RX Model-Based Newton Raphson Load Flow for Distribution Power System Considering Wind Farm with Asynchronous Generators

Trong Tuan Phan and Van Liem Nguyen

Abstract— *This paper presents a power flow (PF) analysis method of distribution power system including a wind farm (WF) with asynchronous generators (AGs) represented by RX bus model using Newton Raphson algorithm. With RX bus model, AG is supposed as a RX load with equivalent impedance Z = R + jX. The power extracted from the WT will be calculated easily based on known initial datum. Since the mechanical power can be figured out by load flow calculation with the assumed initial slip value. The new AG's slip value will be updated if the difference between wind power and mechanical power is larger than the acceptable tolerance. The calculation will continue until the convergence is achieved. By considering characteristics of AGs, the RX bus model is more suitable. To validate of the proposed model, the modified IEEE 30-bus system with a connected wind farm is used. Calculated results of load flow analysis program show that the proposed model is practical and accurate.*

Keywords— **Load flow analysis, asynchronous generator, RX bus model, wind farm.**

1. INTRODUCTION

In the past several decades, because of the rapidly consumption of fossil fuel resources, the remaining petroleum resources are gradually exhausted. As a result, the price of international petroleum has increased unpredictably. In addition, to limit environmentally negative impacts, many studies and projects on renewable energy are developed in order to seek some environmentally friendly energy resources that can be effectively used in the future. Nowadays, wind energy is one of the most promising energy resources in the world [1]–[3]. More large and medium scale wind farms are installed and put into operation with speedy development of wind power technology [4]. It is believed that wind power will maintain promising growth in the coming years. So, researching the impacts of integrating wind energy into power system is really challenge for researchers. Load flow analysis of power system having wind farms is a significant stage for wind farm planning, operating and controlling.

Modeling wind farm is the most important step to calculate PF for electrical network including wind farms [5]. A PQ model of the asynchronous WT has been proposed in [6] that allows to use mechanical power as a unique input variable. The parameters of the wind turbine are needed when using this 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. This model is accurate, but complex. In [7] and [8], the effects of active power and voltage on reactive power are observed. The methods applied in the research are feasible and proper. However, the calculation time became longer because the iterative process includes many complicated steps. In [9]-[11], the relation between power and voltage is considered by modifying Jacobi matrix in every iteration, so the method is accurate, time saving, but complicated. This paper presents a load flow analysis method for distribution power system including wind farm with AGs using RX bus model. It is assumed that asynchronous generator WTs operate as RX load buses. R and X in this supposition are equivalent resistance and reactance of WT. The calculating process for the PF analysis in distribution system having the asynchronous generator WTs represented by RX model using Newton Raphson method can be expressed in concise manner as follows: Firstly, determine the power for each WT extracted from the wind with a given wind speed and rotor speed. Then compute the mechanical power generated from WT, according to the original PF analysis solutions. Finally, compare the wind power and the mechanical power and calculate the slip value. When the two powers are not coincided, a next iteration will be begun continuously. This paper is organized in some sections as follows. Section 2 describes the original Newton Raphson PF solution. Section 3 derives the model of AG wind turbine used for the PF analysis including the two cases: Discounting the stator impedance of AGs and taking into account the AG's stator impedance. Section 4 compares the calculating results of load flow computation for all cases. Specific important conclusions of this paper are expressed in section 5.

2. ORIGINAL NEWTON RAPSHON POWER FLOW SOLUTION

Because of its quadratic convergence, Newton Raphson method is applied in this paper. Moreover, for a complex distribution power system, Newton Rapshon method is more efficient and practical [12]. Based on power system

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analysis principle, the complex power at bus i is

$$P_i - jQ_i = V_i^* I_i = |V_i| \angle -\delta_i \sum_{j=1}^{n} |Y_{ij}||V_j| \angle \theta_{ij} + \delta_i \tag{1}$$

Separating the real and imaginary parts of (1), we have:

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \tag{2}$$

$$Q_i = -\sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) \tag{3}$$

[J] is known as Jacobi matrix, which obtained by partial derivatives of P_i and Q_i with respect to variables of voltage angles and magnitudes:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \tag{4}$$

