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Contingency analysis of a 10-bus power system using power world simulator

In the deregulated regime electricity market is oligopolistically competitive. It is one of the challenging tasks for the power system engineers to maintain security of the power system. The security will be maintained if the system becomes able to operate within system constraints, like limits of bus voltage magnitudes, current and power flow over the lines etc, to name a few, in the event of outage, i.e. contingency, of any component like generator or transmission line. The goal of the contingency analysis is to give the operator about the static security information. Contingency analysis of a power system is a major activity in power system planning and operation. In the present work, the authors have considered a hypothetical 10-Bus system and studied the contingency analysis of the system based on one by one outage of generators and lines using Power World simulator. The results of major violations are shown in the paper. The linear sensitivity factors are the faster techniques to estimate the post contingency values of different quantities of interest. In the present work one sensitivity factor like line outage distribution factor (LODF) has been estimated. Optimal power flow at major violation has been performed to identify the effective system adjustment.

Keywords: *Contingency analysis, power world simulator, LODF.*

1. Introduction

Electrical energy is an essential ingredient for the industrial and all-round growth of a country. The per capita consumption of electrical energy is a reliable indicator of a country's state of development. With the increasing demand for energy, the power system has become a complex network in itself. And failure of any of its devices, like generators, lines, etc hampers the continuity of operation, security, safety and thus leads to outages, thus influencing security of power system. Thus power system security is a foremost part of power system. The November 1965 blackout in the interconnected power systems in the northeastern part of the United States and Ontario had a profound impact on the electric utility industry, particularly in North America. On 30th and 31st July 2012, the Eastern and the Northern India have faced a severe blackouts. If fault continues in a system it gets exposed to disastrous and system may completely blackout. It is dominant importance in having a safe, reliable, continuous and economic operating condition of power system. The system security involves practices suitably designed to survive in looming disturbances conditions (contingencies), without hampering to the safety, reliability and customer service. The most important aspect is evaluation of contingency. Contingency leads to bus limit violations, transmission line overloads during the operating conditions. Severe contingencies must, firstly, be identified and thereafter, it is required to ensure fast secure, reliable and continuous operation. As a major and important part of power system security, operational engineers need to study the effect of outages and contingency on power system in terms of severity. By contingency ranking the system operator can be cautioned about the vulnerable lines present in the system. Power flow or load flow is important part of this analysis. [1-5]

Power World simulator (Version 10.0) is a package simulator with colourful visual interface. It is a powerful tool for solving, efficiently, power flows up to 60,000 buses network. The Simulator could be used for integrated economic dispatch, area transaction economic analysis, power transfer distribution factor (PTDF) computation, short circuit analysis and contingency analysis. The contingency analysis with Power World Simulator would inform about the deviation of the normalcy i.e. base case operation, of the system. Due to loss of one or more elements, like lines, generators etc, of the system, simulator indicates the post-contingency violations. A set of corrective actions is required to be taken either automatically or manually to bring, again, the system to normality. There is a tool in the simulator for modelling contingencies and system adjustments. System adjustments are modelled explicitly as part of each contingency. Simulator's optimal power flow (OPF) or security-constrained optimal power flow (SCOPF) may help the system planner identify appropriate actions for system

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adjustments to mitigate transmission line or interface overloads. System adjustments may include the opening or closing of a transmission element; the opening, closing, or re-dispatch of a generator; the changing of a phase shifting transformer angle; the opening, closing, or changing of the switched shunt set point; or the curtailment of load [6- 7].

In the present paper, the authors have considered a hypothetical 10-bus network, having 7 generators and 16 numbers of lines. The authors have studied the contingency analysis of the network based on one by one outage of lines using Power World simulator. Severe contingency has been identified and various linear sensitivity factors - line outage distribution factor (LODF) is estimated by the simulator the post contingency values of different quantities of interest. Optimal power flow (OPF) has been performed for system adjustments to mitigate transmission line overloads and this analysis helps the system planner identify appropriate actions.

2. Problem formulation

2.1 Modelling for Contingency Analysis

Limit of line flows and bus voltages of the power system, whether they have crossed, are the most important to know in the contingency analysis. Newton-Raphson load flow model is the most fundamental for such information [1-2].

