IMPACT ANALYSIS OF GRID CONNECTED WIND FARM AT DIFFERENT POINTS OF INTERCONNECTIONS ON A POWER SYSTEM

Mudassar Khan[1], Omar Lateef[2], M. Amer Saeed[3], M. Usman Khan[4], Jawad Khalid[5]

[1]*Research fellow and corresponding author, Department of Electrical Engineering, University of Engineering and Technology Lahore, Pakistan. E-mail: mudassar.ee@gmail.com,*

[2]*Lecturer, Department of Electrical Engineering, University of Engineering and Technology Lahore, Pakistan.*

3,4,5 Lecturer, Department of Electrical Engineering, University of Central Punjab Lahore, Pakistan.

ABSTRACT: *The demand of energy is increasing, day in day out, and it is expected to increase at an ever increasing rate. Unfortunately this increase in energy, if met by conventional energy sources, will entail increase in greenhouse gases. Wind energy is the world's fastest and cheapest growing renewable energy source but wind generation and its integration in the existing power network is challenging. With the increase in wind power generation several technical issues are also taking birth because of the unique nature of the wind power. A power system is a highly non-liner system which is continuously perturbed by disturbances and the integration of the wind power increases its complexity. A power system should not only be capable of withstanding these disturbances but also should be able to provide the power keeping all the variables within limits. Power World Simulator (PWS) has been used to model a power system containing a wind farm and analyses such as power flow, short-circuit, contingency and dynamic system stability have been performed on the power system at* different points of interconnections (POIs) .

Key Words: Wind Power Integration, Power Flow, Dynamic System Stability, Power World Simulator (PWS),

1. INTRODUCTION

The demand of the energy is increasing day in day out and the greatest challenge the mankind is facing right now is to meet this demand by environmentally benign energy sources. With the escalating prices of the finite fossil fuels and increased awareness of the greenhouse gases (GHG) emission of these fuels, power generation companies are compelled to move towards inexhaustible sources with zero GHG emissions (renewable energy sources). The aforementioned facts make the renewable energy resources as the energy sources of future [1,2]. The installation of renewable energy resources (excluding hydro power) has increased more than four times in the span from 2000 to 2010. As of 2014, renewable energy has a share of 22.5% in the global energy production [3]. Referring to Figure 1 it is quite clear that wind energy is the fastest growing renewable energy source [4]. Global wind energy electricity production has increased 14 times from 2000 to 2013].

Although wind promises an inexhaustible supply of energy but it is not an elixir. With the integration of large wind farms, many unprecedented technical issues are taking birth in the power system [5].

In early days of the wind integration in power systems, the sizes of wind farms were considerably smaller and thus they were modeled as negative loads [6]. This model of the wind farm can no longer be used because of two reasons:

i. The size of a wind farm is constantly increasing; with the order of several hundred MW representing the typical size of a wind farm and thus it can affect the performance of a power system quite considerably.

Modern wind farms are equipped with the sophisticated control systems which determine their dynamic behavior under transient conditions.Wind Electrical Conversion System

Wind Electrical Conversion System (WECS) [7] is a system that converts the kinetic energy of the wind into electrical energy and transmits it onto the grid. There are following

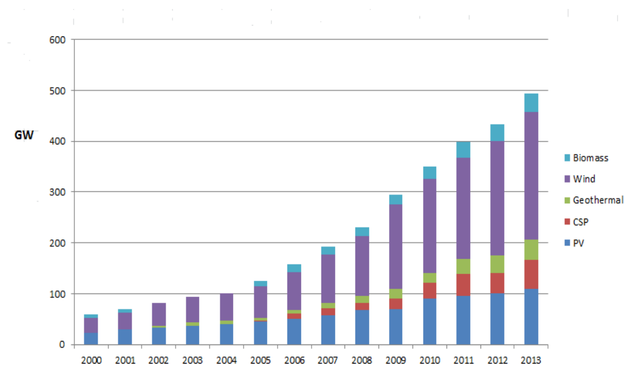

Figure 1: Renewable electricity generating capacity worldwide (excluding hydropower) [3].

four types of WECS

- Fixed Speed (Type-1)
- Limited Variable Speed (Type-2)
- DIFG Partial Variable Speed (Type-3)
- Variable Speed Full Power Control (Type-4)

As evident from the Figure 2

1.1 WECS versus Conventional Power Plants

The wind turbines are different from the conventional energy sources as wind turbines are mostly connected to the grid through the power electronics interface whereas the conventional energy sources are directly connected to the grid. A wind farm may be using the asynchronous machines whereas all the conventional power plants use synchronous generators.