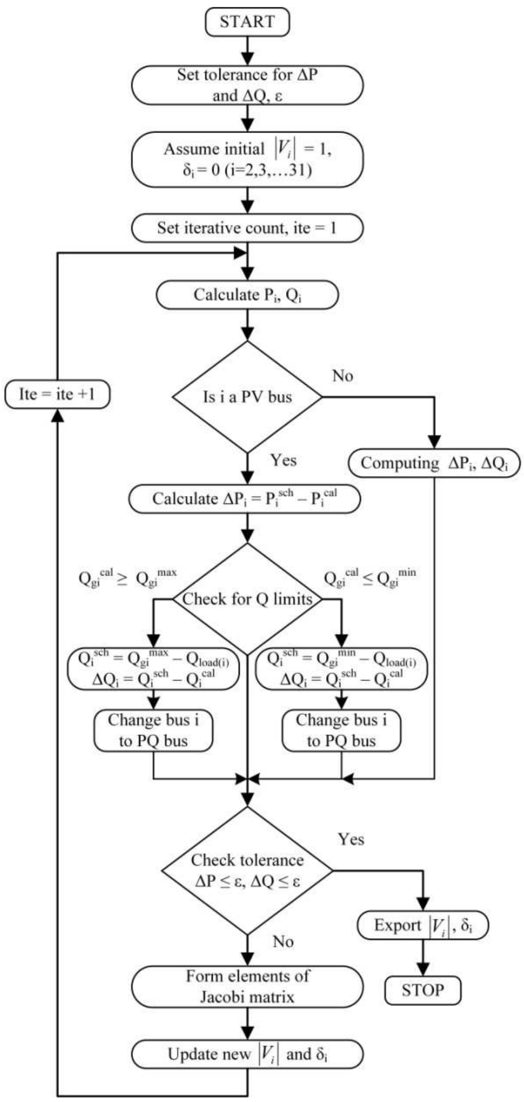

Fig.1. Flow chart of the original PF analysis.

Partial derivate P_i with respect to variable δ_i and δ_j, we have the diagonal and the off-diagonal elements of J_1 as follows:

$$\frac{\partial P_i}{\partial \delta_i} = \sum_{j \neq 1} |V_i||V_j||Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) \tag{5}$$

$$\frac{\partial P_i}{\partial \delta_j} = -|V_i||V_j||Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_i) \qquad j \neq i \tag{6}$$

The diagonal and the off-diagonal elements of J_2 are

$$\frac{\partial P_i}{\partial |V_i|} = 2|V_i||Y_{ii}| \cos\theta_{ii} + \sum_{j \neq 1} |V_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \tag{7}$$

$$\frac{\partial P_i}{\partial |V_j|} = |V_i||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \qquad j \neq i \tag{8}$$

Also, the diagonal and the off-diagonal elements of J_3 are

$$\frac{\partial Q_i}{\partial \delta_i} = \sum_{j \neq 1} |V_i||V_j||Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) \tag{9}$$

$$\frac{\partial Q_i}{\partial \delta_j} = -|V_i||V_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_i) \qquad j \neq i \tag{10}$$

Finally, the diagonal and the off-diagonal elements of J_4 are

$$\frac{\partial Q_i}{\partial |V_i|} = -2|V_i||Y_{ii}| \sin\theta_{ii} - \sum_{j \neq 1} |V_j||Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) \tag{11}$$

$$\frac{\partial Q_i}{\partial |V_j|} = -|V_i||Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) \qquad j \neq i \tag{12}$$

The terms $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$ are the difference between the scheduled and calculated values, known as the power residuals, given by

$$\begin{aligned} \Delta P_i^{(k)} &= P_i^{sch} - P_i^{(k)} \\ \Delta Q_i^{(k)} &= Q_i^{sch} - Q_i^{(k)} \end{aligned} \tag{13}$$

The new estimates for bus voltages are described by

$$\begin{aligned} \delta_i^{(k+1)} &= \delta_i^{(k)} + \Delta \delta_i^{(k)} \\ |V_i^{(k+1)}| &= |V_i^{(k)}| + \Delta |V_i^{(k)}| \end{aligned} \tag{14}$$

Neglecting programming details, the iterative algorithm for the PF calculation by the Newton Raphson method is as follows:

1) Since voltage and angle at slack bus fixed, assume $|V|$ = 1, δ = 0 at all PQ buses and δ = 0 at all PV buses.
2) Calculate ΔP_i (for PV and PQ buses) and ΔQ_i (for all PQ buses) by (13). If all the values are less than the prescribed tolerance, stop the iterations, calculate P_i, Q_i and print the entire solutions.