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = [J] \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \quad \text{... (1)}$$

ΔP: difference between specified and calculated values of active power of each bus (i.e. power mismatch at, say i^{th} bus); ΔQ: difference between specified and calculated values of reactive power of individual buses, (i.e. reactive power mismatch at, say i^{th} bus); J: Jacobian matrix of the simultaneous equations; “$\Delta\delta$: modified phase angle value; ΔV: modified bus voltage value

2.2 Contingency Analysis using Sensitivity Factors - Line Outage Distribution Factors (LODF)

Sensitivity factors indicate the vulnerable components (bus bar voltage or line flow) where the effect is more due to outage of other component. The DC load flow is the most commonly used tool to find the LODF factors and LODF shows the change in line flows when transmission circuits are lost. LODF is formulated as

$$d_{l,k} = \frac{\Delta f_l}{f_k^0} \quad \text{... (2)}$$

where $d_{l,k}$: line outage distribution factor when monitoring line l after an outage of line k

Δf_{l}: change in MW flow on line l

f^0_k : original flow on line k before it is out i.e., pre-contingency line flow on line k

The LODF factors are constant as they are dependent only on the line parameters. Therefore, they would be pre-calculated and stored in the memory. As a result, for the outage of any line ‘m-n’, the new power flows over all the other lines can be estimated very quickly.

3. Algorithm for proposed approach

It is vital to secure the power dispatch scheduling without exceeding the line capacity. The contingency analysis is thus important one for selection of the lines in the maximum violation of the system network. The following steps to involve in the contingency analysis using Power World simulator. Contingency analysis is nothing, but a load flow analysis. Assumptions of load flows such as initial values of bus voltages (Vi) and phase angles (δ_i) for i = 1,2,3,…n PQ buses, phase angles (δ_i) for i = 1,2,3,…n PV buses and fixed slack bus V_1 = 1 p.u. and $/\delta_1 = 0^o$.

A. Contingency analysis algorithm – Line Outage condition

Step 1: Draw the Simulink one line diagram in “New case window” of Power World simulator for the proposed power system network in the edit mode.

Step 2: Save the case with “.apt” extension.

Step 3: Select run mode.

Step 4: Play or run the one line diagram in tool menu.

Step 5: Select Contingency Analysis in tool menu, then the contingency analysis dialogue box is open.

Step 6: Right click on label and select auto insert contingencies through special option.

Step 7: Verify that single transmission line is selected.

Step 8: we can use filter to limit the contingencies to only the selected branches.

Step 9: To insert contingencies for all branches so no filtering is desired.

Step 10: To check the following conditions:

(a) Remove the checkmark in use area/zone filters.

(b) Verify no other options are selected.

Step 11: Click to insert contingencies button to accept the all contingencies.

Step 12: Click YES to get the contingencies.

Step 13: Now the contingency analysis dialog box shows contingencies.

(a) Right click on the list display on the contingency tap and select either special and click auto insert to the local menu.

(b) Select single generating unit then click the do insert contingencies button. Click YES to complete.

Step 14: The auto insert tool did not insert a contingency for the generator connected to the slack bus.

Step 15: Click „start" run on the contingencies tab click start on summary tab or run contingency.

Step 16: Select the maximum violation of contingency analysis taken for account in the secured dispatch of deregulation of power market.

4. Case study

The test system is a 10-bus network as shown in Fig.1. The network consists of seven generators and sixteen transmission lines for dispatch of power. The network is divided into two areas A and B and consists of three zones. The zones are marked by red dotted lines whereas the areas are marked in two different colours. Area A and B are connected by a tie line. All the connected generators are AGC (automatic generation control) enabled. The network is run by Newton-Raphson load flow method and the Fig.1 shows the network after the load flow. Line data and bus data are shown in Tables 1, 2, 3 and 4. The percentage of power flow over each line is mentioned in power flow diagram (Fig.1). In the pre-contingency, there is no over loading of lines i.e. all lines are loaded within their set limit. Also bus voltages are within the limits of 1.05 p.u. to 0.95 p.u. (Table 1). In Fig.1, it is observed that there is a difference of incoming and outgoing power flow of the line and this happens due to line loss.

