Modeling and Analysis of Wind Farms in Load Flow Studies

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***ABSTRACT*— Load flow analysis is the primary tool for assessing the operation of system in steady state. It is important for planning future expansion of power system as well as determining best operation of existing system. Nowadays Distribution generation involves the interconnection of small scale distributed energy resources with main power utility at distribution voltage level. Distribution mainly constitutes non-conventional and renewable energy sources like wind and solar. Environmental considerations, prospects of exhaustion of traditional energy sources and increasing prices in the generation of electric power have provoked in recent years considerable interest in the production of electrical energy from renewable resources. Prominent among these sources is the wind. In this work, two models are used namely PQ model and RX model for modeling the wind farms with asynchronous generator. The above models are used in the load flow studies and their impact in power system is analyzed.**

***Index Terms*— Load flow analysis, Wind energy, Wind farms.**

I. INTRODUCTION

The conventional energy sources are limited and pollute the environment. So more attention and interest have been paid to the utilization of renewable energy source such as Wind Energy, Fuel Cell and Solar Energy etc., Wind Energy is the fastest growing and most promising renewable energy source among them as it is economically viable. In 2008, India was the country that brought online the third largest amount of wind energy, after the US and China, and it now ranks fifth in total installed capacity with 9,645 MW of wind power installed at the end of 2008 [1]. Wind farms are most common and growing application of wind energy.

A wind farm is a collection of wind turbines in the same location. Wind turbines are often grouped together in wind farms because this is the most economical way to create electricity from the wind . Wind farms being built today are much more efficient, more cost effective, much safer for wildlife, and much more carefully sited than early ones.

In order to investigate the effects the wind farms will produce on the grid, adequate models must he used. One of the problems that wind energy will create in electrical power systems is the dependence of the injected power on the wind speed. The wind speed cannot be predicted, but the probability of a particular wind speed occurring can be estimated. This can be done if the probability distribution is known by assuming it to be a Weibull distribution [1] or a Rayleigh one, as recommended in [2]. Once the wind speed is known, the power injected into the grid can be calculated by means of the wind turbine (WT) power curve. So, in order to assess the impact of wind energy on the steady state security of electrical networks, the problem can be planned from a probabilistic point of view, by knowing the probability of injecting a determined power, if previously the probability of a given wind speed is known[3] – [5].

When a wind farm with asynchronous generation is to be included in a load flow analysis, the PQ and RX [6],[7] buses are the most commonly used. When the conventional PQ bus model is used, the real and reactive powers have constant values, although some author[8],[9] propose methods for modifying these values in order to represent loads depending either on the voltage or on the frequency.

In the near future, the use of small isolated or grid connected hybrid energy systems is expected to grow tremendously. In view of the above, in this work two models namely PQ model and RX model are used to model wind farms[10]–[14]. The above said wind farm models are located at various locations of IEEE-14 bus system and the effects are studied.

II. MODELING OF WIND FARMS

A. PQ MODEL OF ASYCHRONOUS WIND TURBINE

A PQ model is presented based on the machine parameters. A PQ model of the asynchronous WT has been proposed that allows us to use mechanical power as a unique input variable . The parameters of the machine are needed when using the model, as they have to be included in the system admittance matrix and for obtaining the specified active and reactive powers of the PQ model.

A way to model a wind farm as a PQ bus is to assume a generated real power and a given power factor, with which

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the consumed reactive power is calculated. Some improvements can be achieved if the steady-state model of the induction machine is taken into account [3].

In this model, By applying the conservation of complex power theorem (Boucherot's theorem) allows the following expression to be written for the reactive power consumed by the machine (positive when consumed):

$$Q = V^2 \frac{X_c - X_m}{X_c X_m} + X \frac{V_2 + 2RP}{2(R^2+X^2)} - X\frac{\sqrt{(V^2+2RP)^2 - 4P^2(R^2+X^2)}}{2(R^2+X^2)} \qquad (1)$$

The following expression [15] is proposed for the reactive power consumed by a WT as a function of its real power:

$$Q = -Q_0 - Q_1 P - Q_2 P^2 \qquad (2)$$

An approximation of (1) to (2) can be made by means of the McLaurin polynomial by taking into account the first two derivatives, neglecting the resistance R for the sake of simplicity and finally writing the expression for the reactive power as:

$$Q \approx V^2 \frac{X_c - X_m}{X_c X_m} + \frac{X}{V^2} P^2 \qquad (3)$$

If the wind speed is desired to be the input datum for the problem, the real power can be obtained as a function of it. This is done by means of the power curve for the turbine and based on

$$P = 1/2 \rho A u^3 C_p \qquad (4)$$

Where A = rotor area, p= density of air, u = wind speed and c_p = power coefficient. The power coefficient is obtainable as a function of the tip speed ratio $C_p = f(\lambda)$. Where $\lambda = (\omega R/u)$ where ω is rotor speed and the real power, reactive power and voltage at various wind speeds. The real power, reactive power and the voltage for various wind speeds are computed and given in Table 1.