The various components of a wind farm [8] as indicated in the figure 2 are listed below:

- Wind turbine
- Pad-mounted transformer
- Collectors
- Substation transformer
- Interconnection transmission line.

1.2 Integration Issues of Wind Farms

The conventional power systems consist of only synchronous generators which rotate at almost same RPM and thus generate the constant frequency and thus are synchronized to the grid. Most of the wind generators being connected to the grid are asynchronous (induction type) generators. As the penetration of the wind generation will increase into a power system the grid will move from the synchronous operation to the asynchronous operation and thus many new challenges will take birth. Moreover, as the size of wind farms integrated into the power systems is increasing their effects on load flow and stability of power system should be considered and new refined models of WECS should be introduced to assess these affects beforehand.

2. MODELING AND ANALYSIS OF BASE CASE POWER SYSTEM

In this chapter the power flow analysis is performed and the base case power system is presented. Contingency analysis is performed on the base case to see if there are any thermal violations during the contingency. After performing the short-circuit analysis, three buses are selected where the wind farm will be integrated into power system and the effect of integration at these buses will be observed.

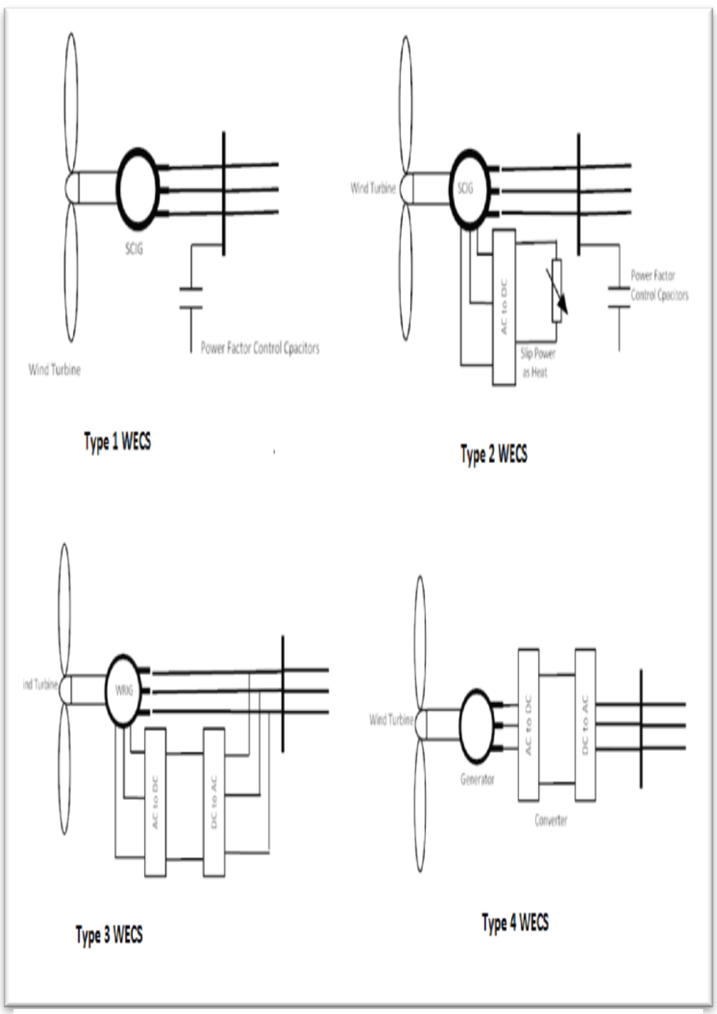

Figure 2: Types of WECS

2.1 Power Flow Analysis

The base case system used in this study consists of 9 generators, 25 loads, 8 switched shunts, 42 transmission lines and 37 buses with three voltage levels; 69 kV, 138 kV, 345 kV. For solving the Power flow bus 20 is treated as slack bus. The total real and reactive load on all the buses is 794.6 MW and 280.6 MVAR respectively. The load flow result of base case power system is shown in Figure 4. Some of the important observations made after solving load flow are:

i) Voltages of all the buses are in the permissible range of 0.95 pu to1.05 pu as is evident from the contour.
ii) The total generation is 804.1 MW and thus the total real power losses are 8.9 MW.

