. It becomes a crucial problem for the daily operation of power system networks if the contingency cases are not investigated [3]-[10]. A commonly used criterion is evaluating the contingencies for a single outage of any equipment including generators, transformers, and transmission lines, and assessing the post-contingency state of the power system network. This is recognised as the *n*-1 contingency case [18]. Another criterion is estimating the contingencies of a double outage of any system element and evaluating the post-contingency state of the system. This is said to be the *n*-2 contingency case [10]-[11]. Both cases are analysed to evaluate the post-contingency state of the network after an outage of one or two system elements. Additionally, they were analysed to assess the most crucial busbar in the IEEE nine bus system. The results for both contingency cases *n*-1 and *n*-2 are presented below.

B.1 Contingency case for n-1

The *n*-1 contingency case was performed on the network model to assess the worst violated components in the power network. According to IEEE standard 141-1993, the busbar voltages must not exceed the maximum voltage limit of 1.05 per unit (p.u.) and must not violate the minimum voltage limit of 0.95 p.u. with a +/-5% tolerance limit [14]-[17]. As shown in Table II, it is evident from the analysis results that, the minimum voltage limit of 0.9 p.u. is violated under the '*n*-1' contingency case. Busbar 6 was discovered as the worst violated busbar in terms of minimum voltage limit when transformer 1 'T1' is out of service. It was violated with 19.1% "0.759 p.u." which was outside the 5% limit as per IEEE standard 141-1993 [14]. Another thing that was observed is the loading of generators and transformers. The loading limit for generators and transformers was 75% according to the network and grid planning standard [19]. It is evident from the results shown in Table II and Table III that the loading limits were violated. Transformer 2 'T2' is the worst violated apparatus in terms of loading limit when ‘T1’ is out of service. It is 79% loaded and which is more than the 75% loading limit.

TABLE II
CONTINGENCY ANALYSIS SHOWING MINIMUM WORST VOLTAGE VIOLATION

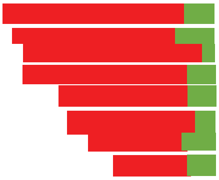
Component	Voltage Min (p.u)	Voltage step (p.u)	Voltage base (p.u)	Contingency number	Contingency name	Base case and post voltage (0.759 p.u.-1.040 p.u.)
Bus 6	0.759	0.254	1.013	10	T1	
Bus 5	0.765	0.230	0.996	10	T2	
Bus 1	0.768	0.272	1.040	7	G1	
Bus 4	0.768	0.258	1.026	10	T1	
Bus 3	0.831	0.194	1.025	10	T1	
Bus 9	0.841	0.191	1.032	10	T1	
Bus 8	0.873	0.143	1.016	10	T1	
Bus 7	0.927	0.099	1.026	10	T1	

TABLE III
CONTINGENCY ANALYSIS SHOWING WORST LOADING VIOLATION

Component	Loading Continuous (%)	Loading Short Term (%)	Loading Base case (%)	Contingency number	Contingency name	Base case & Continuous loading (0%-149%)
T2	149.0	149.0	79.6	10	T1	
T1	93.5	93.5	29.5	8	T2	

B.2 Contingency case for n-2

The *n*-2 contingency case was performed to assess the worst violated components in the power network. Based on the contingency analysis reports shown in Table IV and Table V, the minimum and maximum voltage limits were violated. All the busbar voltages are below the minimum voltage limit of 0.95 p.u. in Table IV. The worst violated busbar in terms of minimum voltage limit is busbar 6 which was violated with the value of 0.748 p.u. This case happened when lines 4-6 and 5-7 are out of service. Two busbars are affected in terms of the maximum voltage limit, which is busbars 9 and 3. The busbar with the worst violated voltage is busbar 9 and is violated with the value of 1.063 p.u. when lines 4-5 and 4-9 are out of service. The contingency analysis report for worst loading violations was generated and the results are shown in Table IV. As mentioned in section A, the loading limit for generators and transformers is 75%. There are 3 components with loading violations ‘T1’, ‘T2’, and ‘T3’. The transformer with the worst violated loading limit is ‘T3’ with a loading of 79.6%. That is the post-contingency state when generator 1 ‘G1’ and ‘T1’ are out of service.

