Review of Frequency Stability Control Schemes in the Presence of Wind Energy Sources

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***Abstract*—Renewable energy sources have become a major area of interest for governments and utilities world-wide. They not only promote use of clean energy but also ensure a friendly and healthy living environment. As a result, large integration of renewable energy into the grid has become common and is growing fast. However, this rapid development has realized drastic and insurmountable challenges. The stability of the power system is compromised because renewable energy sources do not provide system inertia. The inadequacy or lack of system inertia lead to increased system frequency excursions and henceforth frequency instability. Wind energy resource development has seen unprecedented scales of growth and has also been adversely affected by frequency instability especially in isolated power systems. Research has shown that isolated or weak grids not supported by system inertia experience more instability. Most researchers therefore concentrated on finding solutions to the isolated power systems. However, large scale integration of renewables imply conventional sources of energy will be displaced and frequency instability problems would also occur in the grid. There are many frequency control methods utilized at different levels to stabilize the power system. The three levels are inertia, primary and secondary frequency response based on time of the response. This research paper investigates frequency stability with wind energy sources using IEEE 39 bus test system. It is modelled in MATLAB/Simulink and simulated by power system analysis toolbox. The results show huge power system losses and power mismatch values. In conclusion the toolbox is not sufficient to simulate and analyze the grid with the provided IEEE 39 bus data.**

***Index Terms* - frequency instability, renewable energy sources, and power system stability.**

I. INTRODUCTION

The continued interest in the development of renewable energy has seen unprecedented growth in the energy sector. Renewable energy has innumerable benefits with accompanying economic, social, environmental and technical challenges. Renewable energy has been touted as the most economical source of energy compared with fossil-fuelled generators. It is relatively less costly compared to conventional energy sources and does not support carbon emissions, promotes fuel security and energy diversity [1].The use and depletion of fossil-fuel reserves has rekindled interest in renewable energy that would offer a long-term solution to the biting pollution problems and consequent health related complications. It has been found that reduction of carbon dioxide emissions decreases effects of global warming [2].

The benefits accrue with reminiscent problems. On the economic front, it has been found that most of these renewable energy sources occur in areas that are less or least densely populated. As a result, the cost of evacuation of power by constructing long transmission overhead lines or offshore submarine cables to the on shore has been a challenge. Socially, areas inhabited by population are forced to relocate to pave way for transmission line construction and even establishment of the plants. It has also resulted in death of some rare birds in locations where wind turbines have been installed. Environmentalists have even initiated legal actions against setting up of plants of these nature that have killed the rare species of birds in some countries.

The main focus has been the technical constraints related to tapping of renewable energy. Many researchers have said that renewable energy sources contribute less or do not support the system inertia and affect frequency stability after large system disturbances, hence the stability of the power system is compromised [1]- [2]. They have also delved further and concluded that islanded grids would suffer most in terms of frequency instability where conventional power plants are not many enough to contribute to total system inertia [1]- [3].

The area of research interest has been how to provide the system inertia either synthetically or naturally. There are various methods that have been proposed to address the problem of system inertia. External mechanisms have been proposed such as renewable energy storage systems. These are methods where the deficiency in demand or loss of generation is met by use of remedial energy storage systems [4]. The methods have been found viable only that they increase investment cost in establishment of the renewable energy plants.

Internal or natural methods have also been proposed and seem more viable to address the issue with more challenges related to operation and control, system stability and quality of power [4]. They eliminate the additional cost of setting up storage systems more like a parallel plant to support system inertia.

The power system frequency control has three stages: Inertial response, primary control and secondary control. Inertial frequency response extracts kinetic energy from rotating masses to limit frequency excursion from the scheduled frequency value. Primary frequency control activates the generator governors to keep frequency deviation within acceptable levels. Secondary frequency control, on its part restores the frequency to its scheduled frequency and restores used reserves to their initial values [2].

The methods used for frequency control and stability studies included inertial frequency controls. This method resulted into excessive extraction of kinetic energy and led to slower recovery of the rotor speed to a stable operating range [5]-[6].The only advantage is that it provided frequency support in case of a system frequency excursion to some degree. Primary frequency control using automatic droop control method does not participate in rate of change of frequency (ROCOF) [7].