3) If the convergence is not achieved, evaluate elements of the Jacobi matrix using (5)-(12).
4) Solve for corrections of voltage angles and magnitudes with (4).
5) Update voltage angles and magnitudes by adding the corresponding changes to the previous values and return to step 2.

3. MODEL OF ASYNCHRONOUS GENERATOR WIND TURBINE

For the purpose of simplicity in calculation, this paper proposed a simple AG's equivalent circuit by discounting the AG's stator impedance.

Case A: Discounting the stator impedance

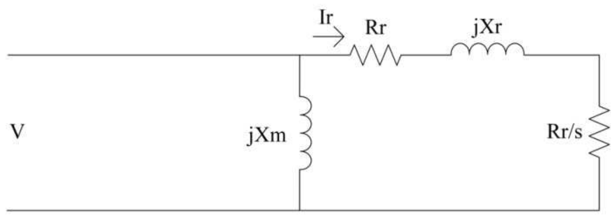

Fig.2. Asynchronous generator's equivalent circuit by discounting the stator impedance.

If it is assumed that $(1-s)/s \cong 1/s$ and discounting values of R_s and X_s, rotor current in Fig.2 is determined by

$$\left|I_r\right|^2 = \frac{|V|^2}{\left(R_r\dfrac{s+1}{s}\right)^2 + X_r^2} \tag{15}$$

Mechanical power of asynchronous generator can be computed as

$$P_{mech} = -\left|I_r\right|^2 \frac{R_r}{s} = -\frac{|V|^2 R_r s}{(s+1)^2 R_r^2 + s^2 X_r^2} \tag{16}$$

Organizing (16), the WT's slip is derived by

$$s = -\frac{(2P_{mech}R_r^2 + |V|^2 R_r) \pm \sqrt{\Delta}}{2(P_{mech}R_r^2 + P_{mech}X_r^2)} \tag{17}$$

where

$$\Delta = (2P_{mech}R_r^2 + |V|^2 R_r)^2 - 4P_{mech}R_r^2(P_{mech}R_r^2 + P_{mech}X_r^2) \tag{18}$$

According to the RX bus model, which based on the steady-state model of WT, where it is described as an impedance Z_{wt}. In some uncertain cases, the mechanical power of asynchronous generator is proposed unchanged. The WT's slip is derived by (17).

In case A, the equivalent impedance of WT can be estimated from following equation:

$$Z_{wt} = \frac{jX_m\left(R_r\dfrac{s+1}{s} + jX_r\right)}{R_r\dfrac{s+1}{s} + j\left(X_m + X_r\right)} = R_1 + jX_1 \tag{19}$$

where, R_1 and X_1 are

$$R_1 = \frac{X_m^2 R_r\dfrac{s+1}{s}}{\left(R_r\dfrac{s+1}{s}\right)^2 + \left(X_m + X_r\right)^2} \tag{20}$$

$$X_1 = \frac{X_m X_r\left(X_m + X_r\right) + X_m\left(R_r\dfrac{s+1}{s}\right)^2}{\left(R_r\dfrac{s+1}{s}\right)^2 + \left(X_m + X_r\right)^2} \tag{21}$$

The active power generated by the rotor windings and the input mechanical power of the WT are expressed respectively by

$$P_{gen} = I_r^2 R_1 = \frac{\left(\dfrac{S}{|V|}\right)^2 R_r\dfrac{s+1}{s}X_m^2}{\left(R_r\dfrac{s+1}{s}\right)^2 + \left(X_m + X_r\right)^2} \tag{22}$$

$$P_{mech} = \left(\frac{S}{|V|}\right)^2 \frac{(1-s)R_r\dfrac{s+1}{s}X_m^2}{\left(R_r\dfrac{s+1}{s}\right)^2 + \left(X_m + X_r\right)^2} \tag{23}$$

The Jacobi matrix can be computed by following equation:

$$[J] = \frac{\partial P_{mech}}{\partial s} = \frac{\partial}{\partial s}\left\{\frac{\left(\dfrac{S}{|V|}\right)^2 X_m^2(1-s)R_r\dfrac{s+1}{s}}{\left(R_r\dfrac{s+1}{s}\right)^2 + \left(X_m + X_r\right)^2}\right\}$$
$$= A.\left\{\frac{R_r^2\left(1-4s^2-4s^3-s^4\right) - \left(s^2+s^4\right)\left(X_m + X_r\right)^2}{\left[R_r^2 + s^2\left(X_m + X_r\right)^2\right]^2}\right\} \tag{24}$$

where $A = \left(S/|V|\right)^2 X_m^2 R_r$ and $S = \sqrt{P_g^2 + Q_c^2}$ [13]. Generated real power and consumed reactive power of AG are P_g and Q_c, respectively.