2.2 Contingency Analysis

In this study, N-1 contingency analysis is used to analyze the reliability and performance of different networks. Table 1 shows the result of the contingency analysis carried on to the base case system. Some of the important aspects of the result are:

i) Contingencies for the transmission lines and transformers are considered. With (N-1) criteria, this implies that there are 56 contingencies to be considered.
ii) No element has violated its thermal limit during any contingency.
iii) No bus has violated the bus voltage limits.

All the aforementioned points imply that our base case system is working well and is meeting all the criteria of reliability

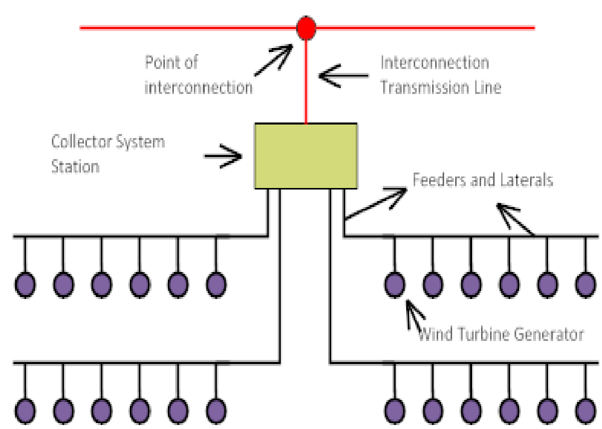

Figure 3: Layout of a wind power plant

2.3 Short Circuit Analysis

The short-circuit analysis is performed on all the buses of the power system except the generator buses. The results of the calculations are shown in Table 2. The fault considered is a three-phase bolted fault. The short-circuit analysis can be used to evaluate the strength of a power system at any bus. Based on the short-circuit currents of all the buses, three non-generator buses are selected where a wind farm will be integrated to analyze its effects on the performance of the power system. From the result of the short-circuit analysis given in Table 3, the maximum fault current of 60 per unit

Table 1: Fault analysis for the base case system

Sr. No	Label	Processed	Solved	Violations	# of iterations
1	Line_000001Bus1-000020Bus20C1	✓	✓	0	2
2	Transformer_000001Bus1-000028Bus28C1	✓	✓	0	2
3	Line_000002Bus2-000028Bus28C1	✓	✓	0	2
4	Line_000002Bus2-000029Bus29C1	✓	✓	0	2
5	Line_000003Bus3-000011Bus11C1	✓	✓	0	2
6	Line_000003Bus3-000030Bus30C1	✓	✓	0	2
7	Line_000004Bus4-000006Bus6C1	✓	✓	0	2
8	Line_000004Bus4-000012Bus12C1	✓	✓	0	2
9	Line_000004Bus4-000027Bus27C1	✓	✓	0	2
10	Line_000005Bus5-000010Bus10C1	✓	✓	0	1
11	Line_000005Bus5-000011Bus11C1	✓	✓	0	2
12	Line_000005Bus5-000016Bus16C1	✓	✓	0	1
13	Transformer_000005Bus5-000028Bus28C1	✓	✓	0	2
14	Transformer_000005Bus5-000028Bus28C2	✓	✓	0	2
15	Line_000006Bus6-000036Bus36C1	✓	✓	0	2
16	Line_000007Bus7-000023Bus23C1	✓	✓	0	2
17	Line_000007Bus7-000030Bus30C1	✓	✓	0	2
18	Line_000008Bus8-000009Bus9C1	✓	✓	0	1
19	Line_000008Bus8-000015Bus15C1	✓	✓	0	2
20	Line_000008Bus8-000035Bus35C1	✓	✓	0	1
21	Line_000008Bus8-000035Bus35C2	✓	✓	0	1
22	Line_000008Bus8-000035Bus35C3	✓	✓	0	1
23	Line_000009Bus9-000016Bus16C1	✓	✓	0	2
24	Line_000010Bus10-000012Bus12C1	✓	✓	0	2
25	Line_000011Bus11-000025Bus25C1	✓	✓	0	1
26	Line_000011Bus11-000025Bus25C2	✓	✓	0	1
27	Line_000013Bus13-000023Bus23C1	✓	✓	0	2
28	Line_000013Bus13-000033Bus33C1	✓	✓	0	2
29	Line_000014Bus14-000032Bus32C1	✓	✓	0	2
30	Line_000014Bus14-000032Bus32C2	✓	✓	0	2
31	Line_000015Bus15-000030Bus30C1	✓	✓	0	2
32	Transformer_000017Bus17-000018Bus18C1	✓	✓	0	2
33	Transformer_000017Bus17-000018Bus18C2	✓	✓	0	2
34	Line_000020Bus20-000017Bus17C1	✓	✓	0	3
35	Line_000021Bus21-000018Bus18C1	✓	✓	0	2
36	Line_000018Bus18-000029Bus29C1	✓	✓	0	2
37	Line_000037Bus37-000018Bus18C1	✓	✓	0	2
38	Line_000019Bus19-000021Bus21C1	✓	✓	0	2
39	Line_000019Bus19-000029Bus29C1	✓	✓	0	2
40	Transformer_000024Bus24-000020Bus20C1	✓	✓	0	2
41	Line_000020Bus20-000026Bus26C1	✓	✓	0	1
42	Transformer_000022Bus22-000021Bus21C1	✓	✓	0	1
43	Line_000022Bus22-000033Bus33C1	✓	✓	0	2
44	Line_000024Bus24-000027Bus27C1	✓	✓	0	2
45	Line_000024Bus24-000037Bus37C1	✓	✓	0	2
46	Transformer_000027Bus27-000026Bus26C1	✓	✓	0	2
47	Transformer_000027Bus27-000026Bus26C2	✓	✓	0	2
48	Line_000027Bus27-000028Bus28C1	✓	✓	0	2
49	Line_000027Bus27-000031Bus31C1	✓	✓	0	2
50	Transformer_000030Bus30-000029Bus29C1	✓	✓	0	1
51	Transformer_000030Bus30-000029Bus29C2	✓	✓	0	1
52	Transformer_000032Bus32-000031Bus31C1	✓	✓	0	1
53	Line_000031Bus31-000034BUs34C1	✓	✓	0	1
54	Line_000032Bus32-000035Bus35C1	✓	✓	0	2
55	Transformer_000035Bus35-	✓	✓	0	2
56	Line_000035Bus35-000036Bus36C1	✓	✓	0	1

