ISSN (Print) : 0974-6846
ISSN (Online) : 0974-5645
Indian Journal of Science and Technology, *Vol 8(11), 55131, June 2015*

Analyzing the Effect of Wind Farm to Improve Transmission Line Stability in Contingencies

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Abstract

Todays, contingency analysis is being used to predict the effect of line outages in power system operation. This analysis is mostly offline to predict the line outage effects on the blackout of power system. To investigate the grid's sensitivity to each line outage, power flow equations are analyzed. The ranking process of line outage and their effects on the other lines overloading is done by calculating an index (PI_{MVA}) which represents the sum of deviations of each line power from the maximum rating of the line. Furthermore the effect of wind farm connection to the grid is investigated to improve the sensitivity of the grid in line outage contingencies. The effectiveness of the method is tested on IEEE-14 Bus standard benchmark. The simulations are done, using ETAP software.

Keywords: Contingency, PV Bus, PQ Bus, Slack Bus, Wind Farm

1. Introduction

Nowadays, propagation of the power system has made the stability and security of the grid to the concerns of power system engineers[1–3]. Traditionally, the problem of stability has been one of maintaining the synchronous operation of generators operating in parallel, known as rotor angle stability. The problem of rotor angle stability is well understood and documented. With continuous increase in power demand, and due to limited expansion of transmission systems, modern power system networks are being operated under highly stressed conditions. These concerns are mostly about the probability of overloading some of transmission lines due to other line outage. In some cases, one line outage occurrence may cause cascade line outages in the whole grid and finally blackout occurs[4,5]. In[1], the formulation method of contingency ranking, is presented which is based on system Performance Indices (PI) is proposed. The variations of the modeling are a function of bus voltages and line power flows and the corresponding limits. This method also uses Tellegen's theorem to calculate PI sensitivities to these outages. Calculating the ranking is done by ordering these PI sensitivities in descending order. In[6], authors have proposed contingency ranking analysis, based on DC load flow. This method benefits less complexity. In[7], authors have improved computating procedure based on DC load flow method, which requires one forward–backward substitution to compute performance index for line outage. On the other hand, in[8], a new approach to find sensitivity of performance index for single branch outage is presented.

In the most of the papers, contingency analysis is investigated by PI index and it is so conventional[9,10]. The megawatt performance index, PI_{MW} is used as an index for quantifying the extent of line overloads in terms of megawatt flows and their MW limits. The most important thing is megavoltampere performance index. The PI_{MVA} represents the line over load in terms of its MVA capacity[10]. It has been reported that PI_{MVA} represents extent of line over load in true sense as MVA flow in a line corresponds to the line current in that line. In this paper the effect of adding a wind farm to the AC grid to improve ability of grid in line outage contingencies is analyzed. In the next part, DC load flow analysis will be investigated in line outage contingency condition. In the third part, the

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simulation results are presented in order to investigate the effectiveness of adding wind farm to improve contingency condition by ETAP Power station. Finally, the conclusion is summarized in the last section.

2. DC Load Flow Analysis

For simulating the load flow analysis, DC load flow solution is used in the contingency analysis[11–13]. In a power system a slack bus is required to take care of system in suddenly active and reactive power changes. For the slack bus, voltage magnitude (V) and voltage phase angle (δ) are known variables and are set to 1 pu and 0 deg □ respectively. Therefore, row and column of B matrix corresponding to slack bus are not included while forming B^{-1} matrix in DC load flow analysis. Without loss of generality taking bus number 1 as the slack bus, the change in real power injection at bus bars can be expressed as bellow.

$$\begin{bmatrix} \Delta P_1 \\ \Delta P_2 \\ \vdots \\ \Delta P_n \end{bmatrix} = \begin{bmatrix} B'_{11} & B'_{12} & \cdots & B'_{1N} \\ B'_{21} & B'_{22} & \cdots & B'_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ B'_{N1} & B'_{N2} & \cdots & B'_{NN} \end{bmatrix} \begin{bmatrix} \delta_1 \\ \delta_2 \\ \vdots \\ \delta_n \end{bmatrix} \tag{1}$$

$$[\Delta P]=[B][\delta] \tag{2}$$

Therefore we can conclude,

$$\begin{bmatrix} \delta_1 \\ \delta_2 \\ \vdots \\ \delta_n \end{bmatrix} = \begin{bmatrix} B'_{11} & B'_{12} & \cdots & B'_{1N} \\ B'_{21} & B'_{22} & \cdots & B'_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ B'_{N1} & B'_{N2} & \cdots & B'_{NN} \end{bmatrix}^{-1} \begin{bmatrix} \Delta P_1 \\ \Delta P_2 \\ \vdots \\ \Delta P_n \end{bmatrix} \tag{3}$$