$$P_g = -\frac{|V|^2}{\left|Z_{wt}\right|^2}\operatorname{Re}\left(Z_{wt}\right) \tag{25}$$

$$Q_c = \frac{|V|^2}{\left|Z_{wt}\right|^2}\operatorname{Im}\left(Z_{wt}\right) \tag{26}$$

It can be easily realised that the steady-state operating condition of asynchronous generator WTs can be solved if the equivalent circuit datum are known. In the other words, when the wind speed v_{wind}, gearbox ratio, swept area, power coefficient C_p, etc are given, the slip value and rotor speed of WTs can be computed smoothly.

Case B: Taking into account the stator impedance

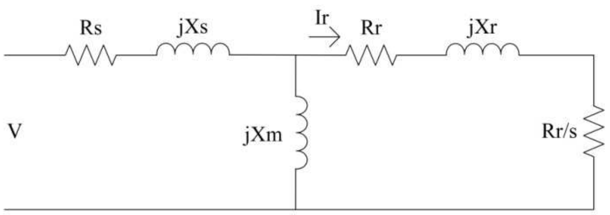

Fig.3. Asynchronous generator's equivalent circuit by taking into account the stator impedance.

By using the Thevenin's theorem, R_s, X_s, and X_m can be combined together to become the equivalent resistance R_{eq} and reactance X_{eq}.

$$Z_{eq} = R_{eq} + jX_{eq} \tag{27}$$

$$R_{eq} = \frac{R_s X_m^2}{R_s^2 + \left(X_s + X_m\right)^2} \tag{28}$$

$$X_{eq} = \frac{X_s X_m\left(X_s + X_m\right) + R_s^2 X_m}{R_s^2 + \left(X_s + X_m\right)^2} \tag{29}$$

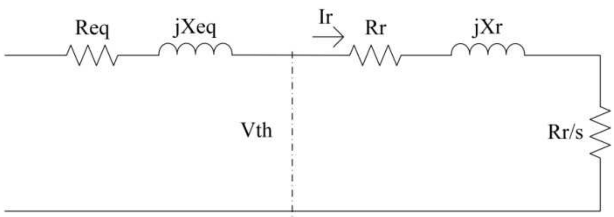

Fig.4. Thevenin equivalent circuit of Fig.3.

The AG's equivalent impedance of case B is calculated by (30):

$$Z_{wt} = \left(R_{eq} + R_r\frac{1+s}{s}\right) + j\left(X_{eq} + X_r\right) \tag{30}$$

The Thevenin's voltage, the rotor current magnitude and the mechanical power in the taking into account the stator impedance case are

$$V_{th} = V\frac{jX_m}{R_s + j\left(X_s + X_m\right)} \tag{31}$$

$$\left|I_r\right|^2 = \frac{\left|V_{th}\right|^2}{\left(R_{eq} + \frac{R_r}{s}\right)^2 + \left(X_{eq} + X_r\right)^2} \tag{32}$$

$$P_{mech} = -\left|I_r\right|^2\frac{R_r}{s} = \frac{-\left|V_{th}\right|^2 R_r s}{s^2R_{eq}^2 + 2sR_{eq}R_r + s^2\left(X_{eq} + X_r\right)^2} \tag{33}$$

Arranging (33), we can calculate the slip value by

$$s = -\frac{(2P_{mech}R_{eq}R_r + \left|V_{th}\right|^2 R_r) \pm \sqrt{\Delta}}{2\left[P_{mech}R_{eq}^2 + P_{mech}\left(X_{eq} + X_r\right)^2\right]} \tag{34}$$

$$\begin{aligned}\Delta = {} & (2P_{mech}R_{eq}R_r + \left|V_{th}\right|^2 R_r)^2 \\ & - 4P_{mech}R_r^2\left[P_{mech}R_{eq}^2 + P_{mech}\left(X_{eq} + X_r\right)^2\right]\end{aligned} \tag{35}$$

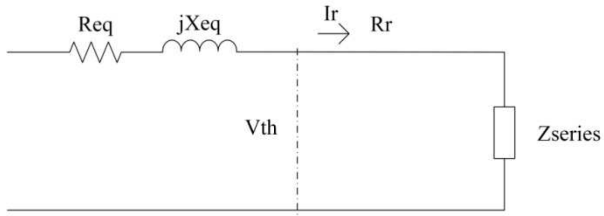

Fig.5. Equivalent circuit of Fig.4.