(pu) occurs at bus 28 and the smallest fault current equal to 9.5 pu at bus 13 and is. Bus 26 with fault current of 40 pu which has fault current in between these values is. The wind farm will be integrated at all of these three buses and its effects will be evaluated based on the power flow, contingency and stability analysis.

2.4 Contingency Analysis

In this study the power system, after the integration of a wind farm, will be subjected to large disturbances and different parameters will be analyzed.

Table 2: Contingency records for the base case

Sr. No.	Fault Name	Fault Object	Fault Current Magnitude	Fault Current Angle	Fault Thev. R	Fault Thev. X
1	B_000001Bus1	Bus '1'	34.88222	-87.53868	0.00123	0.02864
2	B_000002Bus2	Bus '2'	28.73805	-83.98788	0.00364	0.03461
3	B_000003Bus3	Bus '3'	13.81807	-71.73635	0.02268	0.06872
4	B_000004Bus4	Bus '4'	20.74628	-81.76243	0.00691	0.0477
5	B_000005Bus5	Bus '5'	51.41841	-85.74005	0.00144	0.01939
6	B_000006Bus6	Bus '6'	11.22042	-71.39576	0.02843	0.08447
7	B_000007Bus7	Bus '7'	13.47536	-72.44648	0.02238	0.07075
8	B_000008Bus8	Bus '8'	33.42013	-79.65939	0.00537	0.02944
9	B_000009Bus9	Bus '9'	23.93563	-78.64217	0.00823	0.04096
10	B_000010Bus10	Bus '10'	15.26678	-74.08952	0.01796	0.06299
11	B_000011Bus11	Bus '11'	13.77189	-73.5583	0.02055	0.06964
12	B_000012Bus12	Bus '12'	13.2448	-71.16283	0.02438	0.07146
13	B_000013Bus13	Bus '13'	9.4644	-71.84312	0.03293	0.1004
14	B_000014Bus14	Bus '14'	15.81353	-76.13605	0.01515	0.06139
15	B_000015Bus15	Bus '15'	21.98446	-70.7478	0.015	0.04294
16	B_000016Bus16	Bus '16'	22.43162	-79.00056	0.00851	0.04376
17	B_000017Bus17	Bus '17'	45.3926	-87.77705	0.00085	0.02201
18	B_000018Bus18	Bus '18'	33.64845	-86.02727	0.00206	0.02965
19	B_000019Bus19	Bus '19'	23.79175	-82.64188	0.00538	0.04169
20	B_000020Bus20	Bus '20'	50.078	-87.56812	0.00085	0.01995
21	B_000021Bus21	Bus '21'	23.73116	-82.41629	0.00556	0.04177
22	B_000022Bus22	Bus '22'	12.29314	-81.88775	0.01148	0.08053
23	B_000023Bus23	Bus '23'	9.88787	-71.29398	0.03243	0.09579
24	B_000024Bus24	Bus '24'	25.09409	-85.61011	0.00305	0.03973
25	B_000025Bus25	Bus '25'	13.01399	-70.51016	0.02564	0.07244
26	B_000026Bus26	Bus '26'	39.93135	-86.76836	0.00141	0.025
27	B_000027Bus27	Bus '27'	40.04847	-84.56637	0.00236	0.02486
28	B_000028Bus28	Bus '28'	59.99148	-87.24834	0.0008	0.01665
29	B_000029Bus29	Bus '29'	42.35989	-85.84581	0.00171	0.02355
30	B_000030Bus30	Bus '30'	44.10374	-84.13603	0.00232	0.02256
31	B_000031Bus31	Bus '31'	31.50029	-84.18138	0.00322	0.03158
32	B_000032Bus32	Bus '32'	24.60741	-81.48077	0.00602	0.04019
33	B_000033Bus33	Bus '33'	12.0034	-79.08296	0.01578	0.0818
34	B_000034BUs34	Bus '34'	31.26442	-84.67674	0.00297	0.03185
35	B_000035Bus35	Bus '35'	33.82077	-81.29624	0.00447	0.02923
36	B_000036Bus36	Bus '36'	11.34542	-65.61183	0.03639	0.08028
37	B_000037Bus37	Bus '37'	17.97665	-83.58717	0.00621	0.05528