Doubly-fed induction generators, full power converter wind turbines and permanent magnet synchronous generators are the common variable speed wind turbines currently in use on large scale [8]. The single functional control methods utilized in these turbines include rotor speed control that only operates within the designed and rated wind speed range. The pitch angle control has a slow-speed response to support frequency dips and works better under partly loaded-mode of the wind turbine [5].

This paper is organised as follows: Section II delves into frequency control schemes with wind energy, problem formulation of power extraction from wind turbine is covered in Section III. Section IV provides the IEEE 39 Bus test system model in MATLAB/Simulink environment and simulated by Power System Analysis Toolbox (PSAT). Result Analysis and Discussions are done in section V and finally conclusion is given in section VI.

II. FREQUENCY CONTROL SCHEMES WITH WIND ENERGY

A. Inertial Frequency Control

Altin [9] investigated the requirements for synchronised power support and inertial response of wind power plants in high wind penetration scenarios. He considered a generic power system model and a generic wind power plant model implemented in RMS toolbox with different percentage levels of wind power penetration. He proposed a new inertial response control for wind power plants considering the inertial requirements for the generic power system. He carried out sensitivity analysis of the inertial response gain for 40% and 50% penetration levels and found reduced frequency deviation for penetration levels below 40%. He also did sensitivity analysis for variable droop gain from 5-10 p.u. value at 40%-50% penetration levels and found out that 40% penetration level produced an improved minimum frequency value.

Erlich et al. [7] proposed two methods for kinetic energy extraction control strategy. He said it was only suitable for short periods and kinetic energy was dependent on rotor speed and inertia of the rotor. He introduced a lead lag compensator to improve frequency response and named it KEC I. in the second method KEC II, he delayed release of kinetic energy and increased the rotor speed by reducing power output of the wind turbine. The deceleration of rotor speed implies increase power output from the wind turbine. Then the wind turbine was set to operate optimally and rotor re-accelerates.

B. Primary Frequency Control

Nguyen and Mitra [11] studied the effect of wind power on load frequency control. They implemented a mathematical model for one area control in MATLAB/Simulink for load frequency control in the presence of wind energy. Their simulated results showed that increasing wind penetration levels worsened frequency deviation from 0.14 Hz to 0.32Hz due to reduced system inertia and higher frequency regulation constant. In an interconnected system the maximum frequency deviation was from 0.075Hz to 0.125 Hz where in both stand-alone and interconnected system inertia reduction ranged between 0% and 60%. The frequency recovery also worsened with presence of wind energy sources in the grid. They established that maximum tie line power increased and area control error (ACE) reduced in an interconnected system. They recommended a 30% wind penetration level based on system configuration, maximum predicted load level of 0.04 p.u. and safe frequency deviation range of ±0.2 Hz.

Zertek et al. [12] came up with a novel control strategy aimed at maximizing kinetic energy and optimising jointly the rotor speed and pitch angle using differential evolution. They simulated four scenarios while accounting for power reserve margins in the computations. The first case was where the pitch angle was maintained at zero degrees until maximum speed was reached. The minimum frequency was achieved 7 seconds after frequency drop. In the second case where an additional df/dt loop was introduced, it attained 10 seconds from the frequency-time plots. The proposed control approach as the third option, gave a 13 seconds frequency drop delay. Hence translating to almost 100% delay compared to the first method. He concluded that the new control strategy extracted more kinetic energy at same de-loaded power compared to existing approaches. He only considered a single line diagram consisting of an aggregated load, thermal plant and Doubly Fed Induction Generator wind turbine (DFIG WT).

C. Secondary Frequency Control.

Secondary frequency response refers to a situation where power increase or decrease of generators is realised by commands from transmission system operator (TSO).In addition to automatic generation control (AGC), Li et al. [13] also said that rotor speed and pitch angle control were still suitable for secondary frequency control. He stated that both pitch angle and rotor speed control run the VSWT in de-loaded mode to be able to offer frequency support in case of frequency excursions. The wind turbines standard methods of frequency control were absent and effective approaches for dealing with a specific system must be designed [13].

