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Single Line Outage Analysis on IEEE 39 Bus Network

Chokder Alamgir Bartend Russell
Seabreeze International School
Dhaka, Bangladesh
cabr1234@gmail.com

Shahriar Khan
Dept. of EEE
Independent University, Bangladesh
Dhaka, Bangladesh
skhan@iub.edu.bd

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***Abstract* – With the recent blackouts in Texas, Manhattan, and NE US, the importance of analyzing outage is greater than ever. Contingency Analysis is helpful to increase the resiliency of power system by analyzing impact of different contingencies. The effect of single transmission line outage in a transmission network has been studied with IEEE 39 bus network. Each of the branches has been disconnected one at a time to find effect on generator constraints, voltage constraints of buses, transmission line loading and possibility of islanding. PSS®E Xplore 34 was used for the simulation. The results show that single transmission line outage may impact generator power factors, increase demand of reactive power from the generators, and overload other transmission lines. Transmission line outage may lead to several violations of system constraints leading to islanding. This study may help research on different impacts of single transmission line outage and improve power system resilience.**

Keywords – Contingency, Analysis, Power Flow, Line Outage, Power Transmission Network, Steady State, IEEE Bus, Outage, Simulation, Resilience.

I. Introduction

With the recent blackouts in Texas, Manhattan, and NE US, the importance of analyzing outage is greater than ever. It is important to make the power grid capable of withstanding different types of contingencies.

Power system operators must maintain reliability by balancing generation and load at all times including during contingencies. Operators must maintain security of the system during natural disasters, assessing different types of contingencies. It involves three tasks: (i) State estimation (SE), (ii) Contingency Analysis (CA) and (iii) Security-constrained optimal power flow (SCOPF) [1].

In SE data is collected about the power system from a supervisory control and data acquisition (SCADA) system and a real time model of the current state of the power system is generated. Based on the model CA is carried out to assess the resiliency of the power system to recover within a specific time span (usually few minutes) in the event of different types of contingencies. This indicates the stability of power system. Thus CA plays a vital role in power system planning and operation.

Generally contingencies include outage of electrical components such as generators and transmission lines, violations of system constraints and violations of electrical component limitations such as overloads and voltage instability.

CA carries our simulations of different contingencies with the current SE based grid model. CA is carried out utilizing power flow. There are two types of power flow: (i) AC power flow (ii) DC power flow. AC power flow is more accurate but more complex than DC power flow. The power flow solutions can be obtained by using Newton Raphson method, Decoupled Newton Raphson method, Fixed slope decoupled Newton Raphson method, Gauss-Seidel method and Modified Gauss-Seidel method. Contingency analysis can be static or dynamic. This paper utilizes static AC power flow solved by the different aforementioned methods. The CA generates list of high impact line or generator contingencies. Based on contingencies which may emerge the SCOPF module dispatches generators optimally to contain the contingencies and ensure consistent power throughout the power system.

The power system is divided into transmission network and distribution network. Usually the transmission network system operators (TSOs) and distribution network system operators (DSOs) are kept separate. Contingency Analysis is carried out for Transmission Network and Distribution Network separately [2]. This paper is based on Transmission Contingency Analysis (TCA). Distribution Network will be considered as equivalent constant loads.

Recently natural disasters are increasing. During natural disasters transmission lines may cause line-line faults when lines push over each other by winds [3]. Trees may get uprooted and fall on transmission lines disconnecting it from service [3]. Human errors such as wrong setting of protective relays can also lead to transmission line outage [3].

This study investigates the impact of N-1 contingency single transmission line outage of IEEE 39 bus system representing power system transmission network. The purpose is to obtain a systematic static contingency analysis of the IEEE 39 bus system so that it can be used for future research.

Transmission line outage may lead to voltage violations and transmission line overloads [4-7]. [4] did contingency analysis on the Nigerian Power Systems Network. In [4, 6, 7], Active power and voltage Performance Indices has been used to determine critical lines which affect the power system greatly during outage. [5] did contingency analysis on the Brazilian Southern Transmission Subsystem. [5] uses power flow severity index and voltage violation severity index to assess severity of loss of an equipment or transmission line.