Since the models of the elements cannot be linearized so very refined models for all the machines along with their governors, exciters, stabilizers are used while studying the transient stability

3. MODELING OF WIND FARM

The wind farm modeled in the study consists of 70 GE-1.5 MW DFIG machines (Type-3). The voltage at the terminals of an individual machine is 570 V. The collector voltage used is 34.5 kV. When all the machines are online and wind speed

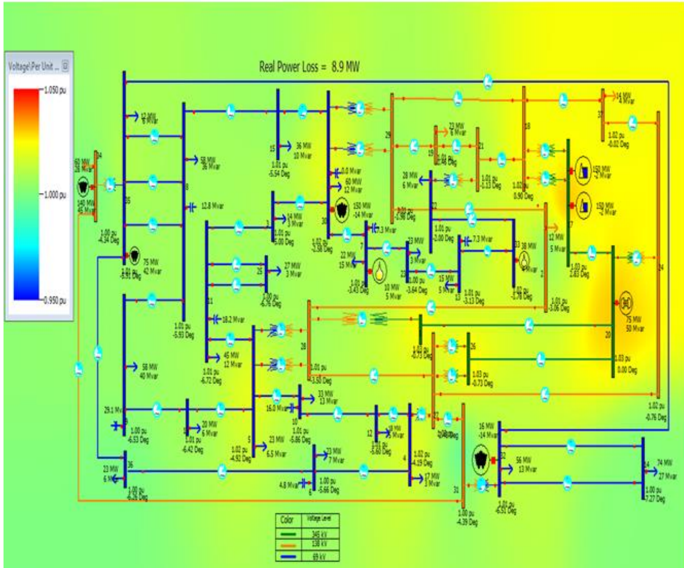

Figure 4: Base case power flow

is greater than the rated speed then the wind farm will generate 105.1 MW which is the rated capacity of the wind farm.

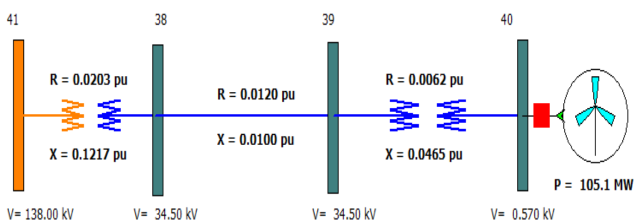

Figure 5: Power Flow Model of Wind Farm

3.1 Power Flow Model of Wind Farm

The power flow model for the analysis of wind farm is shown in figure 5. All the parameters are expressed in pu at base MVA of 100 and corresponding nominal voltages.

4. ANALYSES OF WIND FARM INTEGERATION AT VARIOUS BUSES

Various analyses such as power flow, contingency and stability will be performed on the power system after wind farm has been integrated. Power flow analysis is carried using full newton method, contingency analysis through full power flow method and stability analysis is carried through Second order Runge-Kutta.