TABLE IV
CONTINGENCY ANALYISIS SHOWING MINIMUM WORST VOLTAGE VIOLATION (*n*-2)

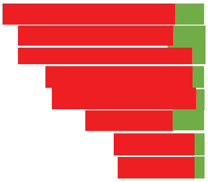
Component	Voltage Min (p.u)	Voltage step (p.u)	Voltage base (p.u)	Contingency number	Contingency name	Base case and post voltage (0.748 p.u.-1.032 p.u.)
Bus 6	0.748	-0.265	1.013	12	Line 4-6, 5-7	
Bus 5	0.765	-0.230	0.996	54	G1-T1	
Bus 1	0.768	-0.258	1.026	54	G1-T1	
Bus 4	0.831	-0.194	1.025	54	G1-T1	
Bus 3	0.841	-0.191	1.032	54	G1-T1	
Bus 9	0.873	-0.143	1.016	54	G1-T1	
Bus 8	0.903	-0.122	1.025	31	Line 6-9, 7-8	
Bus 7	0.906	-0.120	1.026	31	Line 6-9 , 7-8	

TABLE V
CONTINGENCY ANALYSIS SHOWING MAXIMUM WORST VOLTAGE VIOLATION

Component	Voltage Max(p.u.)	Voltage Step (p.u)	Voltage Base (p.u.)	Contingency Number	Contingency Name	Base Case & Post Voltage (1.025 p.u.-1.063 p.u.)
Bus 9	1.063	0.031	1.032	5	Line 4-5,8-9	🟥🟥🟥🟥
Bus 3	1.056	0,031	1.025	5	Line 4-5,8-9	🟥🟥🟥

TABLE VI
CONTINGENCY ANALYSIS SHOWING WORST LOADING VIOLATION

Component	Loading Continuous (%)	Loading short-Term (%)	Loading Base-Case (%)	Contingency Number	Contingency Name	Base Case & Continuous Loading (0%-149%)
T2	149.0	149.0	79.6	54	G1-T1	🟩🟥🟥
T1	134.1	134.1	29.5	57	G2-G3	🟩🟥🟥
T3	133.9	133.9	55.7	14	Line 4-6,7-8	🟩🟥🟥

Based on the contingency analysis cases *n*-1 and *n*-2 explained in section IV above, busbar 6 was found to be the most crucial busbar of the network, therefore, it can be regarded as bus of interest when ideal protection devices or reactive power source are need to be added to the power system.

V. Discussions and recommendations

One of the analysis of power system security assessment is contingency analysis. A power system is operationally secure if blackouts or equipment damage are unlikely. The contingency cases *n*-1 and *n*-2 were analysed using DIgSILENT Power Factory software. These contingency cases were executed to evaluate equipment loading and assess busbars with voltage violation limits. These studies are the major activity to understand which busbar is critical in power system network. Additionally, these contingency analysis assist in strengthening the initial basic power system planning. NRS048 standard stipulates that transmission busbars should operate at a range of 0.95 to 1.05 p.u. If the voltage on the buses falls below 0.95 p. u, it is said to have a low voltage. If the bus voltage exceeds 1.05 p. u, it is regarded as a busbar with a high voltage problem. Based on the simulation results in Table I and Table II, the busbar with the worst voltage violations for both *n*-1 and *n*-2 contingency cases is busbar 6. The minimum voltage limit of 0.95 p.u was violated in both contingency cases as the voltages were 0.759 p. u and 0.748 p.u. The simulation results proved that busbar 6 is the critical busbar as it experienced the worst voltage violations after contingency cases were performed. System security entails methods that are specifically designed to survive in imminent disruption scenarios (contingencies) without jeopardising safety, dependability, or customer service. According to authors [20], if violations or faults continue in a system, the system might become unstable and later on experience blackouts. Hence, it is critical to have a power system that is safe, dependable, continuous, and economical to operate. Severe contingencies must first be identified, and then fast, secure, dependable, and continuous operation is required. Part of the power system analysis involves load flow studies.

Load flow simulations were done using DIgSILENT and the results were analysed. The simulation studies were performed to assess the stability of the IEEE Nine-bus system during normal operating conditions. It is evident from the simulation results in Table VI that the network is stable. The voltages at busbars are all within the voltage deviation of +/-5%.

Suitable recommendations for the best performance of the power system can be directed to implement actions that enhance the stability of the power systems. Some of these actions can be related to adequate protection component to be located on bus 6 to prevent damage of equipment that depends on power from bus 6 or again location of reactive power devise such as STATCOM to provide extra reactive power that will improve power quality at bus 6.

VI. Conclusion

Two contingency cases were investigated in this paper. The *n*-1 contingency case assesses the state of the power system network after a single outage of any component. The *n*-2 contingency case evaluates the post-contingency state of a power system network after a double outage of any system element. The study network was chosen based on the simulation results from both contingency cases. The contingency analysis reports for both *n*-1 and *n*-2 cases obtained from DIgSILENT simulations show that the most crucial busbar of the IEEE Nine-bus network is busbar 6. Hence, this bus required adaptive measure to enhance the power system stability. Load flow simulations were also performed in this paper using DIgSILENT Power Factory software. They were performed to assess if the system voltages would remain within acceptable limits of +/-5% as per IEEE standard 141-1993 under normal and contingency conditions. The simulation results proved that the network is stable as the system voltages were within the acceptable limits of +/-5%.

Conflict of Interest

The authors declare no conflict of interest in the publication process of this research article.

Author Contributions

Luntu S. Mgaga conceptualised the research, performed the analysis, Sampi .D. Lumina fully reviewed and edited the paper. All authors have approved the final version.