During transmission line islanding, reference [8] added more violations related to generators and islanding. References [8, 9] gives some possible solutions to overcome all the violations and bring the power system to a normal state.

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The remaining part of the paper is organized as follows: Section II describes how power flow solution is carried out using Newton Raphson method. Section III describes the System Constraints and Assumptions. Section IV and V describes the contingency analysis with its flowchart. Section VI describes the test system and experimental results are discussed in Section VII. The paper is concluded in Section VIII.

II. Power Flow Solution With Newton Raphson Method

In power flow, there are 3 types of buses with known and unknown variables, as given in Table I.

TABLE I. BUS TYPES

Bus Type	Known Variables	Unknown Variables
Slack Bus	$\|V\|$=1, δ=0	P, Q
Generator Bus	P, $\|V\|$	Q, δ
Load Bus	P, Q	$\|V\|$, δ

$|V|$ = Voltage magnitude, δ = Voltage Phase Angle
P = Real Power, Q = Reactive Power

If n_g and n_l are the number of generator buses and load buses excluding one slack bus, the total number of buses are:

$$n = n_g + n_l + 1 \tag{1}$$

The state variable X is given as

$$X = [\delta_2, \delta_2, \dots, \delta_n, V_2, V_3, \dots, V_n]^T \tag{2}$$

where, δ_n and V_n are voltage phase angle and voltage magnitude at bus n.

The real power and reactive power equations at bus i is given as:

$$P_i = \sum_{j=1}^{n} V_i V_j (G_{ij} cos\delta_{ij} + B_{ij} sin\delta_{ij}) = \sum_{j=1}^{n} V_i V_j Y_{ij} \cos(\delta_{ij} - \theta_{ij}) = P_i(X) \tag{3}$$

$$Q_i = \sum_{j=1}^{n} V_i V_j (G_{ij} sin\delta_{ij} - B_{ij} cos\delta_{ij}) = \sum_{j=1}^{n} V_i V_j Y_{ij} \sin(\delta_{ij} - \theta_{ij}) = Q_i(X) \tag{4}$$

where, $i = 2, 3, \dots, n$. P_i = Real Power injection at bus i. $P_i(X)$ = Real Power injection at bus i based on state variables. Q_i = Reactive power injection at bus i. $Q_i(X)$ = Reactive Power injection at bus i based on state variables. V_i = Voltage at bus i. G_{ij} = Conductance of transmission line between bus i and bus j. B_{ij} = Susceptance of transmission line between bus i and j. δ_{ij} = Voltage phase angle difference between buses i and j. θ_{ij} = Admittance phase angle of transmission line between buses i and j.

Initial state variables will produce mismatch between the left hand side and right hand side of the equations:

$$\Delta P_i = P_i(X) - P_i \tag{5}$$

$$\Delta Q_i = Q_i(X) - Q_i \tag{6}$$

where, ΔP_i is real power mismatch and ΔQ_i is reactive power mismatch.

The mismatch function $F(X)$ can be written as:

$$F(X) = \begin{bmatrix} P_2(X) - P_2 \\ P_3(X) - P_3 \\ \vdots \\ P_n(X) - P_n \\ Q_2(X) - Q_2 \\ Q_3(X) - Q_3 \\ \vdots \\ Q_n(X) - Q_n \end{bmatrix} \tag{7}$$

Values of the state variables are found by Newton Raphson method using the following update rule:

$$X_{k+1} = X_k - J^{-1}(X_k)F(X_k) \tag{8}$$

where the Jacobian matrix, $J(X)$, is given as

$$J(X) = \begin{pmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} \end{pmatrix} = \begin{pmatrix} J^{11} & J^{12} \\ J^{21} & J^{22} \end{pmatrix} \tag{9}$$

The state variable values are obtained by solving power flow equation using Newton Raphson method.