In summary, the frequency control methods for variable speed wind turbines are many and vary depending on desired power output of the wind turbines. These methods also indicate that researchers are yet to develop a robust, optimal and standardised method for supporting system inertia of the grid in the event of frequency excursions.

III. PROBLEM FORMULATION

From the swing equation, the accelerating torque T_a is given by [14],

$$J\dot{W} = T_a \tag{1}$$

Where:

$\dot{W}$ is average angular acceleration in radians/second squared (rad/s^2), J is rotor moment of inertia in Kg-m^2, Ta is accelerating torque in N.M.

$$T_m - T_e = T_a \tag{2}$$

T_m is the driving mechanical torque and T_e is the retarding electrical torque.

We also know that Power, P is given by

$$P = TW \tag{3}$$

Where:

T is torque in N.M and W is angular velocity in rad/s.

However, kinetic energy is given by

$$GH = \left(\frac{1}{2}\right)(J \ast W^2) \tag{4}$$

Hence,

$$\Delta P = Ta \ast W = J\dot{W} \ast W. \tag{5}$$

$$\Delta P = (2GH \ast \dot{W})/W \tag{6}$$

Inertia response is achieved by extraction of kinetic energy

$$GH = \frac{0.5\Delta P \ast W}{\dot{W}} \tag{7}$$

Then,

$$\frac{dW}{dt} = \frac{0.5\Delta P \ast W}{GH} \tag{8}$$

Similarly,

For a synchronous machine as derived from [15],

$$\frac{df}{dt} = \frac{\Delta P \ast f_0}{2 \ast GH} \tag{9}$$

Where:

ΔP is the change in power, f_0 refers to the nominal frequency, $\frac{df}{dt}$ is the rate of change of frequency (ROCOF), G is rated apparent power, H is inertia time constant, K is number of machine poles. Therefore, to determine, the frequency deviations Δf, it is given by,

$$\Delta f = f_0 - f_{nadir} \tag{10}$$

$$\Delta f = f_0 - [(2GH \ast \frac{df}{dt})/\Delta P] \tag{11}$$

To extract maximum kinetic energy, we should maximize the deceleration of the rotor. Hence, min $\frac{df}{dt}$ and min Δf.

The wind power of the wind turbine is derived as shown in equation 12 from [16].

$$P_w = \frac{1}{2}\rho \ast A \ast V^3 \tag{12}$$

The blades swept area is given by

$$A = \pi R^2 \tag{13}$$

Where:

P_w is wind power, ρ is air density and V is wind speed in metres/second (m/s).

The efficiency in extraction of power is given by the wind power coefficient (C_p), ratio of power extracted by the turbine (P_t) to the total wind power (P_w).

$$C_p = \frac{Pt}{P_w} \tag{14}$$

Where:

$$P_t = \frac{1}{2} \ast \rho \ast A \ast V^3 \ast C_p \tag{15}$$

According to [8], [12] the wind power coefficient is given by:

$$C_p = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{\frac{C_5}{\lambda_i}} + C_6\lambda_i \tag{16}$$

$$C_p = 0.5 \ast (\frac{116}{\lambda_i} - 0.4\beta - 5)e^{\frac{-21}{\lambda_i}} \tag{17}$$

Where:

$$\lambda = \frac{RW_r}{V} \tag{18}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + .08\beta} - \frac{0.035}{\beta^3 + 1} \tag{19}$$

Where λ is the tip speed ratio of variable speed wind turbine (VSWT); W_r is the rotational speed of wind turbine; R is radius of the impeller; β is the pitch angle.

C_1-C_6 are constants representing the characteristics of specific wind turbines.

Considering primary power reserve margin, and loading the turbine at 85%, then

$$P_{opt} \geq 0.85P_{opt} + \Delta Pke \tag{20}$$

$$\Delta Pke \leq 0.15P_{opt} \tag{21}$$

Ignoring windage, iron and frictional losses,

$$P_G = P_t \tag{22}$$

P_G is total generated electrical power in MW, Pt is total turbine power equal to total mechanical power

According to [17], the accelerating power is given by

$$JW_r\dot{W}_r = P_{in} - (P_{ref} + \Delta Pke) \tag{23}$$

W_r is mechanical rotational speed, ΔPke is change in power due to kinetic energy, P_{opt} is optimal power of the generator in MW, P_{ref} is reference power and P_{in} is mechanical input power.