4.1 Contingency analysis

Contingency analysis of power system is a planning process - how to tackle the severe violations arising due to outage of line/equipment. Accordingly prior measures are to be taken. After running the contingency tool in Power World simulator, it will process the contingencies by outage of lines one by one and give the results (Table 5) addressing how many violations occur during each contingency. In the Table 5, the violations will be indicated with respect to the value being set in the limit monitoring settings – default setting of bus bar voltage at 0.9 p.u. and line flow at 80 MW. In the Table 5, the contingencies are arranged in descending order of severity. That is, serial number 1 is considered to be most

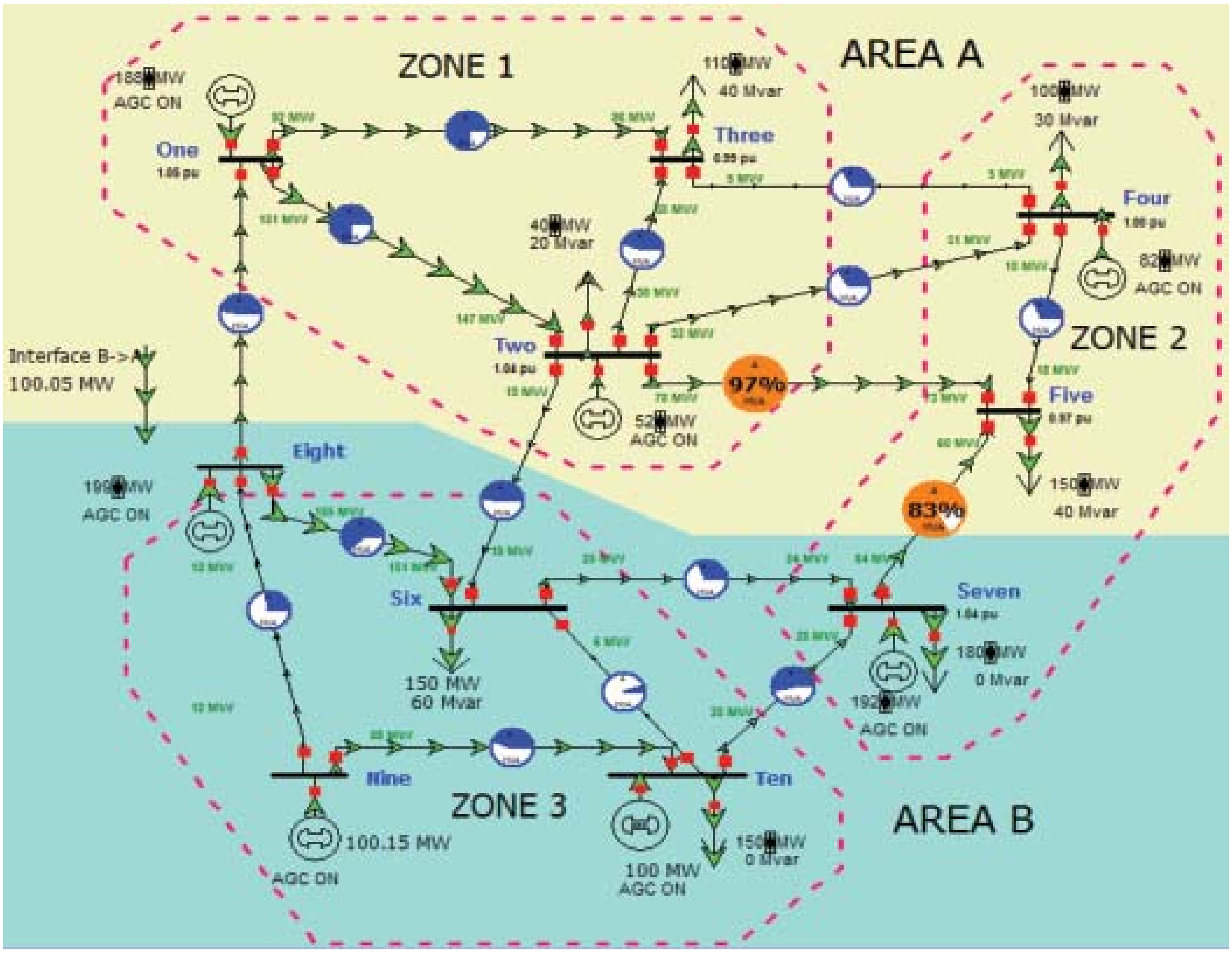

Fig.1: Pre-contingency test system

Table 1: Bus records

	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 Num	Zone Num
1	1	One	A	138.00	1.05004	144.906	6.97			188.11	9.40		0.00	0.00	1	1
2	2	Two	A	138.00	1.04003	143.525	-2.62	40.00	20.00	52.00	132.41		0.00	0.00	1	1
3	3	Three	A	138.00	0.99098	136.756	-5.04	110.00	40.00				0.00	0.00	1	1
4	4	Four	A	138.00	1.00004	138.006	-5.32	100.00	30.00	82.00	52.89		0.00	0.00	1	2
5	5	Five	A	138.00	0.96784	133.562	-7.54	150.00	40.00				0.00	0.00	1	2
6	6	Six	B	138.00	1.00381	138.525	-2.63	150.00	60.00				0.00	0.00	2	3
7	7	Seven	B	138.00	1.04001	143.522	-6.88	180.00	0.00	192.15	75.08		0.00	0.00	2	2
8	8	Eight	B	138.00	1.04002	143.523	14.39			198.94	49.34		0.00	0.00	2	3
9	9	Nine	B	138.00	1.00001	138.001	15.88			100.15	-27.65		0.00	0.00	2	3
10	10	Ten	B	138.00	1.00000	138.000	-2.00	150.00	0.00	100.24	-3.24		0.00	0.00	2	3

Table 2: Line records

	Number of Bus	Name of Bus	Zone Num of Bus	Zone Num of Gen	ID	Status	Gen MW	Gen Mvar	Set Volt	AGC	AVR	Min MW	Max MW	Min Mvar	Max Mvar	Cost Model	Part. Factor
1	1	One	1	1	1	Closed	188.11	9.40	1.05000	YES	YES	50.00	250.00	-200.00	200.00	Piecewise Linear	1.00