III. System Constraints and Assumptions

Generators have operating limits in terms of power factor, real power and reactive power:

$$0.95 \le pf_{gi} \le 1 \tag{10}$$

$$P_{gi}^{min} \le P_{gi} \le P_{gi}^{max} \tag{11}$$

$$Q_{gi}^{min} \leq Q_{gi} \leq Q_{gi}^{max} \quad (12)$$

Transmission lines have static ratings below which it can operate:

$$-I_{\text{static}} \leq I_{ij} \leq I_{\text{static}} \quad (13)$$

The buses have voltage limits within which it can operate:

$$0.95 \text{ p.u.} \leq V_i \leq 1.05 \text{ p.u.} \quad (14)$$

It has been assumed that the loads are static.

IV. Contingency Analysis

Contingency Analysis consists of (i) Contingency selection and (ii) Contingency evaluation [1]. Contingency selection is done to reduce computation burden by listing a reduced number of possible contingencies. The contingencies are then evaluated based on system constraint violations to rank and short list possible severe contingencies. This paper will not carry out Contingency Selection or Contingency Evaluation. Those will be kept for future research. However, an overview of the effect of transmission line outage has been studied.

Each of the branch outage has been analyzed and the following violations has been considered [8]:

(i) V1: Real power demand of generator at slack bus exceeding maximum capacity

(ii) V2: Reactive power demand of generators at plant buses exceeding maximum capacity

(iii) V3: Generators with low power factors

(iv) V4: Negative reactive power produced at generators

(v) V5: Undervoltage at buses

(vi) V6: Overvoltage at buses

(vii) V7: Transmission Line Overload

(viii) V8: Islanding

V. Contingency Analysis Flowchart

The steps of CA for this study are illustrated in flowchart given in Fig. 1.

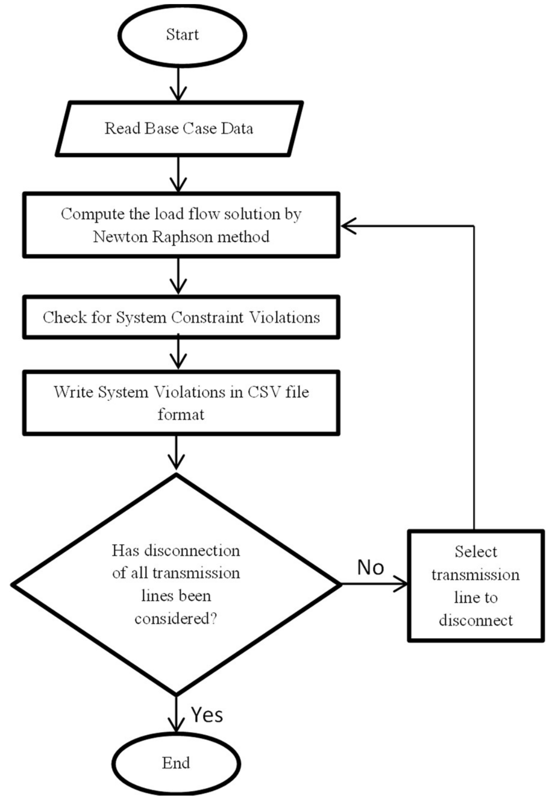

Fig. 1 Contingency Analysis Flowchart

Practically, after data has been collected from SE the contingency analysis are carried out. Every time there is transmission line outage the system is analyzed for possible violations. This list is then to be utilized by the SCOPF during the time of contingency.

VI. Test System

We investigate the effect of single transmission line outage in IEEE 39-bus system, shown in Fig. 2. The IEEE 39 bus system has been clearly detailed in [8] with network information and line thermal limits. System data for the IEEE 39 bus system is provided in Appendix [8]. Fig. 2 includes all generators, transformers, buses, transmission lines and loads. The buses are labeled from 1 to 39. The Bus System is a small size test system which has 10 generators, 12 transformers and 34 lines. The load at different buses is given in Table V. There are 19 buses with loads. Bus 31 is considered to be the slack bus. The generators are labeled from G1 to G10. The transmission lines are represented in the paper as pair of nodes which are connected by the transmission line. For example, 1-6 represents transmission line connecting the nodes 1 and 6.