The power imbalance will be catered by the difference between the input power and power extraction from de-loaded mode due to deceleration of the rotor speed to counter frequency drop. Ignoring variable and fixed losses in the Variable Speed Wind Turbine

$$\Delta Pke = P_{in} - \sum_{k=1}^{n} (JW_{del} \frac{\dot{W}_{del}}{dt}) \quad (24)$$

Taking into consideration a wind farm with reference to equation (25), then maximize the extraction of accelerating power from the wind turbine. Since the reference power is a constant, P_{ref}, then considering a maximum power point tracking (MPPT) curve has maximum and minimum rotor speeds in de-loaded mode.

$$Max\ \Delta Pke = Max\ \{\sum_{k=1}^{n} (P_{in} - JW_{del} \frac{\dot{W}_{del}}{dt})\} \quad (25)$$

The wind farm power output, according to [17] is given by,

$$P_{ref,wf} = \sum_{k=1}^{n} P_{del,k} = \sum_{m=1}^{n} 0.85 P_{opt,k} \quad (26)$$

The objective function will be

$$Max\ \Delta Pke = Max\ \left\{\sum_{k=1}^{n} \left(P_{in,k} - JW_{del,k} \frac{\dot{W}_{del,k}}{dt}\right)\right\} \quad (27)$$

Subject to the constraints:

Total $\Delta Pke \leq 0.15$ Total P_{opt}

$$P_{ref,wf} = \sum_{k=1}^{n} P_{del,k} = \sum_{k=1}^{n} 0.85 P_{opt,k}$$

$$P_{min} \leq P_{del} \leq P_{max}$$

$$W_{del,min} \leq W_{del} \leq W_{max}$$

$$\beta min \leq 0 \leq \beta\ max$$

$$C_p \leq 0.59$$

IV. SIMULATION APPROACH

In order to achieve the objectives of this research, IEEE 39 Bus test system was modelled in MATLAB/Simulink and simulated by power system analysis toolbox (PSAT).In scenario I: Without wind energy sources in the grid, scenario II: One Wind farm will be introduced in the grid to determine the response of various parameters. Scenario III: Two wind farms will be incorporated in the grid to determine the performance of various system parameters. Finally, scenario IV: Five wind farms will be introduced in the grid to determine the system response.

V. RESULTS AND DISCUSSIONS

a) Scenario I: Without Wind Farm connected to the Grid.

In this case, IEEE 39 Bus was modelled in MATLAB/Simulink environment and simulated in PSAT. The choice of simulation parameters are provided for as per IEEE 39 test bus data. The initial voltage guesses and lines power capacities are assumed. The PV bus parameter block was used and specifically power capacity in MVA was critical in the initialization of synchronous machines and Automatic voltage regulators (AVR).This parameter was gotten by trial and error and took a lot of time to guess the right value. The criteria used was to get a value that gives the least maximum error of convergence in the power flow iterations. In PSAT, power flow must be executed first before time domain simulation is carried out. With the assumed values, the grid experienced voltage collapse in various buses and the Newton Raphson method did not converge. The Newton Raphson (NR) did not converge and therefore carrying out time domain simulation was not achieved. This points to the fact that this NR method fails to converge for large power system networks. There was also likely singular values pointing to infinity values in the process of iteration.

The network data computed for the power flow using PSAT was as shown in Table I, and appendix A in Table II and III.

TABLE I. OUTPUT RESULTS WITHOUT A WIND FARM CONNECTED TO THE GRID

NETWORK STATISTICS	
Buses:	39
Lines:	34
Transformers:	12
Generators:	10
Loads:	19
SOLUTION STATISTICS	
Number of Iterations:	9
Maximum P mismatch [p.u.]	2.07096E-05
Maximum Q mismatch [p.u.]	2.97945E-05
Power rate [MVA]	100

The NR has power mismatch calculations as shown in Table I and are quite small and falls outside tolerance values of 1E-05. I adjusted the power flow tolerance to 3E-05 but the NR did not converge. Therefore other methods have to be incorporated like using elements of the Jacobian matrix in normalized form [15]. The voltage values at various buses violated the limits and some buses have low voltages likely to trigger voltage collapse (total system blackout). Voltage collapse signals a system that is highly unstable in terms of voltage stability and overall power system stability.