4.1 Power Flow Analysis after integration at Bus 28

Figure 6 shows the load flow analysis after the wind farm has been integrated at bus 28. Some important observations are as follows:

- All the bus voltages are within the limits of 0.95 pu to 1.05 pu.
- The real power losses are 15.5 MW.
- No element of the power system is operating near its rated capacity

4.2 Contingency Analysis after integration at Bus 28

The N-1 contingency analysis is performed at the power system and some important observations are as follows:

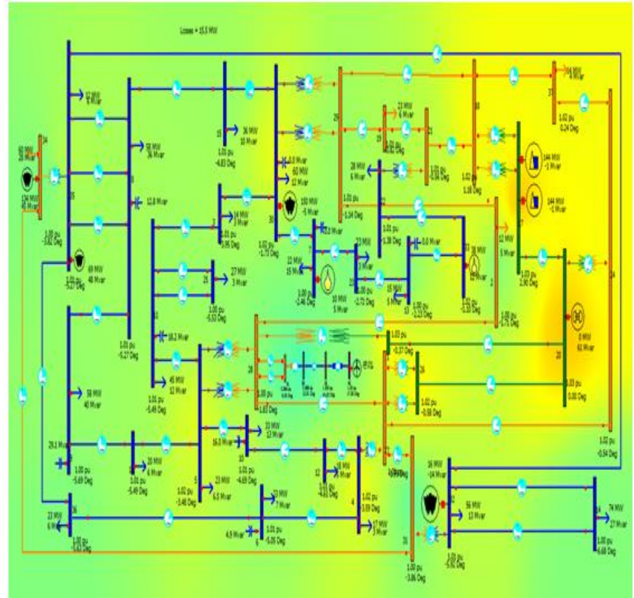

Figure 6: Power Flow Analysis With Wind Farm At Bus 28

- There is no thermal violation in any of the contingencies.
- There is no voltage violation in any of the contingencies.

4.3 Stability Analysis after integration at Bus 28

For the stability analysis, a 3-phase bolted fault is considered on the line from bus 26 to bus 38 at the near end of bus 28 at time of 1 second. The fault is cleared by the removal of the line after 5 cycles. Some important observations are:

Figure 7 which shows the plot of the angles of the generators against their frequencies (speeds). The rotor angle-speed curves of all the generators are converging after the initial disturbance which implies that all the generators are synchronized to the power system even after the disturbance

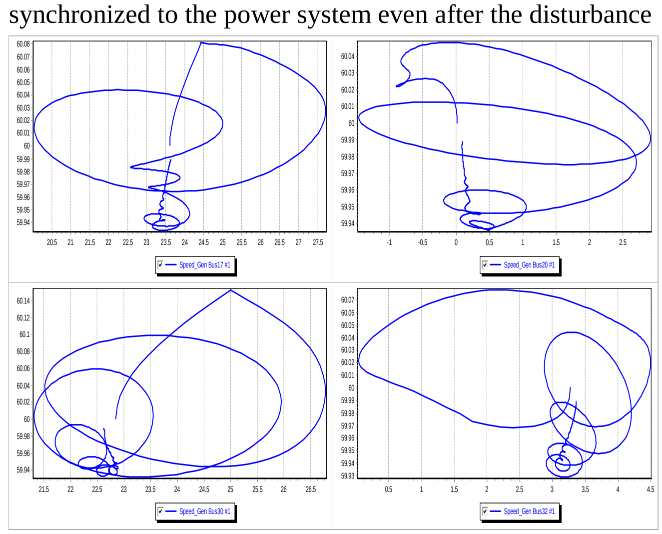

Figure 7: Frequency-angle plots of the generators

Figure 8 is the plot of the rotor angles as a function of time. From Figure 8 it is clear that the maximum angle is 7.67^{o} for the generator connected at bus 17, whereas the minimum deviation of the angle is 2.683^{o} for generator connected at bus 35.