2	2	Two	1	1	1	Closed	52.00	132.41	1.04000	YES	YES	50.00	300.00	-200.00	200.00	Piecewise Linear	1.00
3	4	Four	2	2	1	Closed	82.00	52.89	1.00000	YES	YES	50.00	200.00	-200.00	200.00	Piecewise Linear	1.00
4	7	Seven	2	2	1	Closed	192.15	75.08	1.04000	YES	YES	0.00	300.00	-200.00	200.00	Piecewise Linear	1.00
5	8	Eight	3	3	1	Closed	198.94	49.34	1.04000	YES	YES	150.00	300.00	-200.00	200.00	Piecewise Linear	1.00
6	9	Nine	3	3	1	Closed	100.15	-27.65	1.00000	YES	YES	0.00	200.00	-200.00	200.00	Piecewise Linear	10.00
7	10	Ten	3	3	1	Closed	100.24	-3.24	1.00000	YES	YES	0.00	1000.00	-9900.00	9900.00	Piecewise Linear	10.00

Table 3: Generator records

	Number of Bus	Name of Bus	Zone Num of Bus	Zone Num of Gen	ID	Status	Gen MW	Gen Mvar	Set Volt	AGC	AVR	Min MW	Max MW	Min Mvar	Max Mvar	Cost Model	Part. Factor
1	1	One	1	1	1	Closed	188.11	9.40	1.05000	YES	YES	50.00	250.00	-200.00	200.00	Piecewise Linear	1.00
2	2	Two	1	1	1	Closed	52.00	132.41	1.04000	YES	YES	50.00	300.00	-200.00	200.00	Piecewise Linear	1.00
3	4	Four	2	2	1	Closed	82.00	52.89	1.00000	YES	YES	50.00	200.00	-200.00	200.00	Piecewise Linear	1.00
4	7	Seven	2	2	1	Closed	192.15	75.08	1.04000	YES	YES	0.00	300.00	-200.00	200.00	Piecewise Linear	1.00
5	8	Eight	3	3	1	Closed	198.94	49.34	1.04000	YES	YES	150.00	300.00	-200.00	200.00	Piecewise Linear	1.00
6	9	Nine	3	3	1	Closed	100.15	-27.65	1.00000	YES	YES	0.00	200.00	-200.00	200.00	Piecewise Linear	10.00
7	10	Ten	3	3	1	Closed	100.24	-3.24	1.00000	YES	YES	0.00	1000.00	-9900.00	9900.00	Piecewise Linear	10.00

TABLE 4: LOAD RECORDS

	Number of Bus	Name of Bus	Area Name of Load	Zone Name of Load	ID	Status	MW	Mvar	MVA	S MW	S Mvar
1	2	Two	A	1	1	Closed	40.00	20.00	44.72	40.00	20.00
2	3	Three	A	1	1	Closed	110.00	40.00	117.05	110.00	40.00
3	4	Four	A	2	1	Closed	100.00	30.00	104.40	100.00	30.00
4	5	Five	A	2	1	Closed	150.00	40.00	155.24	150.00	40.00
5	6	Six	B	3	1	Closed	150.00	60.00	161.55	150.00	60.00
6	7	Seven	B	2	1	Closed	180.00	0.00	180.00	180.00	0.00
7	10	Ten	B	3	1	Closed	150.00	0.00	150.00	150.00	0.00