The bus system was simulated in Power System Simulator for Engineering (PSS®E) Xplore 34. The system admittance matrix, Y_{bus}, has been obtained from PSS®E Xplore 34. Python and MS Excel has been used to communicate with PSS®E Xplore 34 to give input data, collect output data and to carry out necessary calculations and present results using simulation of IEEE 39 bus system in PSS®E Xplore 34. Load flow analysis of the power system has been carried out by PSS®E Xplore 34 before and after contingency. Newton Raphson method has been used to generate results of load flow. Newton Raphson method is one of the frequently used and most accurate methods for calculating load flow. The results are computed using a desktop PC with Intel® Core™i7-2600 CPU @ 3.40 GHz processor and 16.0 GB RAM on Windows 8.1 Pro (64 bits).

VII. Results

In the base case there are no system violations. For our study each transmission line is disconnected one at a time and the types of violations are noted down. The power flow solutions are obtained by using Newton Raphson method, Decoupled Newton Raphson method, Fixed slope decoupled Newton Raphson method, Gauss-Seidel method and Modified Gauss-Seidel method. The summary of violations for outage of different transmission lines are given in Table II for all the methods with exceptions. All methods gives almost results as the Newton Raphson method. Some exceptions are provided by Gauss-Seidel and modified Gauss-Seidel method and one exception by Fixed slope decoupled Newton Raphson method. Among all the methods Newton Raphson method is accurate. Therefore we concentrate on Newton Raphson method. Table III gives the percentage of violations by type based on power solutions obtained by Newton

Raphson method. The following result discussions are based on Newton Raphson method.

TABLE II VIOLATIONS DURING SINGLE BRANCH OUTAGES

Transmission line outage	VIOLATION TYPES	No. Of types of violations
1-2	V3	1
1-39	None	0
2-3	V2, V3, V7	3
2-25	None	0
3-4	V3	1
3-18	V3	1
4-5	V3 Exception: No violations in Gauss-Seidel and Modified Gauss-Seidel method	1
4-14	V3	1
5-6	V3, V7	2
5-8	V3, V7 Exception: No V3 in Gauss-Seidel and Modified Gauss-Seidel method	2
6-7	V3, V5, V7 Exception: No V5 in Gauss-Seidel and Modified Gauss-Seidel method	3
6-11	V3 Exception: Includes V7 in Gauss-Seidel and Modified Gauss-Seidel method	1
7-8	V7	1
8-9	V3, V5	2
9-39	V3, V5 Exception: No V5 in Modified Gauss-Seidel method	2
10-11	V3 Exception: Includes V7 in Gauss-Seidel and Modified Gauss-Seidel method	1
10-13	V3	1
13-14	V3, V7	2
14-15	V3	1
15-16	V2, V3, V5, V7	4
16-17	V3, V7	2
16-19	V1, V2, V3, V5, V6, V7, V8 Exception: No V5 in Gauss-Seidel and Modified Gauss-Seidel method	7
16-21	V2, V3	2
16-24	V2, V3	2
17-18	V3	1
17-27		0
21-22	V2, V3, V7 Exception: No V7 in Fixed slope decoupled Newton-Raphson.	3
22-23		0
23-24	V2, V3	2
25-26	V3	1
26-27	V2, V3, V6, V7	4
26-28	V3, V7	2
26-29	V3, V7	2
28-29	V3, V7	2

TABLE III PERCENTAGE OF VIOLATIONS BY TYPE BASED ON POWER FLOW SOLUTIONS BY NEWTON RAPHSON METHOD

VIOLATION TYPE	NO. OF OCCURRENCES (PERCENTAGE)
V1: Real power demand of generator at slack bus exceeding maximum capacity	1 (2.94%)
V2: Reactive power demand of generators at plant buses exceeding maximum capacity	8 (23.53%)
V3: Generators with low power factors	29 (85.29%)
V4: Negative reactive power produced at generators	0 (0%)
V5: Undervoltage at buses	5 (14.71%)
V6: Overvoltage at buses	2 (5.88%)
V7: Transmission Line Overload	14 (41.18%)
V8: Islanding	1 (2.94%)

The highest number of types of violations occurs during islanding when branch 16-19 has been disconnected. Although islanding occurrence is only 2.94% it has huge impact on the whole power system. The real power requirement from slack bus 31 exceeds its limit which is about 159% of the maximum capacity. Islanding leads to all types of violations except negative reactive power at the generators.