The active power system loss accounts for 86.18% showing that the system is very inefficient. The line capacities need to be improved and more reactive power injected into the network to stabilize the network. The reactive power losses account for 99.7%, quite a high value, explaining the need to inject more reactive power to compensate for active power losses.

b) Scenario II: With one Wind Farm in the Grid.

The wind farm was composed of 30 wind turbines with a total capacity of 600 MVA. The power mismatch values increased marginally worsening the convergence criterion as shown in Table IV. The voltage profile showed changes in voltage magnitude at some buses to an improved value or a much lesser value while others remained constant values as shown in Table V. It shows that wind turbine is a source of reactive power and hence helps inject some reactive power in the network. The active power loss increased marginally to 88.6% while the reactive power loss remained constant at 99.7% when Table III and Table IV are compared in appendix A. The major observation is that active generated increased almost twice as reactive power generation. Active power generated increased by 34.7% while the reactive power generated increased by 17.8%.The total load power also increased as well as total losses. This points to the fact that the wind generator at one time acts as a generator and other instances as a load due its variable output power causing increased power system losses. The voltage levels at various buses also increased to a higher value due to the presence of increased reactive power in the grid.

TABLE IV. OUTPUT RESULTS FOR ONE WIND FARM CONNECTED TO THE GRID

NETWORK STATISTICS	
Buses:	39
Lines:	34
Transformers:	12
Generators:	9
Loads:	19
SOLUTION STATISTICS	
Number of Iterations:	8
Maximum P mismatch [p.u.]	7.21584E-05
Maximum Q mismatch [p.u.]	7.5171E-05
Power rate [MVA]	100

c) Scenario III: With Two Wind Farms connected to the Grid.

The power mismatch values in Table VII did not meet the convergence criterion of 1E-05 and were much worse compared to values in both Table I and IV. Wind farm at bus 36 had a capacity of 600 MVA with 30 wind turbines while wind farm at bus 32 had 630 MVA with 30 wind turbines. Integrating individual wind turbines is not feasible because it may not be possible to control the response required. It is also complex to design controls for individual wind turbines and coordinate with others in the grid. Some buses like 10 and 24 in Table VIII had voltage overshoots while other buses the voltages were zero as others recorded normal voltage profiles within the tolerance limits. It implies there was over-generation at some buses while others experienced substantial voltage drops due to line limitations or excessive loading at the buses.

The total power generated, total losses increased to high values to orders 1*10^10 which were much worse and recorded values beyond the capability of the system to handle as shown in Table IX. However, the active power losses reduced to 72.85% while reactive power dropped marginally to 99.50%. It implies the wind turbines injected reactive power into the network thus reducing the power losses.

TABLE VII. OUTPUT RESULTS FOR TWO WIND FARMS CONNECTED TO THE GRID

NETWORK STATISTICS	
Buses:	39
Lines:	34
Transformers:	12
Generators:	8
Loads:	19
SOLUTION STATISTICS	
Number of Iterations:	7
Maximum P mismatch [p.u.]	1.253926881
Maximum Q mismatch [p.u.]	5.078144908
Power rate [MVA]	100

d) Scenario IV: With Five Wind Farms connected to the Grid

The wind farms were connected one at a time until they reached five to ensure proper initialization of the DFIG because fixing the PV parameters would be complicated if done all at once and their rated capacities are shown in Table X.

TABLE XI. OUTPUT RESULTS FOR FIVE WIND FARM CONNECTED TO THE GRID

NETWORK STATISTICS	
Buses:	39
Lines:	34
Transformers:	12
Generators:	6
Loads:	19
SOLUTION STATISTICS	
Number of Iterations:	8
Maximum P mismatch [p.u.]	128.8572411
Maximum Q mismatch [p.u.]	2.4057E-05

The active power mismatch was higher compared to the previous values as shown in Table XI. The reactive power mismatch was minimal. This is explained by the capability of wind turbines to absorb or inject more reactive power into the grid thus compensating for the mismatch. The voltage profile for the sampled buses shows that bus 22 and 24 changed values as shown in Table XII. These buses could be weak buses as shown by their continuity high voltage volatility. The other buses relatively have constant values hence least affected by the wind integration.