TABLE 5: CONTINGENCIES IN THE NETWORK- ONE BY ONE OUTAGE OF BRANCHES

	Label	Skip	Category	Processed	Solved	Post-CTG AUX	Islanded Load	Islanded Gen	Global Actions	Transient Actions	Remedial Actions	QV Autoplot	Custom Monitor Violation	Violations	Max Branc	Min Volt	Max Volt	Max Interface %
1	L_000007Seven-000005Five	NO		YES	YES	none			0	0	0	NO	0	2	165.7	0.900		
2	L_000001One-000002TwoC	NO		YES	YES	none			0	0	0	NO	0	1	150.8			
3	L_000002Two-000005FiveC1	NO		YES	YES	none			0	0	0	NO	0	1	143.6			
4	L_000008Eight-000006SixC1	NO		YES	YES	none			0	0	0	NO	0	2	132.7			
5	L_000004Four-000005FiveC	NO		YES	YES	none			0	0	0	NO	0	2	112.8			
6	L_000001One-000003Three	NO		YES	YES	none			0	0	0	NO	0	2	112.1			
7	L_000006Six-000007SevenC	NO		YES	YES	none			0	0	0	NO	0	1	108.1			
8	L_000009Nine-000010TenC	NO		YES	YES	none			0	0	0	NO	0	1	108.1			
9	L_000002Two-000006SixC1	NO		YES	YES	none			0	0	0	NO	0	1	107.6			
10	L_000010Ten-000007Seven	NO		YES	YES	none			0	0	0	NO	0	1	107.4			
11	L_000002Two-000004FourC	NO		YES	YES	none			0	0	0	NO	0	1	105.4			
12	L_000002Two-000003Three	NO		YES	YES	none			0	0	0	NO	0	1	103.6			
13	L_000008Eight-000009Nine	NO		YES	YES	none			0	0	0	NO	0	0				
14	L_000006Six-000010TenC1	NO		YES	YES	none			0	0	0	NO	0	0				
15	L_000008Eight-000001One	NO		YES	YES	none			0	0	0	NO	0	0				
16	L_000003Three-000004Four	NO		YES	YES	none			0	0	0	NO	0	0				

	Category	Element	Value	Limit	Percent	Area Name Assoc.	Nom kV Assoc.
1	Branch MVA	Two (2) -> Five (5) CKT 1 at Two	132.55	80.00	165.68	A	138.00
2	Bus Low Volts	Five (5)	0.90	0.90		A	138.00

severe. A violation includes an overload on a branch or an overload on an interface or a high or low voltage at a bus. In the Table 5, the results indicate that outage of line between buses 7 and 5, i.e. contingency serial no.1, there are two violations occurred - one due to 165.7% overloading of line 2-5 and other due to low voltage (0.9 p.u.) at bus 5. Fig.2 depicts the status of the network after outage of line between buses 7 and 5. Line 2-5 are shown red due to overloading (value rounding off to 166%).

The network is a mesh type. Over loading power is coming from different lines, generators are not overloaded as AGC of the generators are ON. Knowing these violations, it is the duty of the system designer to take remedial measures. Optimal power flow analysis helps in this regards.

4.2 Line Outage Distribution factor (LODF)

LODF can be obtained directly by clicking its tab. As outage of line 5-7 causes severe contingency in the system, LODF for this case has shown in the present work. Table 6 shows the LODF results due to outage of line 7-5. Lossless DC load flow tool has been applied. The -100% LODF against the line 7-5 means that the 100% of the flow of the line will go away due to outage of this line. As load is not changed, therefore there is readjustment of power flow through rest of the lines and some of the lines might be overloaded. Here we can see that due to outage of line 7-5, line between bus 2 and 5 will have real power of 129.1 MW flowing from bus 2 instead of 78 MW (in steady state condition). Also the real power received at bus 5 stands at 114.4 MW instead of 73 MW (in steady state condition). From the LODF analysis it is observed that line 2-5 is most sensitive compared to other line due to outage of line 7-5 marked in red.