2.1 DC Load Flow Analysis in Line Outage Condition

In line outage contingency situation, the matrix $[B]$ changes to $[B+\Delta B]$ as bellow equation.

$$[\Delta P] = [B + \Delta B][\delta_{old} + \Delta\delta] \tag{4}$$

$$[\Delta P] = [B\,\delta_{old} + B\Delta\delta + \Delta B\,\delta_{old} + \Delta B\Delta\delta] \tag{5}$$

By putting equation (2) in (5) and neglecting from $\Delta B\Delta\delta$ term, we have:

$$[\Delta P] = [\Delta P + B\Delta\delta + \Delta B\,\delta_{old} + \Delta B\Delta\delta] \tag{6}$$

$$[B\Delta\delta + \Delta B\,\delta_{old}] = 0 \tag{7}$$

$$[\Delta\delta] = -[B]^{-1}[\Delta B][\Delta\delta_{old}] \tag{8}$$

So:

$$[\delta_{new}] = [\delta_{old}] + [\Delta\delta] \tag{9}$$

3. Quantification and Ranking of Line Outage Contingency

In the line outage condition, the most important thing is the location of transmission lines in power grid and MVA flows into the line. In some situations which the power flow is greater than 60% of the line MVA capacity the line is selected for contingency analysis[10]. Though, megavoltampere performance index, PI_{MVA} quantifies the extent of line overloads, but in our study, for analyzing the line outage ranking accurately, all of the transmission lines are assumed in PI_{MVA} index computation.

3.1 MVA Index in Line Outage Condition

The MVA index is used to quantify the importance and effect of each line outage on the other transmissions lines overloading. This index is verified as bellow:

$$PI_{MVA} = \sum_{i=1}^{N} \left(\frac{S_i - S_{i\,Limit}}{S_{i\,Limit}} \right)^2 \tag{10}$$

where S_i is the MVA flows to the line number i, and S_{iLimit} is maximum capacity of i th transmission line. Finally, N is number of the transmission lines[10].

4. Simulation Results

In this part, sensitivity analysis of a standard 14 Bus IEEE benchmark is investigated with and without wind farm connected to the grid. This analysis is also about the transmission lines overloading and each Bus voltage. Figure 1, illustrates the standard 14 Bus IEEE benchmark used as the case study system.

The line data and load data of the network are proposed in the Tables 1 and 2 respectively.

The base case parameters of IEEE 14 bus system load flow are listed in Table 3. In the following, PI_{MVA} is calculated for each line outage in the system and are listed in the Table 4. The simulation is done by ETAP power system software. The similar analysis is done in [16].

It is deduced from the Table 4, that the worst line outage (Maximum PI_{MVA}) effect, is related to line number 1. In this case (outage of line 1), the bus voltages are listed in the Table 5.

Table 6 shows the power flow results while line 1 is disconnected. In this table, the overloading of other lines is investigated.

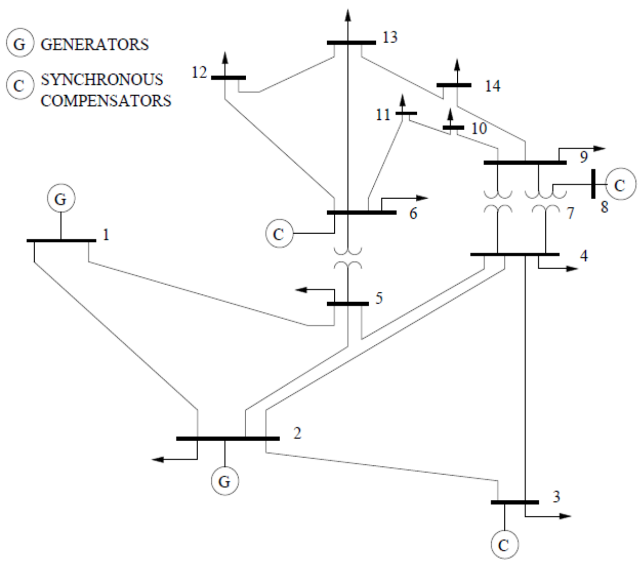

Figure 1. 14 Bus standard IEEE benchmark[13,14].