References

[1] R. H. McFadden, “An American National Standard IEEE Recommended Practice for Industrial and Commercial Power Systems Analysis,” *Inst. Electr. Electron. Eng.*, pp. 1–223, 1980.

[2] M. Ratshitanga, “Ivestigation and Design of an Intergrated monitoring, Protection, and Control System of a Power Reticulation Network,” Cape Peninsula University of Technology, 2018.

[3] J. M. Da Silva, I. Costa, J. V. C. Dos Santos, J. L. V. Barbosa, T. Braun, and G. Pessin, “Toward a more reliable system for contingency selection in static security analysis of electric power systems,” *IEEE Syst. J.*, vol. 14, no. 1, pp. 1183–1194, 2020.

[4] S. Taheri and V. Kekatos, “Power Flow Solvers for Direct Current Networks,” *IEEE Trans. Smart Grid*, vol. 11, no. 1, pp. 634–643, 2020.

[5] M. Jiang, Q. Guo, H. Sun, and H. Ge, “Decoupled piecewise linear power flow and its application to under voltage load shedding,” *CSEE J. Power Energy Syst.*, vol. 7, no. 5, pp. 976–985, 2020.

[6] E. Cengiz, C. Yilmaz, E. N. Yilmaz, and H. Tolga Kahraman, “Importance of Power Flow and Load Analysis in Pre-Installation Power Systems,” *3rd Int. Symp. Multidiscip. Stud. Innov. Technol. ISMSIT 2019 - Proc.*, no. 2, pp. 3–6, 2019.

[7] A. Pandey, M. Jereminov, M. R. Wagner, D. M. Bromberg, G. Hug, and L. Pileggi, “Robust Power Flow and Three-Phase Power Flow Analyses,” *IEEE Trans. Power Syst.*, vol. 34, no. 1, pp. 616–626, 2019.

[8] DIgSILENT, “PowerFactory 2018,” 2018.

[9] C. A. Bartend Russell and S. Khan, “Single Line Outage Analysis on IEEE 39 Bus Network,” *Proc. 2022 25th Int. Conf. Comput. Inf. Technol. ICCIT 2022*, pp. 821–826, 2022.

[10] H. Gao, L. Miao, S. Liu, J. Liu, X. Lin, and Y. Zhao, “An Assistant Decision-Making Method for Power Grid Contingency Management Based on Case-Based Reasoning,” *2021 3rd Asia Energy Electr. Eng. Symp. AEEES 2021*, pp. 514–522, 2021.

[11] W. Irfan, M. Awais, D. N. Zareen, and I. Ahmed, “N-1 Contingency Analysis for Offsite Power System of an HPR-1000 Power Plant Using ETAP Software,” *2022 Int. Conf. Recent Adv. Electr. Eng. Comput. Sci. RAEE CS 2022*, pp. 1–5, 2022.

[12] P. Sai Nandini, R. Krishan, and D. Pullaguram, “Static Security Assessment of Large Power Systems Under Contingency Cases,” *2022 IEEE 10th Power India Int. Conf. PIICON 2022*, pp. 1–6, 2022.

[13] S. D. Lumina, M. E. S. Mnguni, and Y. D. Mfoumboulou, “Stability Evaluation of Non-ideal Grid-tied Photovoltaic on IEEE-9 Bus System,” vol. 6, no. 2, pp. 0–7, 2023.

[14] C. B. Cooper, “IEEE Recommended Practice for Electric Power Distribution for Industrial Plants,” *Power Eng. J.*, vol. 2, no. 2, p. 103, 1988.

[15] L. Yun, “Voltage Balancing on Three-Phase Low Voltage Feeder,” University of Manchester for the degree of Doctor of Philosophy, Manchester, 2015.

[16] S. D. Lumina, M. E. S. Mnguni, and Y. D. Mfoumboulou, “Photovoltaic Controller Design Based on Adaptive Volt / Var Algorithm to Stand the Impact of Load Increase in Grid Tied Microgrid System,” vol. 12, no. 3, 2023.

[17] K. A. R. Medapati, S. Mandal, R. Paul, A. Samanta, D. Bose, and A. Chakrabarti, “Assessment of Power System Security using Contingency Ranking Analysis,” *5th Int. Conf. Energy, Power, Environ. Towar. Flex. Green Energy Technol. ICEPE 2023*, pp. 1–6, 2023.

[18] A. Bernstein, C. Wang, E. Dallanese, J. Y. Le Boudec, and C. Zhao, “Load flow in multiphase distribution networks: Existence, uniqueness, non-singularity and linear models,” *IEEE Trans. Power Syst.*, vol. 33, no. 6, pp. 5832–5843, 2018.

[19] K. Dedekind, “Network and Grid Planning Standard for Generation Grid Connection,” 2019.

[20] B. Molla and A. Basu, “Contingency analysis of a 10-bus power system using power world simulator,” *Indian J. Power River Val. Dev.*, 2020.