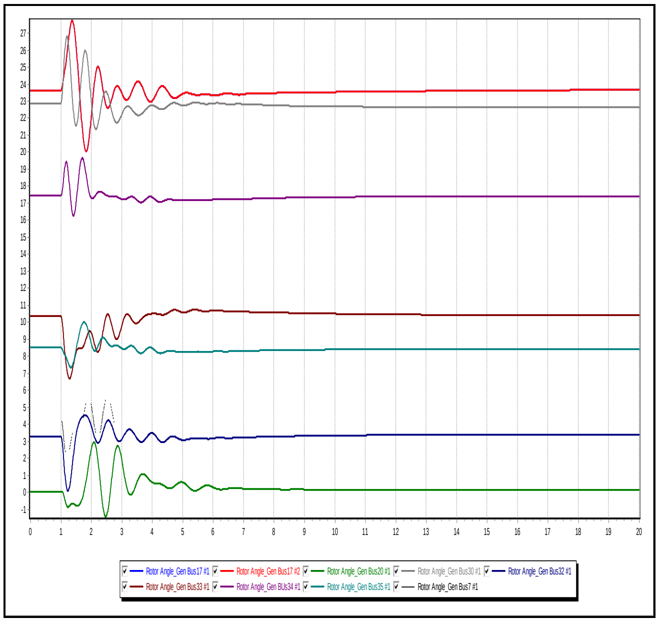

Figure 8: Rotor angles of generators

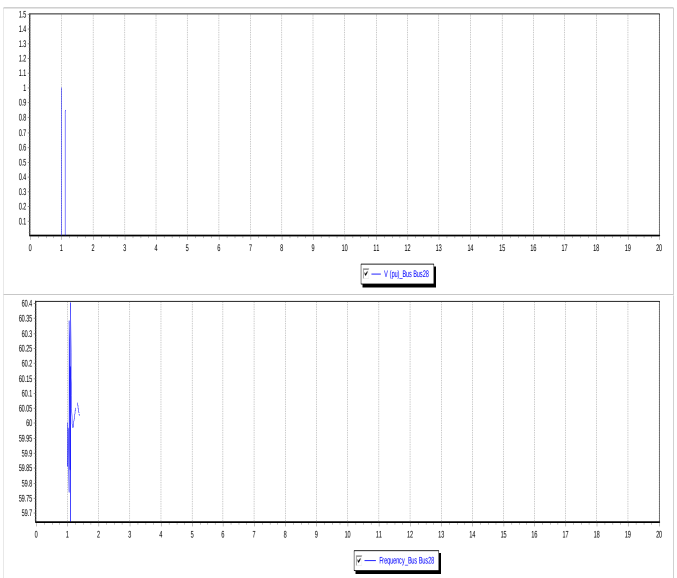

Figure 9:Voltage and frequency plots at bus 28

Figure 9 is the plot of the magnitude and frequency of the voltage at bus 28. From figure 9, the voltage of bus 28 is equal to 0 pu during the fault but recovers very quickly to 1 pu once the fault is removed. The frequency also reached to its nominal value but after some delay

5. RESULTS and DISCUSSION

Power flow analysis, Contingency analysis and stability analysis were performed after integration of the wind farm at Buses 13 and Buses 26 as shown in Figure 10 and Figure 11 and following Tables 3-5 summarize the results obtained after simulations

Although there are no voltage or thermal violations in any of the cases but there is quite a difference in the MW losses of all the cases. Maximum losses occur when wind farm is integrated at bus 13 whereas minimum losses occur when the integration is made at bus 26. It is not hard to imagine there can be buses in a power system at which an interconnection

Table 3: Load flow analyses results

	Base Case	Wind Farm Integrated at:		
		Bus 13	Bus 26	Bus 28
Voltage Violations	0	0	0	0
Thermal Violations	0	0	0	0
Losses (MW)	8.9	19.8	13.3	15.5

may decrease the losses (from the Base Case value)

There is neither voltage nor thermal violation in any of N-1 contingencies considered for the base case but this may not hold true once the wind farm has been integrated into the system because the integration of wind farm changes the load flow in all of the elements of power system depending on the its rating as well as point of interconnection. Table 4 summarizes the contingency analyses results for three POIs.

Table 4: Contingency analyses results

	Base Case	Wind Farm Integrated at:		
		Bus 13	Bus 26	Bus 28
Voltage Violations	0	0	0	0
Thermal Violations	0	14	0	0

Depending on location of interconnection, a wind farm may stress or relief a power system. In our case there is no voltage violation in any of the contingencies considered for three points of interconnections but there are thermal violations for 14 out of 61 contingencies when interconnection is made at bus 13 which means that many components of the power system have to be replaced if interconnection is to made at bus 13. This problem does not exist if interconnection is made at bus 26 or 28.