Table 1: Real and Reactive power obtained by PQ model

U m/s	Real power	Reactive power	Voltage
m/s	Mw	MVAR	p.u
7	3.132	0.140	1.004
9	6.807	0.647	1.003
11	11.366	1.837	1.000
13	15.413	3.395	0.995
15	17.543	4.392	0.992
17	17.120	4.182	0.992
19	15.388	3.377	0.995
21	14.400	2.957	0.996

B. *RX MODEL OF ASYNCHRONOUS WIND TURBINE*

The another model of a wind farm is proposed based on using the RX bus model instead of the PQ bus model [10], following the next three steps :

i. Calculate the power that each WT can extract from the wind for a given wind speed and a given rotor speed, according to its power coefficient curve.
ii. Calculate the power that each WT can generate, according to the results of the load flow analysis, and to the rotor speed given .
iii. Compare both powers and look for the value of the slip, for which the electrical and the mechanical powers coincide for the wind speed given.

The RX model is based on the steady-state model of the induction machine, where it is represented by means of an impedance. And a shunt capacitor with susceptance B_c **,** The magnetizing branch is here considered to be located between the stator and the rotor, which is a better approximation to the real machine. The mechanical power developed by a WT can be calculated with equation (4).

$$Z = R_s + jx_1 + (jx_m // ((R_R/s) + jx_2)) \qquad (5)$$

Where

R_S - Stator Resistance in Ω

R_R - Rotor Resistance in Ω

X_1 - Stator reactance in Ω

X_2 - Rotor reactance in Ω

X_m - Excitation reactance in Ω

s - Slip

A first, inexact way of working can be to fix the mechanical power and to assume that the slip can be calculated from then following equation:

$$S = \frac{-V^2 R_R + \sqrt{V^4 R_R^2 - 4PR_R^2(PX^2 + V^2 R_R)}}{2(PX_2 + V^2 R_R)} \qquad (6)$$

This equation is obtained, based on the steady-state model of the machine , by applying Boucherot's theorem and assuming the stator resistance to be negligible. The iterative process consists of the following: an initial value of the slip is considered at the beginning of the process, a suitable value of which is the machine's rated slip, or the value obtained from . With this value introduced in the expression for Z, an initial load flow analysis can be carried out. With the results obtained, the mechanical power of the machine can be calculated as

$$P_m = -I_R^2 R_R((1-s/s) \qquad (7)$$

Where I_R is the rms value of the rotor current, calculated from the rms value of the stator current I_S, as

$$I_R = (jx_m/(R_R/s)+j(x_2+x_m))I_S \quad (8)$$

Where I_R and I_S, are the phasors for the rotor and stator currents.

On the other hand, taking into account the wind speed and the slip of the machine, the value of the power coefficient can be calculated and the power extracted from the wind from equation (4).

When these two powers are not equal, then a process of convergence for both values begins. In this case, the slip is modified

$$s_k = s_{k-1} + \Delta s \quad (9)$$

where s_{k-1} and s_k are the present slip and the new slip (slip that must be taken into account in the next load flow analysis), respectively,

$$\Delta s = j^{-1}\Delta P_m \quad (10)$$

where ΔP_m is the difference between both powers. If the approximation ((1- s)/s) ≈ (l/s) is assumed in the proximity of the working point, J can be calculated as:

$$J = R_R\left(\frac{S}{V}\right)^2 \frac{A+B}{s^2\left(\left(\frac{R_R}{s}\right)^2+(X_2+X_m)^2\right)} \quad (11)$$

$$S = \sqrt{P_g^2 + Q_c^2} \quad (12)$$

and P_g and Q_c are the real power generated and the reactive power consumed by the machine. These powers can be written as

$$P_g = -\left(\frac{V^2}{Z^2}\right)Real\{\bar{Z}\}$$

$$Q_c = (V^2/Z^2)Imag\{\bar{Z}\} \quad (13)$$

where

$$A = \frac{2X_mR_R}{s}\left(\left(\frac{R_R}{s}\right)^2 + (X_2 + X_m)^2\right) \quad (14)$$

$$B = -\left(\left(X_m(X_2 + X_m)\right)^2 + \left(\frac{X_mR_R^2}{s}\right)\right)\left(\frac{R_R}{s} + \left(\left(\frac{R_R}{s}\right)^2 + (X_2 + X_m)^2\right)^2\right) \quad (15)$$

With the new values of **z** and ***J***, the load flow analysis is repeated, and the process finishes when the mechanical power, P_{mk}, and the power taken out from the wind, P_k, are equal, or the difference between both is acceptable. This error is calculated as

$$\sum_{k=1}^{n}(P_{mk} - P_k)^2 \quad (16)$$

Where n is the number of machines in the wind farm.