The active power losses increased to 77.62% while reactive power losses reduced marginally to 99.46%. This implies the wind turbines could be becoming loads drawing more current from the network thus increasing active power losses. As said earlier, they have reactive power production capabilities thus maintains the reactive almost constant.

VI. CONCLUSION

This paper has reviewed frequency stability control schemes with wind turbines integration using PSAT simulation tool in MATLAB/Simulink and has established that the tool is not sufficient to provide accurate results for IEEE 39 Bus system using time domain simulation. This therefore calls for further research using other simulation tools so as be able to provide more accurate results. It also points out that Newton Raphson method easily gets trapped in local optima and hence other methods either metaheuristic or numerical methods or IEEE 39 Bus data needs to be re-organized to overcome inability of Newton Raphson in conducting time domain simulation of wind farms in the grid.

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Appendix A

TABLE II. MAGNITUDE AND PHASE ANGLE PROFILE OF POWER PARAMETERS WITHOUT A WIND FARM CONNECTED TO THE GRID

Bus	V	phase	P gen	Q gen	P load	Q load
	[p.u.]	[rad]	[p.u.]	[p.u.]	[p.u.]	[p.u.]
22	0.00	-67579.11	-2.86E-05	1.40E-05	0	0
24	0.60	-176.51	-36.26	24.11	1.02	-0.31
30	1.05	-350.14	0.26	5.21	0	0
31	0.98	0	1.41	8.07	0.37	0.18
32	0.91	-500.61	-3.10	2.25	0	0
33	1.00	-338763.66	3.39	18.04	0	0
34	1.01	-1.09E+12	1.13	19.04	0	0
35	1.05	-482588.19	0.78	15.68	0	0
36	0.98	-350.48	-0.05	4.13	0	0
37	1.03	-294.55	0.25	5.01	0	0
38	1.03	122.00	-4.25	0.11	0	0
1	0.00	-142.34	-2.43E-05	-3.32E-05	0	0
10	0.83	-72.23	-222.85	450.00	0	0

TABLE III. GENERATION, LOAD AND LOSSES FROM POWER FLOW WITHOUT A WIND FARM

TOTAL GENERATION		PERCENT (%)
REAL POWER [p.u.]	346.59	
REACTIVE POWER [p.u.]	3899.01	
TOTAL LOAD		
REAL POWER [p.u.]	47.89	13.82
REACTIVE POWER [p.u.]	11.56	0.30
TOTAL LOSSES		
REAL POWER [p.u.]	298.69	86.18
REACTIVE POWER [p.u.]	3887.45	99.70

TABLE V. MAGNITUDE AND PHASE ANGLE PROFILE OF POWER PARAMETERS WITH ONE WIND FARM CONNECTED TO THE GRID

Bus	V	phase	P gen	Q gen	P load	Q load
	[p.u.]	[rad]	[p.u.]	[p.u.]	[p.u.]	[p.u.]
22	1.14	22.14	-20.50	118.26	0	0
24	0.00	30.99	2.27E-05	2.14E-05	0.00	-0.00
30	1.05	-35.66	-5.44	18.53	0	0
31	0.98	0	2.04	6.57	0.367	0.18
32	0.91	-176.06	-1.47	-0.55	0	0
33	1.00	18.58	0.87	17.33	0	0
34	1.01	45.84	2.34	-4.10	0	0
35	1.05	6.14	6.74	32.20	0	0
36	0.98	-108.22	5.47	3.66	0	0
37	1.03	0.81	14.26	9.72	0	0
38	1.03	131.83	2.98	5.20	0	0
1	0.00	6405843.33	-8.56E-05	-2.20E-05	0	0
10	1.05	81.87	333.33	496.97	0	0

TABLE VI. GENERATION, LOAD AND LOSSES FROM POWER FLOW WITH ONE WIND FARM.