During transmission line outage it has been observed that there is no occurrence of negative reactive power production by the generators in any of the cases.

It has been found that in 85.29% cases, the power factors of different generators goes below acceptable limits. It shows that transmission line outage leads to changes in reactive power demands which lead to low power factors of generators. About 23.53% cases show that reactive power demand from different generators exceeds the capacities. Therefore generators are at risk whenever there is transmission line outage.

About 41.18% of the cases transmission line outage leads to overload of other transmission lines. About 14.71% of the cases lead to undervoltages at buses. There is less likelihood of overvoltage which occurred 5.88% times.

This paper only analyzed IEEE 39 Bus Transmission Network using Newton Raphson method for power flow solution making it reliable for the concerned bus system as power flow solution by Newton Raphson method is highly accurate.

VIII. CONCLUSION

Transmission line outage is a common scenario in power systems. The transmission line network of IEEE 39 bus has been analyzed. Each of the branches has been disconnected and the types of power system violence have been noted. The power system is highly affected by various types of violations when transmission line outage leads to islanding. 85.29% of the cases cause the power factor of generators to go below acceptable level due to increase in reactive power demand. More than 23.53% of the cases show reactive power demand

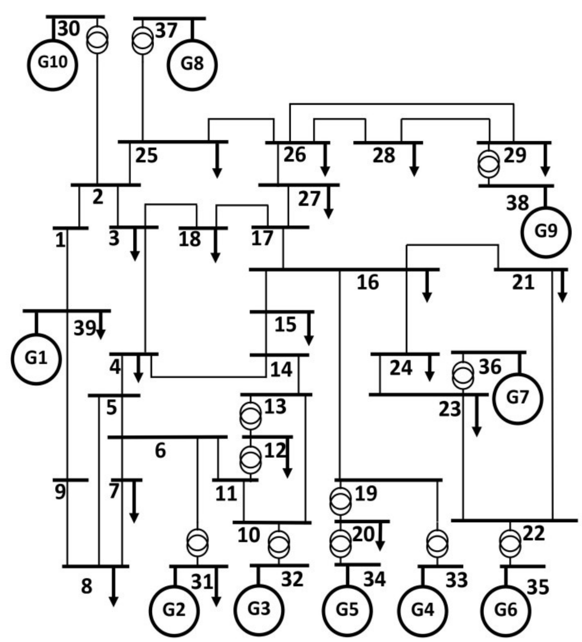

Fig. 2. IEEE 39 bus system

of generators go beyond capacity. This gives an indication that transmission line outage may severely affect generators. Transmission line outage also increases the risk of overloading of other transmission lines which has been seen in 41.18%. of the cases. About 14.71% of the cases show emergence of undervoltage at the buses. The power system has less chance of overvoltage at the buses of about 5.88% . Further studies about the impact of transmission line outage on the various types of violations can be studied and remedies may be found out. Also further studies can be carried out on different types of systems.

APPENDIX

A. *Data for IEEE 39 Bus System*

System Data for IEEE 39-Bus Test System is given in Tables IV to IX taken from [8].

TABLE IV BUS DATA

Bus Codes used: 1-Load bus, 2-Generator bus, 3-Swing bus

BUS #	BUS BASE kV	BUS TYPE CODE	BUS #	BUS BASE kV	BUS TYPE CODE
1	345	1	21	345	1
2	345	1	22	345	1
3	345	1	23	345	1
4	345	1	24	345	1
5	345	1	25	345	1
6	345	1	26	345	1
7	345	1	27	345	1
8	345	1	28	345	1
9	345	1	29	345	1
10	345	1	30	22	2
11	345	1	31	22	3
12	345	1	32	22	2
13	345	1	33	22	2
14	345	1	34	22	2
15	345	1	35	22	2
16	345	1	36	22	2
17	345	1	37	22	2
18	345	1	38	22	2
19	345	1	39	345	2
20	345	1			