The flowchart to compute real power, reactive power and voltage magnitude for a given wind speed is given in Fig.1. Based upon the real power, reactive power and voltage for various wind speeds are computed and given in Table 2.

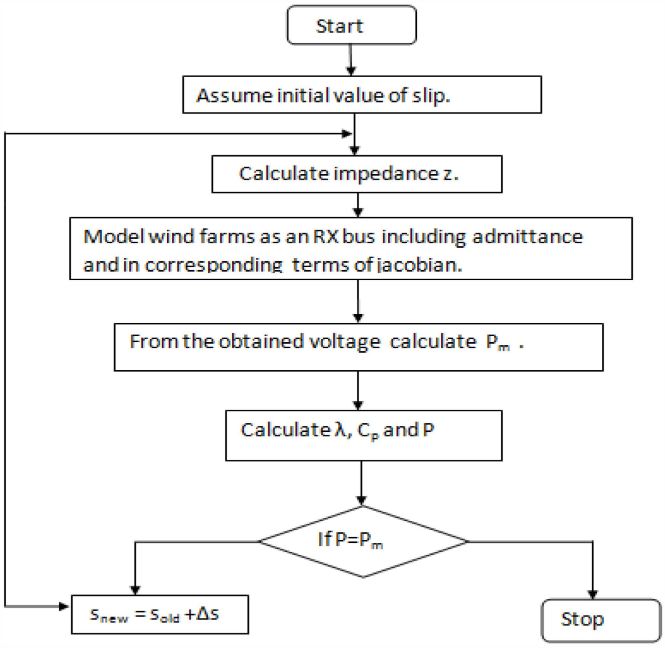

Fig.1.Flowchart to compute real power, reactive power and voltage by RX model.

Table 2: Real and Reactive power obtained by RX model

U m/s	Real power	Reactive power	Voltage
m/s	Mw	MVAR	p.u
7	3.102	0.013	1.004
9	6.696	0.560	1.003
11	11.036	1.785	1.000
13	14.843	3.449	0.995
15	16.859	4.603	0.991
17	16.640	4.467	0.992
19	14.929	3.494	0.995
21	13.550	3.211	0.997

SIMULATION RESULTS AND DISSCUSSION

The IEEE-14 bus system is chosen to implement the application of the proposed method. The single line diagram is shown in Fig.2. In which, the first bus is the slack bus, followed by the PV buses from bus 2 to 5 and PQ buses from bus number 6 to 14. Load flow simulation has been carried out on IEEE-14 bus system. The results were obtained at the end of 5th iteration [16].

The wind farm modeled by PQ and RX model is injected at various locations of IEEE-14 bus system and following analysis are carried out.

ANALYSIS 1:

For this case the wind speed is chosen as 7m/s

a) The wind farms are located at all PV buses except slack bus.

b) The wind farms are located at all PQ bus.

c) The wind farms are located at all PV and PQ buses except the slack bus.

Simulations are carried out for the above three cases. For easy comparison the results are summarized and given in Table 3 and 4.

ANALYSIS 2:

Outage study of line 6-8 is carried out on IEEE 14 bus system with and without distribution generation and the results are summarized in Table 5 and 6.

ANALYSIS 3:

Bus outage study is also carried out on IEEE 14 bus system with and without distribution generation and the results are summarized in Table 7 and 8.

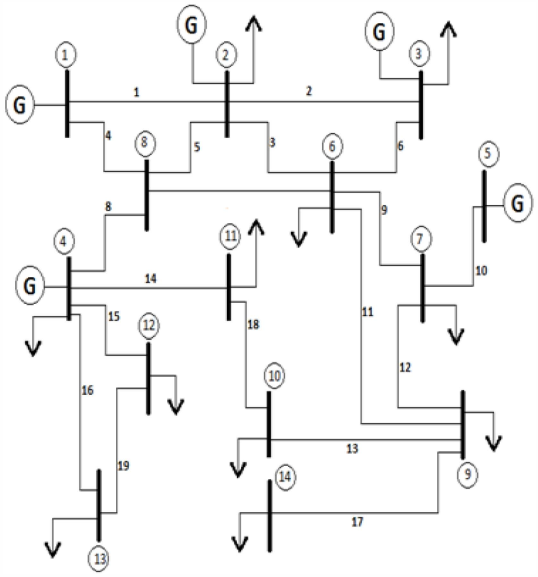

Fig.2. Single line diagram for IEEE – 14 bus system

ANALYSIS 4:STABILITY LIMIT ANALYSIS

The maximum power flow possible through some particular point in the system while maintaining stability in the entire system or the part of the system to which the stability limit refers. If the stability limits are violated there would be oscillation which are dangerous.