Table 1. Line data of 14 Bus system[15]

From Bus	To Bus	Line Impedance(p.u)		Half line Charging Susceptance(p.u.)	MVA Rating
		Resistance	Reactance		
1	2	0.01938	0.05917	0.02640	180
5	6	0.05403	0.22304	0.02190	65
2	4	0.04699	0.19797	0.01870	36
3	4	0.05811	0.17632	0.02460	65
1	5	0.05695	0.17388	0.01700	50
5	4	0.06701	0.17103	0.01730	65
2	5	0.01335	0.04211	0.00640	45
7	9	0	0.20912	0	55
14	13	0	0.55618	0	32
11	10	0	0.25202	0	45
4	9	0.09498	0.1989	0	18
6	11	0.12291	0.25581	0	32
8	7	0.06615	0.13027	0	32
9	10	0	0.17615	0	32
6	12	0	0.11001	0	32
12	13	0.03181	0.08450	0	32
9	14	0.12711	0.27038	0	32
6	13	0.08205	0.19207	0	12
4	7	0.22092	0.19988	0	12
2	3	0.17093	0.34802	0	12

Table 2. Bus data[12]

Bus Number	$P_{Generated}$(pu)	$Q_{Generated}$(pu)	P_{Load} (pu)	Q_{Load} (pu)	Bus Type	$Q_{Generated\ MAX}$ (pu)	$Q_{Generated\ Min}$ (pu)
1	2.32	0.00	0.00	0.00	Slack	10	−10
2	0.4	-0.424	0.217	0.127	PV	0.5	−0.4
3	0.00	0.00	0.942	0.19	PV	0.4	0.00
4	0.00	0.00	0.478	0.00	PQ	0.00	0.00
5	0.00	0.00	0.076	0.016	PQ	0.00	0.00
6	0.00	0.00	0.112	0.075	PV	0.24	−0.06
7	0.00	0.00	0.00	0.00	PQ	0.00	0.00
8	0.00	0.00	0.00	0.00	PV	0.24	−0.06
9	0.00	0.00	0.295	0.166	PQ	0.00	0.00
10	0.00	0.00	0.09	0.058	PQ	0.00	0.00
11	0.00	0.00	0.035	0.018	PQ	0.00	0.00
12	0.00	0.00	0.061	0.016	PQ	0.00	0.00
13	0.00	0.00	0.135	0.058	PQ	0.00	0.00
14	0.00	0.00	0.149	0.50	PQ	0.00	0.00

Table 3. Base case control parameters of IEEE 14 bus test system

Bls Number	Generation (p.u)		Bus Voltage (p.u.)	Phase (Degree)
	Active	Reactive		
1	2.308	0.0121	1.06	0
2	0.4	0.43	1.045	–4.8
3	0	0.4	1.0058	–12.7
4	0	0	0.9958	–9.9
5	0	0	1.0062	–8.4
6	0	0.253	1.00	–14
7	0	0	1.00	–11.8
8	0	0.092	1.00	–11.8
9	0	0	0.975	–13.8
10	0	0	0.972	–14.1
11	0	0	0.9822	–14.2
12	0	0	0.984	–14.8
13	0	0	0.9787	–14.8
14	0	0	0.9589	–15.3

In the following, a 60 MW wind farm is added into the grid at bus number 4. The contingency analysis has been done and the results are listed in Table 7. As shown in this table, the wind turbine connection improves the contingency ranking of the grid. Table 8 shows this effect in line overloading other transmission lines.

As illustrated in Tables 7 and 8 the wind farm improves the contingency ranking and prevents overloading transmission lines in the grid.