To facilitate the computation, we transform the rotor winding impedance to parallel elements. Transforming process of rotor impedance from series elements to parallel elements is expressed as follows:

$$Y_{series} = \frac{1}{Z_{series}} = \frac{1}{R_r\frac{1+s}{s} + jX_r} = G + jB \tag{36}$$

$$R_{p-eq} = \frac{1}{G} = R_r\frac{1+s}{s} + \frac{X_r^2}{R_r}\frac{s}{s+1} \tag{37}$$

$$X_{p-eq} = -\frac{1}{B} = X_r + \frac{\left(R_r\frac{1+s}{s}\right)^2}{X_r} \tag{38}$$

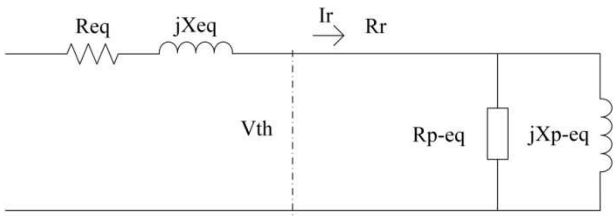

Fig.6. Equivalent circuit of Fig.5 by transforming rotor impedance to parallel elements.

The active power generated by the rotor windings, the WT's mechanical power and the its derivative with respect to variable *s* in case B are follows, respectively:

$$P_{gen} = \frac{\left|V_{th}\right|^2}{R_{p-eq}} \tag{39}$$

$$P_{mech} = \left(1-s\right)P_{gen} = \frac{\left(1-s\right)\left|V_{th}\right|^2}{R_r\frac{1+s}{s} + \frac{X_r^2}{R_r}\frac{s}{s+1}} \tag{40}$$

$$[J]=\frac{\partial P_{mech}}{\partial s}=\frac{\partial}{\partial s}\left\{\frac{|V_{th}|^2(1-s)}{R_r\frac{1+s}{s}+\frac{X_r^2}{R_r}\frac{s}{s+1}}\right\}$$
$$=-|V_{th}|^2\frac{\left[R_r\frac{s^2+2s-1}{s^2}+\frac{X_r^2}{R_r}\frac{1+s^2}{(s+1)^2}\right]}{\left(R_r\frac{1+s}{s}+\frac{X_r^2}{R_r}\frac{s}{s+1}\right)^2} \quad (41)$$

With assumed initial slip value, active power extracted from the wind is determined by:

$$P_{wind}=\frac{1}{2}\rho A v_{wind}^3 C_p \quad (42)$$

where ρ is the air density, A is the swept area of blades, v_{wind} is the wind speed, and C_p is the power coefficient [14].

$$C_p=\frac{1}{2}(\lambda-5.6)e^{-0.17\lambda} \quad (43)$$

where λ is the tip speed ratio (TSR) of the WT while R is blade's length and ω_r is rotor speed.

$$\lambda=\frac{\omega_r R}{v_{wind}}=\frac{\omega_s(1-s)R}{v_{wind}} \quad (44)$$

Generally, the mechanical power is not equal to the wind power because of unsuitable initial slip value. After the first iteration of load flow calculation, if the difference between the two powers is not equal to zero, the new slip value will be updated continuously. Calculating process will be continuous untill $\Delta P_m \le \varepsilon$.

$$\Delta P_m = P_{wind} - P_{mech} \quad (45)$$

When the two powers are not coincided, a next iteration will be begun continuously. As a result, the new slip is updated:

$$s_{k+1}=s_k+\Delta s \quad (46)$$

where $\Delta s = J^{-1}\Delta P_m$ (47)

where ΔP_m is the difference between the two powers, calculated by (45) and the Jacobi matrix's components are represented in (24) and (41) for two corresponding proposed cases. To sum up, the iterative algorithm for solving the load flow calculation by simulating WT as a RX bus is given follows:

1) Assume that the slip in each WT is equal to the rated slip. Then calculate the equivalent impedance Z_{wt} based on the proposed slip value.
2) By the corresponding Z_{wt} value, modify the admittance matrix of the distribution power system including the asynchronous generator WTs.
3) After the first iteration of the original PF calculation, using the obtained voltages to compute the WT's input mechanical power by (23) and (40) for two corresponding proposed cases.
4) Compute the wind power P_{wind} with the slip value, the TSR and the power coefficient C_p using (42).
5) Calculate the difference between the wind power and the mechanical power by (45) and, if ΔP_m is not satisfied, update the slip by means of (46) and go to step 2. Otherwise, if ΔP_m is satisfied, stop the iteration and print the solutions.

4. CACULATION RESULTS

Table 1. Parameters of the asynchronous generator WT

Parameters	Value
Rated power, P (MW)	1.6
Rated voltage, V (kV)	0.69
Rated frequency, f (Hz)	50
Number of pole pairs, p	4
Rotor diameter, d (m)	100
Stator resistance, R_s (pu)	0.00706
Rotor resistance, R_r (pu)	0.005
Stator leakage inductance, X_s (pu)	0.171
Rotor leakage inductance, X_r (pu)	0.310
Magnetizing inductance, X_m (pu)	2.0
Gear ratio	1:91

Table 2. Convergence characteristics, results for the WT's slip value and the power system's total power losses

Solutions	Value	
	Case A	Case B
No. of iteration of original PF analysis	5	5
No. of iteration of main program	2	2
Tolerance, ε	1×10^{-4}	1×10^{-4}
Maximum error	1.205×10^{-5}	4.725×10^{-7}
WT's slip, s	-8.971×10^{-5}	-1.02×10^{-5}
Total active power loss (MW)	17.27	17.26
Total reactive power loss (MVar)	32.33	32.28

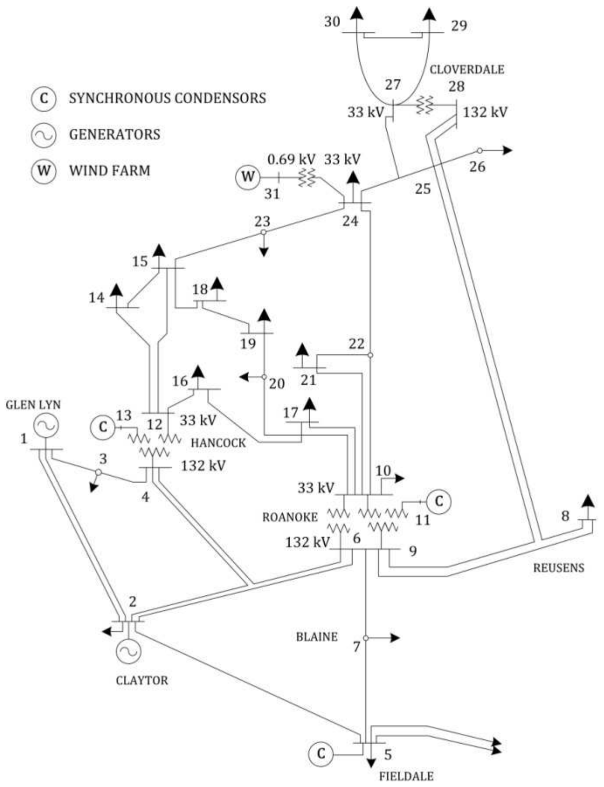

Fig. 7. Single-line diagram of the modified IEEE 30 bus system using for calculation.

Fig.7 shows the single-line diagram of the modified IEEE 30 bus system using for calculation. A wind farm including 20 asynchronous generator WTs is combined to a new bus, bus 31, which is connected to bus 24 of the IEEE 30 bus system through a step-up transformer. The parameters of the WTs are characterized sufficiently in Table 1. The results obtained in this paper are under the assumption that the wind speed is the identical for all wind farm.

It is observed from the results obtained in Table 2 that the iterative algorithm for PF analysis converged well in both case A and B, after only 2 iterations. The calculated WT's slip value of the discounting stator impedance case is $-8.97\text{x}10^{-5}$ and $-1.02\text{x}10^{-5}$ for the considering the stator impedance case.