The stability violation index is calculated by

$$Min\ \Psi = \sum \frac{|S_i - S_i^{limlt}|}{S_i^{limit}} \qquad (17)$$

Where

Ψ - Stability violation index.

s_i - complex power .

s_i^{limit} - complex power limit.

The stability violation index is computed by using equation (17) and summarized in Table 9.

CONCLUSIONS AND FUTURE SCOPE

Two models for wind farms have been developed in order to achieve better results in the load flow analysis and their effects in the load flow studies are reported in this paper, for various cases. Further the above analysis can be extended to multiple wind farms. PV solar panels can also be modeled and their effects in the load flow studies can also be studied.

Appendix

SYSTEM PARAMETER OF INDUCTION GENERATOR

f	=	50Hz
R_S	=	0.00708Ω
R_R	=	0.00759Ω
X_1	=	0.07620 Ω
X_2	=	0.23289 Ω
X_M	=	3.44979 Ω
P	=	330KW
A	=	531m^2
V	=	660V
ω	=	34rpm

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Table 3: Comparison of voltage magnitude and angle for a wind speed 7m/s

Bus No:	IEEE 14 Bus System		Wind Generation injected at PV Bus (2,3,4,5) by RX model		Wind Generation injected at PV Bus (2,3,4,5) by PQ model		Wind Generation injected at PQ Bus (6,7,8,9,10,11,12,13,14) by RX model		Wind Generation injected at PQ Bus (6,7,8,9,10,11,12,13,14) by PQ model		Wind Generation injected at all Bus by RX model		Wind Generation injected at all Bus by PQ model	
	V_M	V_A	V_M	V_A	V_M	V_A	V_M	V_A	V_M	V_A	V_M	V_A	V_M	V_A
1	1.06	0	1.06	0	1.06	0	1.06	0	1.06	0	1.06	0	1.06	0
2	1.045	-0.08634	1.045	-0.09251	1.045	-0.09256	1.045	-0.0997	1.045	-0.09871	1.045	-0.10551	1.045	-0.1045
3	1.03	-0.22541	1.03	-0.23609	1.03	-0.23619	1.025	-0.24621	1.03	-0.24539	1.025	-0.25729	1.025	-0.25564
4	1.07	-0.25136	1.07	-0.26607	1.07	-0.26622	1.06	-0.30335	1.065	-0.29685	1.055	-0.31867	1.06	-0.31235
5	1.085	-0.25081	1.085	-0.26957	1.085	-0.26976	1.08	-0.2963	1.08	-0.29319	1.075	-0.3158	1.075	-0.31285
6	1.02988	-0.18312	1.02874	-0.1921	1.02873	-0.19219	1.02094	-0.20969	1.02349	-0.20793	1.01833	-0.21864	1.01964	-0.21685
7	1.0497	-0.25081	1.04906	-0.26477	1.04905	-0.26491	1.0409	-0.2963	1.04291	-0.29319	1.03671	-0.3109	1.03813	-0.30791
8	1.03466	-0.15491	1.0353	-0.16291	1.03529	-0.16299	1.02782	-0.17927	1.0302	-0.17755	1.02515	-0.18711	1.02676	-0.18541
9	1.04139	-0.27836	1.04079	-0.29175	1.04078	-0.29228	1.03163	-0.33028	1.03404	-0.32659	1.02702	-0.3446	1.02917	-0.34103
10	1.03871	-0.27853	1.03822	-0.29215	1.03822	-0.28146	1.02727	-0.33362	1.03054	-0.32943	1.02287	-0.3482	1.02562	-0.34414
11	1.05039	-0.26717	1.05016	-0.28133	1.05016	-0.2784	1.03825	-0.32356	1.04243	-0.31824	1.03354	-0.33856	1.03747	-0.33339
12	1.05739	-0.26355	1.05739	-0.27826	1.05739	-0.2784	1.04317	-0.32337	1.04932	-0.31528	1.03809	-0.33887	1.04424	-0.33095
13	1.05511	-0.26349	1.05511	-0.2782	1.05511	-0.27834	1.04142	-0.32219	1.04789	-0.31349	1.03633	-0.33769	1.0428	-0.32914
14	1.02565	-0.31549	1.02503	-0.32892	1.02503	-0.32905	1.01464	-0.37621	1.0178	-0.37234	1.0103	-0.39091	1.01284	-0.38723