TABLE V LOAD DATA

BUS #	P LOAD (MW)	Q LOAD (MVar)	BUS #	P LOAD (MW)	Q LOAD (MVar)
3	322	2.16	23	247.5	76.14
4	500	165.6	24	308.6	-82.98
7	233.8	75.6	25	224	42.48
8	522	158.4	26	139	15.3
12	8.5	79.2	27	281	67.95
15	320	137.7	28	206	24.84
16	329.4	29.07	29	283.5	114.21
18	158	27	31	9.2	4.14
20	680	92.7	39	1104	225
21	274	103.5			

TABLE VI MACHINE DATA

BUS #	Pgen (MW)	Pmax (MW)	Pmin (MW)	Qmax (MVar)	Qmin (MVar)
30	250.00	1040	0	400	-140
31	Slack	646	0	300	-100
32	650.00	725	0	300	-150
33	632.00	652	0	250	0
34	508.00	508	0	167	0
35	650.00	687	0	300	-100
36	560.00	580	0	240	0
37	540.00	564	0	250	0
38	830.00	865	0	300	-150
39	1000.00	1100	0	300	-100

TABLE VII TWO WINDING TRANSFORMER DATA

FROM BUS #	TO BUS #	SPECIFIED R (PU)	SPECIFIED X (PU)	WND 1 RATIO (PU)
2	30	0	0.0181	1.025
6	31	0	0.05	1.07
10	32	0	0.02	1.07
11	12	0.0016	0.0435	1.006
12	13	0.0016	0.0435	1.006
19	20	0.0007	0.0138	1.06
19	33	0.0007	0.0142	1.07
20	34	0.0009	0.018	1.009
22	35	0	0.0143	1.025
23	36	0.0005	0.0272	1
25	37	0.0006	0.0232	1.025
29	38	0.0008	0.0156	1.025

TABLE VIII PLANT DATA

BUS #	Vsched (pu)	BUS #	Vsched (pu)	BUS #	Vsched (pu)
30	1.02	34	1.005	38	1.025
31	0.96	35	1.035	39	1.03
32	0.96	36	1.05		
33	0.995	37	1.025		

TABLE IX BRANCH DATA

LINE	Resistance (PU)	REACTANCE (PU)	SUSCEPTANCE (PU)	STATIC RATING (A)
1-2	0.0035	0.0411	0.6987	450
1-39	0.0020	0.0500	0.3750	450
2-3	0.0013	0.0151	0.2572	950
2-25	0.0070	0.0086	0.1460	590
3-4	0.0013	0.0213	0.2214	590
3-18	0.0011	0.0133	0.2138	450
4-5	0.0008	0.0128	0.1342	590
4-14	0.0008	0.0129	0.1382	950
5-6	0.0002	0.0026	0.0434	1220
5-8	0.0008	0.0112	0.1476	820
6-7	0.0006	0.0092	0.1130	1110
6-11	0.0007	0.0082	0.1389	1110
7-8	0.0004	0.0046	0.0780	770
8-9	0.0023	0.0363	0.3804	360
9-39	0.0010	0.0250	1.2000	310
10-11	0.0004	0.0043	0.0729	1130
10-13	0.0004	0.0043	0.0729	1110
13-14	0.0009	0.0101	0.1723	1110
14-15	0.0018	0.0217	0.3660	270
15-16	0.0009	0.0094	0.1710	830
16-17	0.0007	0.0089	0.1342	800
16-19	0.0016	0.0195	0.3040	1110
16-21	0.0008	0.0135	0.2548	1170
16-24	0.0003	0.0059	0.0680	1070
17-18	0.0007	0.0082	0.1319	740
17-27	0.0013	0.0173	0.3216	450
21-22	0.0008	0.0140	0.2565	1780
22-23	0.0006	0.0096	0.1846	1110
23-24	0.0022	0.0350	0.3610	1780
25-26	0.0032	0.0323	0.5130	540
26-27	0.0014	0.0147	0.2396	890
26-28	0.0043	0.0474	0.7802	360
26-29	0.0057	0.0625	1.0290	450
28-29	0.0014	0.0151	0.2490	820

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