TOTAL GENERATION		PERCENT (%)
REAL POWER [p.u.]	466.75	
REACTIVE POWER [p.u.]	4593.08	
TOTAL LOAD		
REAL POWER [p.u.]	53.23	11.40
REACTIVE POWER [p.u.]	13.54	0.29
TOTAL LOSSES		
REAL POWER [p.u.]	413.52	88.60
REACTIVE POWER [p.u.]	4579.53	99.71

TABLE VIII. MAGNITUDE AND PHASE ANGLE PROFILE OF POWER PARAMETERS WITH TWO WIND FARMS CONNECTED TO THE GRID

Bus	V	phase	P gen	Q gen	P load	Q load
	[p.u.]	[rad]	[p.u.]	[p.u.]	[p.u.]	[p.u.]
22	0.02	91074618.93	0.24	1.39	0	0
24	2.10	91074621.54	279.43	-164.96	5.67	-1.69
30	1.05	15571672.78	-61.34	21.12	0	0
31	0.98	0	0.58	4.38	0.37	0.18
32	0.91	91074300.47	5.44	28.64	0	0
33	1.00	91074621.67	-1.86	45.74	0	0
34	1.01	91074627.34	4.86	11.71	0	0
35	1.05	91074619.72	1.04	15.40	0	0
36	1.00	91074536.13	0.25	4.96	0	0
37	1.03	15571526.4	0.25	5.01	0	0
38	1.03	4.38E+11	-1.09	7.39	0	0
1	0.00	293161383	0.00	-5.80E-05	0	0
10	6.00	91074743.6	11319.94	-778.61	0	0

TABLE IX. GENERATION, LOAD AND LOSSES FROM POWER FLOW WITH TWO WIND FARMS CONNECTED TO THE GRID.

TOTAL GENERATION		PERCENT (%)
REAL POWER [p.u.]	1.78E+11	
REACTIVE POWER [p.u.]	1.41E+12	
TOTAL LOAD		
REAL POWER [p.u.]	48363500829	27.15
REACTIVE POWER [p.u.]	6479770651	0.46
TOTAL LOSSES		
REAL POWER [p.u.]	1.30E+11	72.85
REACTIVE POWER [p.u.]	1.40E+12	99.54

TABLE X. FIVE WIND FARMS WITH RATED CAPACITIES AND NUMBER OF WIND TURBINES IN EACH WIND FARM.

Bus No	Wind Farm Capacity(MVA)	No of Wind Turbines in the Farm
32	630	30
36	600	30
37	500	30
38	900	60
39	100	30

TABLE XII. MAGNITUDE AND PHASE ANGLE PROFILE OF POWER PARAMETERS WITH FIVE WIND FARMS CONNECTED TO THE GRID

Bus	V	phase	P gen	Q gen	P load	Q load
	[p.u.]	[rad]	[p.u.]	[p.u.]	[p.u.]	[p.u.]
22	0.01	4540337.13	0.03	-0.07	0	0
24	0.00	4540284.63	3.53E-10	5.08E-10	1.42E-07	-4.24E-08
30	1.05	-525.23	-0.34	6.87	0	0
31	0.98	0	0.62	4.41	0.37	0.18
32	0.91	24638278.82	0.18	3.63	0	0
33	1.00	394741.47	6.37	23.05	0	0
34	1.01	394779.81	5.06	8.04	0	0
35	1.05	4540324.10	0.74	15.61	0	0
36	0.982	4540308.06	0.24	4.81	0	0
37	1.03	-505.29	0.25	5.01	0	0
38	1.03	-16592014.06	6.55	0.45	0	0
1	0.75	-252.33	27.42	12.87	0	0
10	0.00	307959.72	9.49E-08	-0.00	0	0

TABLE XIII. GENERATION, LOAD AND LOSSES FROM POWER FLOW WITH FIVE WIND FARMS CONNECTED TO THE GRID.

TOTAL GENERATION		PERCENT (%)
REAL POWER [p.u.]	263.51	
REACTIVE POWER [p.u.]	3154.20	
TOTAL LOAD		
REAL POWER [p.u.]	58.97	22.38
REACTIVE POWER [p.u.]	17.18	0.54
TOTAL LOSSES		
REAL POWER [p.u.]	204.54	77.62
REACTIVE POWER [p.u.]	3137.01	99.46