Table 4: Comparison of real and reactive power for a wind speed 7m/s

IEEE 14 Bus System		Wind Generation injected at PV Bus (2,3,4,5) by RX model		Wind Generation injected at PV Bus (2,3,4,5) by PQ model		Wind Generation injected at PQ Bus (6,7,8,9,10,11,12,13,14) by RX model		Wind Generation injected at PQ Bus (6,7,8,9,10,11,12,13,14) by PQ model		Wind Generation injected at all Bus by RX model		Wind Generation injected at all Bus by PQ model	
P_L	Q_L	P_L	Q_L	P_L	Q_L	P_L	Q_L	P_L	Q_L	P_L	Q_L	P_L	Q_L
1.566694	1.566694	1.664922	-0.25419	1.665875	-0.22643	1.789782	-0.25419	1.772597	-0.2504	1.890777	-0.27613	1.873949	-0.27252
0.740446	0.740446	0.766847	-0.07081	0.767103	-0.07083	0.784493	-0.04658	0.783154	-0.07224	0.812118	-0.04891	0.808535	-0.04861
0.564296	0.564296	0.584471	-0.08647	0.584666	-0.08645	0.652401	-0.0563	0.645056	-0.06936	0.67302	-0.04558	0.666918	-0.05183
0.756982	0.756982	0.795562	-0.03781	0.795935	-0.03779	0.875635	-0.00852	0.866793	-0.01903	0.913428	0.001732	0.905	0.005276
0.402096	0.402096	0.417107	-0.08145	0.417252	-0.08142	0.479767	-0.05289	0.472358	-0.0651	0.494907	-0.04088	0.488589	-0.04882
-0.22523	-0.22523	-0.23157	0.085951	-0.23163	0.086047	-0.18401	0.082305	-0.18533	0.097817	-0.18931	0.100532	-0.19294	0.094157
-0.69299	-0.69299	0.713796	0.070141	0.713997	0.070219	-0.73344	0.070759	-0.73482	0.074605	-0.75399	0.07967	-0.75624	0.07282
0.423764	0.423764	0.45265	-0.11919	0.45293	-0.11921	0.535029	-0.09802	0.518154	-0.11131	0.562995	-0.08432	0.546701	-0.10067
0.349703	0.349703	0.374703	-0.08631	0.374944	-0.08632	0.439559	-0.07839	0.434664	-0.07653	0.465122	-0.06802	0.460288	-0.0692
0	0	0.03102	-0.21399	0.03132	-0.21403	0	-0.23103	0	-0.21959	0.03102	-0.22529	0.03132	-0.21721
0.273703	0.18339	0.191509	-0.01273	0.191587	-0.01273	0.227725	-0.0052	0.225261	-0.00604	0.236234	-0.00101	0.233706	-0.00296
0.18339	0.273703	0.267683	0.082458	0.267624	0.082453	0.331539	0.096799	0.327345	0.089561	0.326082	0.09684	0.321648	0.089847
0.12794	0.012794	0.014892	0.025984	0.014912	0.025962	0.052793	0.028957	0.045538	0.02576	0.055841	0.02984	0.048283	0.025134
0.114057	0.114057	0.111923	0.053957	0.111902	0.053959	0.136585	0.051848	0.144691	0.053033	0.13346	0.05116	0.141886	0.053533
0.064506	0.064506	0.064506	0.022075	0.064506	0.022075	0.097869	0.023577	0.09119	0.022226	0.097882	0.023604	0.0912	0.022245
0.133202	0.133202	0.133202	0.055341	0.133202	0.055341	0.188554	0.051848	0.170275	0.054641	0.18858	0.056997	0.170293	0.054679
0.149298	0.149298	0.149299	0.056356	0.149299	0.056356	0.180451	0.059037	0.180747	0.057698	0.180455	0.059114	0.180752	0.057794
-0.07723	-0.07723	-0.07513	0.032085	-0.07511	-0.03211	-0.06834	-0.02921	-0.07586	-0.03105	-0.0653	-0.02871	-0.07313	-0.03171
-0.00301	0.005037	0.003007	0.005037	0.003007	0.005037	-0.00025	0.005413	-0.00108	0.00564	0.000253	0.005412	-0.00208	0.00564

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Table 5: Comparison of voltage magnitude and angle for a wind speed 7m/s