Table 5: Stability analyses results

	Wind Farm Integrated at:		
	Bus 13	Bus 26	Bus 28
System remains Stable	YES	YES	YES
Max. Angle	13.903	8.53	7.67
Minimum Angle	1.757	2.901	2.683

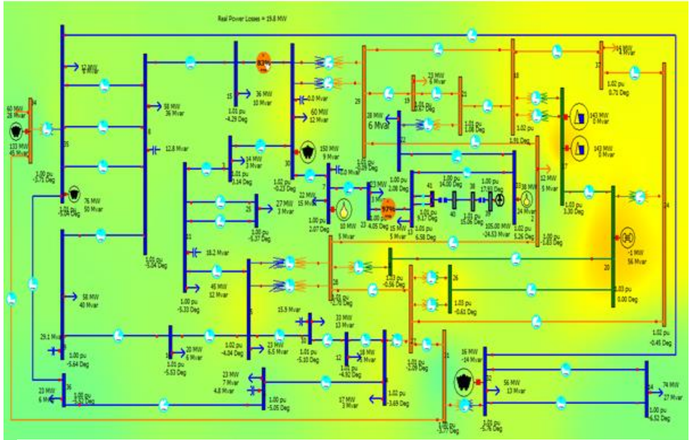

Figure 10: Power Flow Analysis With Wind Farm At Bus 13

Although the power system remained stable for all the cases considered but there is bit of difference in the angular deviations caused by the disturbances. As is evident from the table 5 that the largest deviation of angles occurs for the integration of wind farm at bus 13 whereas the smallest angular deviation occurs for the wind farm connected at bus 28

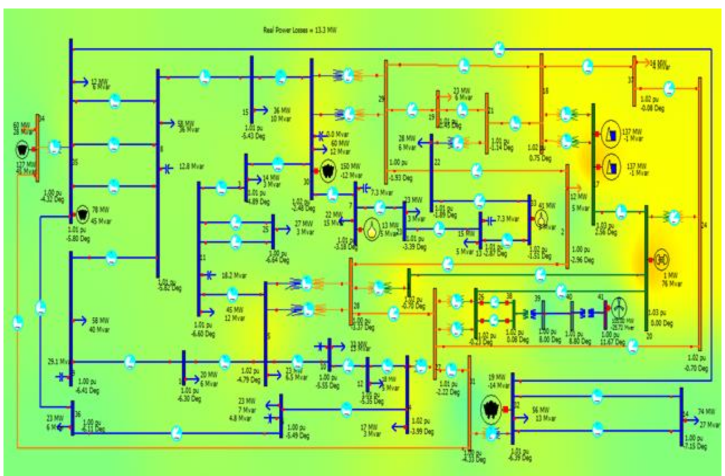

Figure 11: Power Flow Analysis With Wind Farm At Bus 26

6. CONCLUSION

When a wind farm is integrated into a power system, it varies the power flow in the elements of the power system as a consequence of which total losses in the power system will be changed.. The integration of a wind farm at some points in a power system will stress the system and the elements of the power system will start to operate in overloaded conditions, whereas the integration at other points may relief the system and loading on the power system can decrease. A wind farm will have different effects on the reliability of a power system depending upon the point of Interconnection (POI). There may be several thermal violations for some contingencies at a specific point of interconnection but there may be some points in a power system which will not result in any thermal violations even during contingency conditions. The integration of wind farms at different POIs in a power system affects the power system stability in different manners. For some POIs the wind farm will add to the stability of power system whereas for other it will negatively affect the stability of the power system. Whenever a new wind farm is to be connected to a power system, all the feasible POIs should be thoroughly analyzed so that the wind farm can be used to enhance the performance of the power system.

7. REFERENCES

[1] U.S. Department of Energy – Energy Efficiency and Renewable Energy, “20% Wind Energy by 2030 – Increasing Wind Energy’s Contribution to U.S. Electricity Supply”, May, 2008.

[2] J.C. Smith, M.R. Milligan, E.A. DeMeo and B. Parsons, "Utility Wind Integration and Operating Impact State of the Art," IEEE Transaction Power Systems, Vol. 22, pp. 900-908, August 2007.

[3] “Renewable Energy Databook 2010 ”, National Renewable Energy Laboratory (NREL).

[4] E. Muljadi, N. Samaan, V. Gevorgian, J. Li and S. Pasupulati, “Different Factors Affecting Short Circuit Behavior of a Wind Power Plant”, IEEE Industry Applications Society Annual Meeting, 3-7 October, 2010.

[5] “Wind Plant Integration Costs, Status and Issues”, IEEE power & Energy Magazine November/ December 2005.

[6] “Final Project Report WECC Wind Generator Development”, National Renewable Energy Laboratory, March 2010.

[7] G.M. Masters, “Renewable and Efficient Electric Power Systems”, John Wiley & Sons, Inc. Publications, 2004.

[8] M.R. Patel, “Wind and Solar Power Systems Design Analysis, and Operation”, CRC press, 2005.