Table 3 illustrates the comparative solutions of the bus voltages from the original PF algorithm for all proposed cases. It can be deduced from these results that the deviation of the bus voltages between case A and B is insignificant. However, neglecting the stator impedance of WTs in the calculating process has a remarkable influence on the bus voltage where the WTs are connected.

The calculated voltage at all busses of power system, including wind farm bus, in this case study are within the permitted limits. However, in case of a short circuit fault occurring at the wind farm bus, the voltage values will be changed significantly. On the other hand, dynamic changes of wind speed make amount of power injected to the electrical network highly variable. Depending on intensity and rate of changes, difficulties with voltage regulation could appear making a direct impact to quality level of delivered electrical energy.

Table 3. Comparison of the computed bus voltage values from the case A and case B

Node	Discounting stator impedance (case A)		Considering stator impedance (case B)	
	$\|V\|$, *pu*	δ, *deg*	$\|V\|$, *pu*	δ, *deg*
1	1.060	0.00	1.060	0.00
2	1.040	-5.27	1.040	-5.27
3	1.020	-7.47	1.020	-7.47
4	1.010	-9.20	1.011	-9.21
5	1.010	-14.13	1.010	-14.13
6	1.009	-10.97	1.009	-10.98
7	1.002	-12.80	1.002	-12.80
8	1.010	-11.74	1.010	-11.75
9	1.045	-13.90	1.046	-13.92
10	1.034	-15.45	1.036	-15.46
11	1.082	-13.90	1.082	-13.92
12	1.054	-14.85	1.055	-14.85
13	1.071	-14.85	1.071	-14.85
14	1.039	-15.73	1.040	-15.74
15	1.034	-15.80	1.035	-15.81
16	1.038	-15.35	1.039	-15.36
17	1.030	-15.64	1.032	-15.65
18	1.022	-16.38	1.023	-16.39
19	1.018	-16.53	1.019	-16.54
20	1.021	-16.32	1.023	-16.33
21	1.025	-15.94	1.027	-15.97
22	1.026	-15.91	1.028	-15.94
23	1.024	-16.14	1.027	-16.20
24	1.020	-16.26	1.024	-16.37
25	1.022	-15.97	1.026	-16.02
26	1.005	-16.38	1.008	-16.43
27	1.033	-15.52	1.035	-15.54
28	1.007	-11.63	1.007	-11.64
29	1.020	-16.93	1.022	-16.94
30	1.017	-18.01	1.019	-18.02
31	0.994	-15.72	1.011	-15.88

After the convergence of the main PF calculation is achieved, the details of the load flows in each branch are represented in Table 4 and 5. As displayed in the two below tables, the sent-received active and reactive powers in each breach are slightly different.

From the results expressed in Table 5, it can be easily observed in the taking into account the stator impedance case, the consumed reactive power at bus #1 (slack bus) is 15.31 MVAr and the generated active power is 171.81 MW. This is the biggest generated active power among all buses in whole proposed power system. Especially, by observing the power flow in the branch 31-24, which have sending end bus represented by the WF bus, we can recognize that the active power generated from WF is 35.4 MW. It is assumed that the positive and negative signs in front of calculated active and reactive power values describe for generating or consuming modes.

Table 4. Branches' load flows for the discounting the stator impedance case

Node 1	Node 2	P_s, MW	Q_s, MVar	P_r, MW	Q_r, MVar
1	2	171.90	-15.47	-166.82	24.85
1	3	87.15	5.19	-84.07	1.64
2	4	43.19	2.88	-42.20	-3.71
3	4	81.67	-2.84	-80.82	4.41
2	5	82.20	0.25	-79.24	7.75
2	6	59.73	-0.68	-57.81	2.57
4	6	71.50	-16.87	-70.87	18.14
5	7	-14.96	12.20	15.14	-13.81
6	7	38.32	-3.44	-37.94	2.91
6	8	29.64	-10.11	-29.53	9.60
6	9	26.56	-6.30	-26.56	7.76
6	10	15.15	1.70	-15.15	-0.51
9	11	-0.00	-18.01	0.00	18.62
9	10	26.56	10.25	-26.56	-9.43
4	12	43.92	14.58	-43.92	-9.92
12	13	0.00	-12.01	-0.00	12.20
12	14	7.81	2.46	-7.73	-2.31
12	15	17.66	7.00	-17.44	-6.58
12	16	7.25	4.96	-7.19	-4.82
14	15	1.53	0.71	-1.53	-0.71
16	17	3.69	3.02	-3.68	-2.98
15	18	6.21	2.71	-6.16	-2.61
18	19	2.96	1.71	-2.95	-1.70
19	20	-6.55	-1.70	6.56	1.73
10	20	8.84	2.60	-8.76	-2.43
10	17	5.34	2.84	-5.32	-2.82
10	21	14.80	4.87	-14.72	-4.70
10	22	6.94	1.94	-6.90	-1.86
21	22	-2.78	-2.20	2.78	2.20
15	23	4.57	2.08	-4.54	-2.03
22	24	4.12	-0.34	-4.10	0.37
23	24	1.34	0.43	-1.34	-0.43
24	25	-1.64	0.53	1.65	-0.52
25	26	3.54	2.37	-3.50	-2.30
25	27	-5.19	-1.85	5.22	1.91
28	27	18.49	2.17	-18.49	-0.91
27	29	6.18	-0.11	-6.10	0.25
27	30	7.09	-0.89	-6.93	1.18
29	30	3.70	-1.15	-3.67	1.22
31	24	32.4	56.8	-32.4	-57.4
8	28	-0.47	-0.73	0.47	-3.62
6	28	19.02	-2.55	-18.96	1.45