Outage line = 6-8

Bus No:	IEEE 14 Bus System		Wind Generation injected at PV Bus (2,3,4,5) by RX model		Wind Generation injected at PV Bus (2,3,4,5) by PQ model		Wind Generation injected at PQ Bus (6,7,8,9,10,11,12,13,14) by RX model		Wind Generation injected at PQ Bus (6,7,8,9,10,11,12,13,14) by PQ model		Wind Generation injected at all Bus by RX model		Wind Generation injected at all Bus by PQ model	
	V_M	V_A	V_M	V_A	V_M	V_A	V_M	V_A	V_M	V_A	V_M	V_A	V_M	V_A
1	1.06	0	1.06	0	1.06	0	1.06	0	1.06	0	1.06	0	1.06	0
2	1.045	-0.10158	1.045	-0.10775	0.99	-0.1853	1.045	-0.11551	1.045	-0.11452	1.045	-0.12185	1.045	-0.12092
3	1.02	-0.27676	1.02	-0.28927	0.95	-0.47482	1.02	-0.30211	1.02	-0.30049	1.015	-0.31439	1.015	-0.31288
4	1.07	-0.24036	1.07	-0.2549	0.955	-0.5625	1.065	-0.29186	1.07	-0.28562	1.06	-0.30689	1.065	-0.3007
5	1.07	-0.31657	1.065	-0.33776	0.93	-0.71055	1.06	-0.36702	1.06	-0.36391	1.055	-0.38959	1.055	-0.38663
6	1.00999	-0.26456	1.00787	-0.2761	0.88517	-0.49418	1.00161	-0.29714	1.00243	-0.29527	0.99694	-0.3092	0.99775	-0.30742
7	1.03066	-0.31657	1.02726	-0.33276	0.89143	-0.68175	1.02051	-0.36702	1.02166	-0.36391	1.01527	-0.38449	1.01641	-0.38149
8	1.04554	-0.11044	1.04437	-0.11699	0.95827	-0.22977	1.03904	-0.13201	1.04111	-0.1304	1.03635	-0.13824	1.03843	-0.13668
9	1.01957	-0.3357	1.01664	-0.35102	0.87822	-0.73139	1.00911	-0.39194	1.01094	-0.38826	1.00361	-0.40878	1.00544	-0.40519
10	1.01926	-0.3235	1.0168	-0.33864	0.87673	-0.72639	1.00832	-0.38203	1.01077	-0.37786	1.00282	-0.39862	1.00528	-0.39453
11	1.03896	-0.28396	1.03767	-0.29873	0.9029	-0.66315	1.02933	-0.34168	1.03306	-0.33644	1.02401	-0.35752	1.02774	-0.35234
12	1.05739	-0.25254	1.05739	-0.26709	0.93091	-0.61399	1.04826	-0.31169	1.05439	-0.30388	1.04317	-0.32692	1.04932	-0.31913
13	1.05511	-0.25248	1.05511	-0.26703	0.93121	-0.60361	1.04651	-0.31052	1.05297	-0.3021	1.04142	-0.32573	1.04789	-0.31734
14	1.00345	-0.37447	1.00046	-0.39002	0.86314	-0.83271	0.99205	-0.43995	0.99426	-0.43617	0.98644	-0.45732	0.98865	-0.45364

Table 6: Comparison of real and reactive power for a wind speed 7m/s

Outage line = 6-8

IEEE 14 Bus System		Wind Generation injected at PV Bus (2,3,4,5) by RX model		Wind Generation injected at PV Bus (2,3,4,5) by PQ model		Wind Generation injected at PQ Bus (6,7,8,9,10,11,12,13,14) by RX model		Wind Generation injected at PQ Bus (6,7,8,9,10,11,12,13,14) by PQ model		Wind Generation injected at all Bus by RX model		Wind Generation injected at all Bus by PQ model	
P_L	Q_L	P_L	Q_L	P_L	Q_L	P_L	Q_L	P_L	Q_L	P_L	Q_L	P_L	Q_L
1.822452	-0.26136	1.92986	-0.28446	3.411772	0.41051	2.064878	-0.31252	2.047685	-0.309	2.17557	-0.33471	2.159254	-0.33148
0.936485	-0.03183	0.969624	-0.03365	1.373329	0.05031	0.996262	-0.03495	0.99297	-0.0348	1.028369	-0.01065	1.025365	-0.01052
0.961379	-0.05042	0.993314	-0.04327	1.607743	0.2756	1.072739	-0.01916	1.067154	-0.02304	1.108119	0.002634	1.102815	-0.00129
0.539931	-0.05946	0.571983	-0.058	1.117757	0.30477	0.646597	-0.04167	0.637876	-0.05038	0.677557	-0.03237	0.66916	-0.0412
0.049376	-0.03776	0.053544	-0.03206	0.274087	0.07964	0.103955	-0.01591	0.096894	-0.02614	0.107819	-0.00104	0.100765	-0.0113
-0.04326	0.059119	-0.04386	0.072063	0.20515	0.26502	0.011548	0.087211	0.008537	0.083525	0.009835	0.085608	0.006797	0.08197
0.575093	-0.06405	0.609592	-0.0641	1.186048	0.21157	0.698856	-0.05108	0.683368	-0.0662	0.731658	-0.03542	0.716533	-0.05059
0.258777	-0.0931	0.280379	-0.08553	0.703615	0. 03969	0.341287	-0.0786	0.335907	-0.08064	0.364027	-0.07369	0.358839	-0.07575
0	-0.2302	0.03102	-0.22	0.135501	-0.19323	0	-0.22876	0	-0.22239	0.03102	-0.22892	0.03132	-0.22257
0.131614	-0.01272	0.137901	-0.01073	0.328451	0.0502	0.172022	-0.00534	0.169195	-0.00747	0.178834	-0.00305	0.176065	-0.00518
0.182777	0.105601	0.173359	0.10078	0.353112	0.11579	0.233267	0.108729	0.228587	0.10232	0.224987	0.11033	0.220199	0.103974
-0.12992	0.053604	-0.13305	0.049084	-0.03483	0.02871	-0.1012	0.048123	-0.10931	0.043807	-0.10267	0.048612	-0.11083	0.044367
0.265384	0.045595	0.268863	0.050882	0.460532	0.05219	0.300448	0.054387	0.309927	0.057881	0.302198	0.054513	0.311745	0.057972
0.064506	0.022075	0.064506	0.022075	0.182239	0.00699	0.097856	0.023553	0.091181	0.022209	0.097869	0.023579	0.091191	0.022227
0.133202	0.055341	0.133202	0.055341	0.295777	0.03001	0.188531	0.056896	0.170259	0.054608	0.188556	0.056947	0.170276	0.054644
0.149312	0.056633	0.149314	0.056673	0.285897	0.04993	0.180471	0.059457	0.180768	0.058139	0.180476	0.059566	0.180774	0.058248
-0.22053	-0.006	-0.22367	-0.01056	-0.26041	0.00006	-0.22262	-0.01079	-0.23106	-0.01394	-0.2241	-0.01034	-0.2326	-0.01343
0.003007	0.005037	0.003007	0.005037	-0.01874	0.01123	-0.00026	0.005413	-0.00208	0.005641	-0.00025	0.005413	-0.00208	0.00564
1.822452	-0.26136	1.92986	-0.28446	3.411772	0.41051	2.064878	-0.31252	2.047685	-0.309	2.17557	-0.33471	2.159254	-0.33148