4.3 Optimal Power Flow

The OPF tool may be used with the contingency analysis to help identify effective system adjustments to occur in either the base case, following a primary contingency or any of the secondary contingencies. This is just one possible approach, as other tools such as sensitivity analysis and the line loading replicator may also provide valuable insight. In addition, the OPF may be operated with various mixes of controls. Possible controls include re-dispatch of generation, curtailment of load, adjustment of phase-shifting transformer angles, adjustment of DC line set points, or changes in control

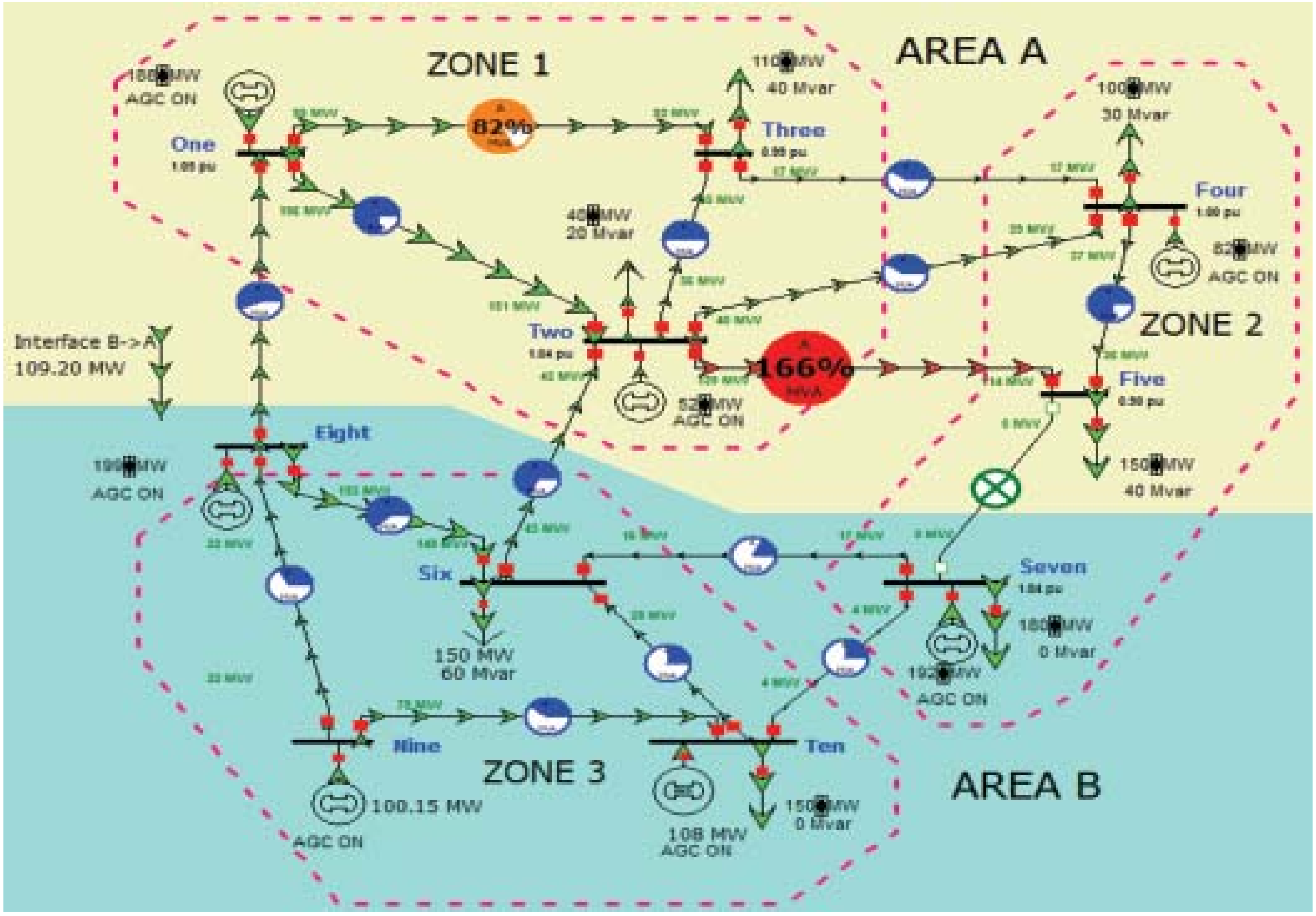

Fig.2: State of network after contingency

TABLE 6: LINE OUTAGE DISTRIBUTION FACTOR

LODFs | Interface LODFs

	From Number	From Name	To Number	To Name	Circuit	% LODF	MW From	MW To	CTG MW From	CTG MW To
1	7	Seven	5	Five	1	-100.0	0.0	0.0	0.0	0.0
2	2	Two	6	Six	1	-85.0	-41.6	43.0	-41.6	43.0
3	6	Six	7	Seven	1	-61.2	-16.3	16.6	-16.3	16.6
4	10	Ten	7	Seven	2	-38.8	4.7	-4.5	4.7	-4.5
5	6	Six	10	Ten	1	-26.8	-28.0	28.0	-28.0	28.0
6	8	Eight	9	Nine	1	-12.0	-21.7	22.1	-21.7	22.1
7	9	Nine	10	Ten	1	-12.0	78.1	-75.0	78.1	-75.0
8	8	Eight	6	Six	1	-3.1	153.0	-148.6	153.0	-148.6
9	1	One	2	Two	1	6.0	155.8	-151.4	155.8	-151.4
10	2	Two	3	Three	1	8.0	36.3	-35.4	36.3	-35.4
11	1	One	3	Three	1	9.0	98.6	-91.5	98.6	-91.5
12	2	Two	4	Four	1	10.9	39.6	-38.7	39.6	-38.7
13	8	Eight	1	One	1	15.0	67.6	-66.3	67.6	-66.3
14	3	Three	4	Four	1	17.0	16.9	-16.8	16.9	-16.8
15	4	Four	5	Five	1	27.9	37.5	-35.6	37.5	-35.6
16	2	Two	5	Five	1	72.1	129.1	-114.4	129.1	-114.4