5. Conclusion

Based on DC load flow, contingency analysis is done while each line outage appears. In this condition, line outage ranking has been done by the MVA index. This analysis has operated into a 14 bus IEEE standard benchmark. This analysis shows the worst line outage is related to line number 1. By this outage, three transmission lines are overloaded. It is illustrated that by adding wind turbine into bus number 4, the contingency behavior of the grid improves much better. Also the voltage profile of the grid improves by adding wind turbine. This system is modeled

Table 4. Line outage ranking without presence of wind farm

Line Number	From Bus	To Bus	PI_{MVA}	Rank
1	**1**	**2**	**15.392**	**1**
2	5	6	8.47	2
3	2	4	8.315	3
4	3	4	8.174	4
5	1	5	8	5
6	5	4	7.863	6
7	2	5	6.51	7
8	7	9	6.394	8
9	14	13	6.237	9
10	11	10	6.17	10
11	4	9	5.94	11
12	6	11	5.86	12
13	8	7	5.472	13
14	9	10	5.43	14
15	6	12	5.4	15
16	12	13	5.261	16
17	9	14	5.1	17
18	6	13	5.08	18
19	4	7	4.96	19
20	2	3	4.76	20

Table 5. Voltage magnitude for the outage of line 1-2 In IEEE 14 bus system

Bus Number	Generation (p.u)		Bus Voltage (p.u.)
	Active	Reactive	
1	2.308	0.497	1.06
2	0.4	0.43	1.045
3	0	0.4	1.0058
4	0	0	0.9958
5	0	0	1.0062
6	0	0.52	1.00
7	0	0	1.00
8	0	0.25	1.00
9	0	0	0.975
10	0	0	0.972
11	0	0	0.9822
12	0	0	0.984
13	0	0	0.9787
14	0	0	0.9589

Table 6. Power flow results without wind farm

Line Number	From Bus	To Bus	Pre Contingency MVA Flow	Post Contingency MVA Flow	Over Loading Line
1	**1**	**2**	**157.6**	**0**	----
2	5	6	39.4	46.4	No
3	2	4	55.8	13	No
4	3	4	27.4	47.8	No
5	1	5	75.1	238.7	Yes
6	5	4	63.8	130.3	Yes
7	2	5	40.7	35.2	No
8	7	9	36.2	30.7	No
9	14	13	5.3	8.1	No
10	11	10	4.8	8.8	No
11	4	9	12.9	10.1	No
12	6	11	8.1	12.5	No
13	8	7	8.6	25	No
14	9	10	7.2	4.2	No
15	6	12	7.8	8.4	No
16	12	13	1.7	2.3	No
17	9	14	10.1	7.6	No
18	6	13	17.9	20	Yes
19	4	7	34.2	29.7	No
20	2	3	74.4	44.4	No

Table 7. Contingency ranking in presence of wind farm

From Bus	To Bus	PI_{MVA}	Rank
1	**2**	8.89	2
5	6	7.03	3
2	4	6.7	6
3	4	9.66	1
1	5	6.86	4
5	4	6.73	5
2	5	6.5	7
7	9	6.46	8
14	13	6.018	9
11	10	5.98	10
4	9	5.93	11
6	11	5.02	17
8	7	5.48	13
9	10	5.33	14
6	12	5.25	15
12	13	5.71	12
9	14	5.06	16
6	13	4.98	18
4	7	4.2	20
2	3	4.93	19

Table 8. Power flow results in presence of wind farm

Line Number	From Bus	To Bus	Pre Contingency MVA Flow	Post Contingency MVA Flow	Over Loading Line
1	**1**	**2**	**116.4**	**0**	----
2	5	6	38.1	40.9	No
3	2	4	37.3	11.3	No
4	3	4	36.5	52.3	No
5	1	5	54.5	170.1	No
6	5	4	34.8	85.3	Yes
7	2	5	29.2	28.1	No
8	7	9	37.9	34.6	No
9	13	14	4.5	6.1	No
10	11	10	4	5.9	No
11	4	9	14	11.9	No
12	6	11	6.9	9.4	No
13	7	8	3	14.9	No
14	9	10	8.5	6	No
15	6	12	7.6	8	No
16	12	13	1.6	1.9	No
17	9	14	11	9.3	No
18	6	13	17.2	18.5	No
19	4	7	37.9	31.6	No
20	2	3	65.8	43.8	No

by ETAP Power system software and the simulation results are validated the effect of adding wind farm in order to reduce the contingency risks.

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