Table 7: Comparison of voltage magnitude and angle for a wind speed 7m/s

Outage bus = 4

Table 8: Comparison of real and reactive power for a wind speed 7m/s

Outage bus = 4

Bus No:	IEEE 14 Bus System		Wind Generation injected at PV Bus (2,3,4,5) by RX model		Wind Generation injected at PV Bus (2,3,4,5) by PQ model		Wind Generation injected at PQ Bus (6,7,8,9,10,11,12,13,14) by RX model		Wind Generation injected at PQ Bus (6,7,8,9,10,11,12,13,14) by PQ model		Wind Generation injected at all Bus by RX model		Wind Generation injected at all Bus by PQ model	
	V_M	V_A	V_M	V_A	V_M	V_A	V_M	V_A	V_M	V_A	V_M	V_A	V_M	V_A
1	1.06	0	1.06	0	1.06	0	1.06	0	1.06	0	1.6	0	1.06	0
2	1.045	-0.10158	1.045	-0.10775	1.045	-0.08811	1.045	-0.11551	1.045	-0.09547	1.045	-0.12185	1.045	-0.09996
3	1.02	-0.27676	1.02	-0.28927	1.03	-0.22905	1.02	-0.30211	1.03	-0.24017	1.015	-0.31439	1.025	-0.24812
4	1.07	-0.24036	1.07	-0.2549	1.07	-0.23767	1.065	-0.29186	1.065	-0.27602	1.06	-0.38959	1.065	-0.28308
5	1.07	-0.31657	1.065	-0.33776	1.085	-0.25718	1.06	-0.36702	1.08	-0.28401	1.055	-0.38959	1.08	-0.29964
6	1.00999	-0.26456	1.00787	-0.2761	1.03018	-0.18315	1.00161	-0.29714	1.02463	-0.20135	0.99694	-0.3092	1.0226	-0.20786
7	1.03066	-0.31657	1.02726	-0.33276	1.04923	-0.25233	1.02051	-0.36702	1.04312	-0.28401	1.01527	-0.38449	1.04189	-0.29474
8	1.04554	-0.11044	1.04437	-0.11699	1.03723	-0.15367	1.03904	-0.13201	1.03172	-0.17077	1.03635	-0.13824	1.03027	-0.17625
9	1.01957	-0.3357	1.01664	-0.35102	1.04023	-0.27753	1.00911	-0.39194	1.03374	-0.31611	1.00361	-0.40878	1.0323	-0.32579
10	1.01926	-0.3235	1.0168	-0.33864	1.03755	-0.27542	1.00832	-0.38203	1.03014	-0.31712	1.00282	-0.39862	1.0289	-0.32633
11	1.03896	-0.28396	1.03767	-0.29873	1.04959	-0.25882	1.02933	-0.34168	1.04205	-0.30171	1.02401	-0.35752	1.04137	-0.30984
12	1.05739	-0.25254	1.05739	-0.26709	1.05739	-0.24985	1.04826	-0.31169	1.04932	-0.29445	1.04317	-0.32692	1.04932	-0.30151
13	1.05511	-0.25248	1.05511	-0.26703	1.05511	-0.2498	1.04651	-0.31052	1.04789	-0.29266	1.04142	-0.32573	1.04789	-0.29972
14	1.00345	-0.37447	1.00046	-0.39002	1.02447	-0.31474	0.99205	-0.43995	1.01749	-0.3619	0.98644	-0.45732	1.01602	-0.3717