area import schedules. The opening and closing of transmission lines cannot be considered as OPF controls, but could be analyzed with line outage or line closure distribution factors. Following adjustments to the base case, primary contingencies, and secondary contingencies, contingency analysis may be run as described previously to verify compliance of the system with the appropriate planning requirements. In this situation, the OPF is applied to mitigate violations in the post-contingent system state, without considering violations that could exist under further contingencies.

TABLE 7: OPTIMAL POWER FLOW ANALYSIS.

LP Solution Details

All LP Variables | LP Basic Variables | LP Basis Matrix | Inverse of LP Basis | Trace Solution

Records ▾ Set ▾ Columns ▾ f(x) ▾ Options ▾

	ID	Org. Value	Value	Delta Value	BasicVar	NonBasicVar	Cost(Down)	Cost(Up)	Down Range	Up Range	Reduced Cost Up	Reduced Cost Down	At Breakpoint?
1	Gen 1 #1 MW Control	191.234	74.074	-117.160	1	0	10.00	10.00	24.074	55.926	0.000	0.000	NO
2	Gen 2 #1 MW Control	55.128	50.000	-5.128	0	1	At Min	12.00	At Min	130.000	31.820	-19900.130	YES
3	Gen 4 #1 MW Control	85.128	200.000	114.872	0	3	22.00	At Max	30.000	At Max	19570.094	-107.106	YES
4	Gen 7 #1 MW Control	192.099	101.873	-90.226	4	0	22.00	22.00	41.873	18.127	0.000	0.000	NO
5	Gen 8 #1 MW Control	198.886	300.000	101.114	0	6	25.00	At Max	30.000	At Max	19972.348	-2.652	YES
6	Gen 9 #1 MW Control	99.596	150.000	50.404	0	4	23.00	25.00	50.000	50.000	0.216	-1.784	YES
7	Gen 10 #1 MW Control	98.648	50.002	-48.647	0	7	24.00	24.00	0.002	49.998	2.471	2.471	NO
8	Slack-Area A	-0.461	0.000	0.461	0	2	At Min	At Max	At Min	At Max	5013.830	-4988.170	YES
9	Slack-Area B	0.461	0.000	-0.461	0	5	At Min	At Max	At Min	At Max	4978.471	-5021.529	YES
10	Slack-Line 2 TO 3 CKT 1	-51.975	-35.839	16.135	3	0	At Min	-1000.00	At Min	35.839	0.000	0.000	NO
11	Slack-Line 8 TO 1 CKT 1	-6.669	4.440	11.109	2	0	0.00	0.00	4.440	115.560	0.000	0.000	NO