IEEE 14 Bus System		Wind Generation injected at PV Bus (2,3,4,5) by RX model		Wind Generation injected at PV Bus (2,3,4,5) by PQ model		Wind Generation injected at PQ Bus (6,7,8,9,10,11,12,13,14) by RX model		Wind Generation injected at PQ Bus (6,7,8,9,10,11,12,13,14) by PQ model		Wind Generation injected at all Bus by RX model		Wind Generation injected at all Bus by PQ model	
P_L	Q_L	P_L	Q_L	P_L	Q_L	P_L	Q_L	P_L	Q_L	P_L	Q_L	P_L	Q_L
1.566694	1.566694	1.664922	-0.25419	1.665875	-0.22643	1.789782	-0.25419	1.772597	-0.2504	1.890777	-0.27613	1.873949	-0.27252
0.740446	0.740446	0.766847	-0.07081	0.767103	-0.07083	0.784493	-0.04658	0.783154	-0.07224	0.812118	-0.04891	0.808535	-0.04861
0.564296	0.564296	0.584471	-0.08647	0.584666	-0.08645	0.652401	-0.0563	0.645056	-0.06936	0.67302	-0.04558	0.666918	-0.05183
0.756982	0.756982	0.795562	-0.03781	0.795935	-0.03779	0.875635	-0.00852	0.866793	-0.01903	0.913428	0.001732	0.905	0.005276
0.402096	0.402096	0.417107	-0.08145	0.417252	-0.08142	0.479767	-0.05289	0.472358	-0.0651	0.494907	-0.04088	0.488589	-0.04882
-0.22523	-0.22523	-0.23157	0.085951	-0.23163	0.086047	-0.18401	0.082305	-0.18533	0.097817	-0.18931	0.100532	-0.19294	0.094157
-0.69299	-0.69299	0.713796	0.070141	0.713997	0.070219	-0.73344	0.070759	-0.73482	0.074605	-0.75399	0.07967	-0.75624	0.07282
0.423764	0.423764	0.45265	-0.11919	0.45293	-0.11921	0.535029	-0.09802	0.518154	-0.11131	0.562995	-0.08432	0.546701	-0.10067
0.349703	0.349703	0.374703	-0.08631	0.374944	-0.08632	0.439559	-0.07839	0.434664	-0.07653	0.465122	-0.06802	0.460288	-0.0692
0	0	0.03102	-0.21399	0.03132	-0.21403	0	-0.23103	0	-0.21959	0.03102	-0.22529	0.03132	-0.21721
0.273703	0.18339	0.191509	-0.01273	0.191587	-0.01273	0.227725	-0.0052	0.225261	-0.00604	0.236234	-0.00101	0.233706	-0.00296
0.18339	0.273703	0.267683	0.082458	0.267624	0.082453	0.331539	0.096799	0.327345	0.089561	0.326082	0.09684	0.321648	0.089847
0.12794	0.012794	0.014892	0.025984	0.014912	0.025962	0.052793	0.028957	0.045538	0.02576	0.055841	0.02984	0.048283	0.025134
0.114057	0.114057	0.111923	0.053957	0.111902	0.053959	0.136585	0.051848	0.144691	0.053033	0.13346	0.05116	0.141886	0.053533
0.064506	0.064506	0.064506	0.022075	0.064506	0.022075	0.097869	0.023577	0.09119	0.022226	0.097882	0.023604	0.0912	0.022245
0.133202	0.133202	0.133202	0.055341	0.133202	0.055341	0.188554	0.051848	0.170275	0.054641	0.18858	0.056997	0.170293	0.054679
0.149298	0.149298	0.149299	0.056356	0.149299	0.056356	0.180451	0.059037	0.180747	0.057698	0.180455	0.059114	0.180752	0.057794
-0.07723	-0.07723	-0.07513	0.032085	-0.07511	-0.03211	-0.06834	-0.02921	-0.07586	-0.03105	-0.0653	-0.02871	-0.07313	-0.03171
-0.00301	0.005037	0.003007	0.005037	0.003007	0.005037	-0.00025	0.005413	-0.00108	0.00564	0.000253	0.005412	-0.00208	0.00564

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Table 9: Stability Violation Index

SYSTEM	Ψ	
IEEE 14 bus system	0.9090	
IEEE 14 bus system with distributed generation at all PV buses	PQ model	RX model
	0.09090	0.09090
IEEE 14 bus system with distributed generation at all PQ buses	0.09091	0.9090
IEEE 14 bus system with distributed generation at all PV and PQ buses except slack bus	0.09090	0.9091

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