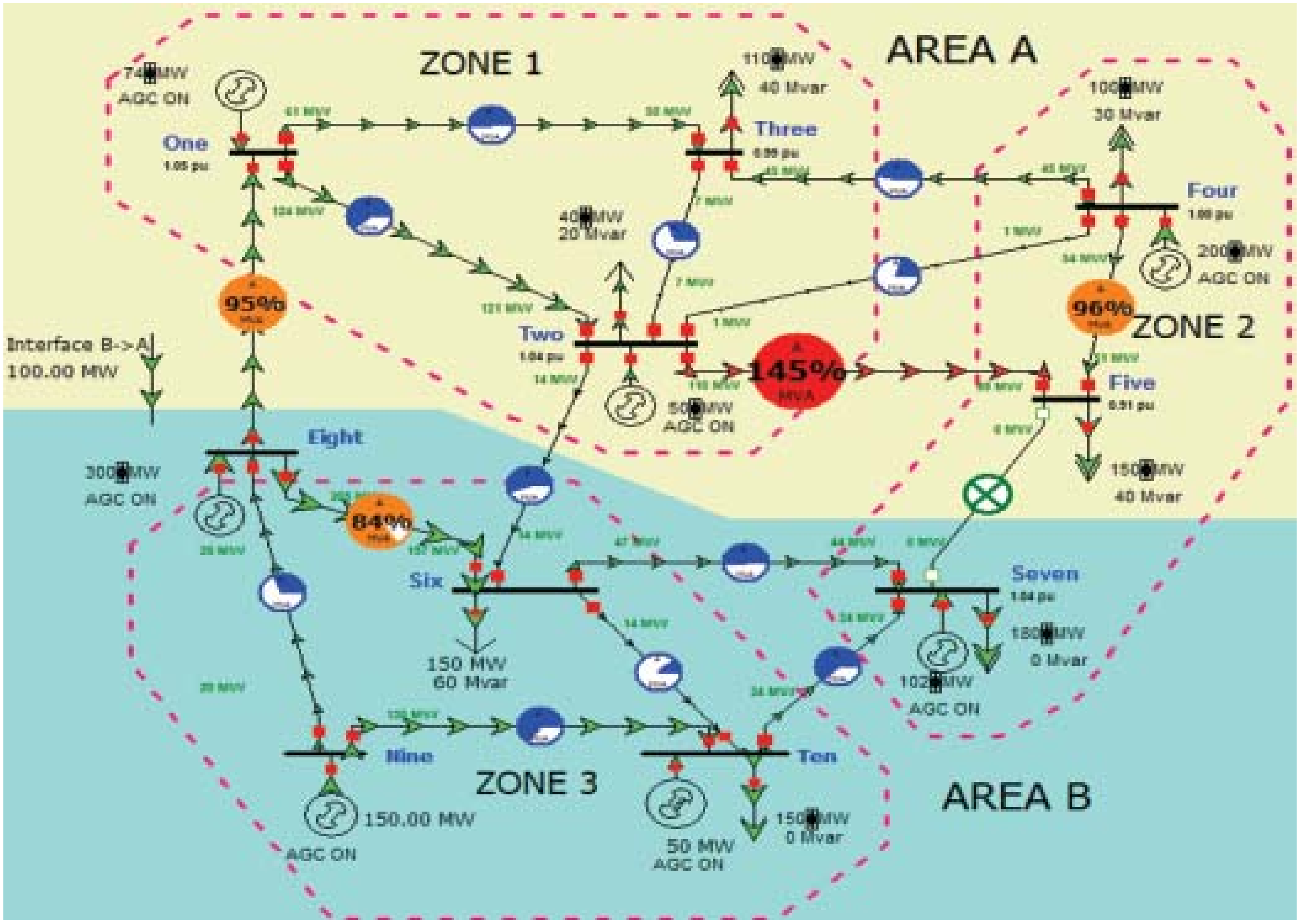

Fig.3: System state after optimal power flow analysis

For calculating the optimal power flow we have to consider an objective function. In our system the contingency having the most severe impact on our system (outage between bus 7 and 5) has been considered as the objective function. We hence have to run this contingency in the actual system and converge the power flow.

After comparison of the Figs.2 and 3, then it is observed that line over loading has been reduced to 145% and bus 5 voltage has been improved from 0.9 p.u. to 0.91p.u. These have been possible with the adjustment of generators output.

5. Conclusion

Contingency analysis is one of the analyses of power system security assessment. A power system is operationally secured if there is a low probability of blackouts or equipment damage.

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CONTINGENCY ANALYSIS OF A 10-BUS POWER SYSTEM USING POWER WORLD SIMULATOR

(Continued from page 85)

The standard load flow methods like Newton-Raphson model, DC model etc, are the important tools to evaluate the contingency analysis and helps the operators, in advance, to locate the defensive operating state to combat the line overloads and/or voltage violations. Contingency ranking helps the severity of the outages and this is done by the sensitivity factors. The sensitivity factor, LODF, have been addressed here. The authors have used Power World simulator in their study. Power World simulator is designed to evaluate all these analyses on a power system network.

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