5. CONCLUSIONS

Based on the steady-state model of AG, the paper has represented an assumption that the wind farm is modelled as a RX load bus. So, it reflects the real steady output of generators and is accurate. Accordingly, the RX model has built and applied in order to obtain solid results in the PF analysis calculation. In this paper, a wind farm having 20 WTs is added to the IEEE 30 bus system to evaluate the effectiveness of the proposed RX model. The iterative process may be more applicable because the fundamental load flow calculation is separated from the main PF analysis program. The proposed model and the computing method in this work can be extensively utilized for more complex distribution electrical network with integration of wind energy. This has a significant meaning in the power systems' planning, operating and dispatching.

Table 5. Branches' load flows for the taking into account the stator impedance case

Node 1	Node 2	P_s, MW	Q_s, MVar	P_r, MW	Q_r, MVar
1	2	171.81	-15.31	-166.74	24.67
1	3	87.09	5.33	-84.01	1.50
2	4	43.17	2.99	-42.17	-3.82
3	4	81.61	-2.70	-80.77	4.26
2	5	82.19	0.21	-79.24	7.79
2	6	59.69	-0.57	-57.77	2.46
4	6	71.40	-16.86	-70.78	18.12
5	7	-14.96	12.33	15.14	-13.94
6	7	38.33	-3.57	-37.94	3.04
6	8	29.64	-10.71	-29.52	10.20
6	9	26.50	-5.99	-26.50	7.43
6	10	15.11	1.97	-15.11	-0.78
9	11	-0.00	-18.44	0.00	19.09
9	10	26.50	10.02	-26.50	-10.19
4	12	43.94	14.83	-43.94	-10.14
12	13	0.00	-12.65	-0.00	12.85
12	14	7.83	2.60	-7.75	-2.45
12	15	17.64	7.55	-17.42	-7.12
12	16	7.27	5.14	-7.20	-5.00
14	15	1.55	0.85	-1.55	-0.84
16	17	3.70	3.20	-3.69	-3.16
15	18	6.24	2.72	-6.19	-2.63
18	19	2.99	1.73	-2.98	-1.71
19	20	-6.52	-1.69	6.53	1.72
10	20	8.841	2.58	-8.73	-2.42
10	17	5.342	2.67	-5.31	-2.64
10	21	14.77	5.60	-14.69	-5.43
10	22	6.92	2.41	-6.88	-2.34
21	22	-2.81	-1.47	2.81	1.48
15	23	4.53	2.73	-4.50	-2.68
22	24	4.07	0.86	-4.05	-0.83
23	24	1.30	1.08	-1.30	-1.07
24	25	-1.58	0.06	1.58	-0.06
25	26	3.54	2.37	-3.50	-2.30
25	27	-5.12	-2.31	5.16	2.37
28	27	18.42	2.64	-18.42	-1.37
27	29	6.18	-0.11	-6.10	0.25
27	30	7.09	-0.89	-6.93	1.18
29	30	3.70	-1.15	-3.67	1.22
31	24	35.4	11.6	-35.4	-11.2
8	28	-0.48	-0.53	0.48	-3.82
6	28	18.96	-2.29	-18.90	1.18

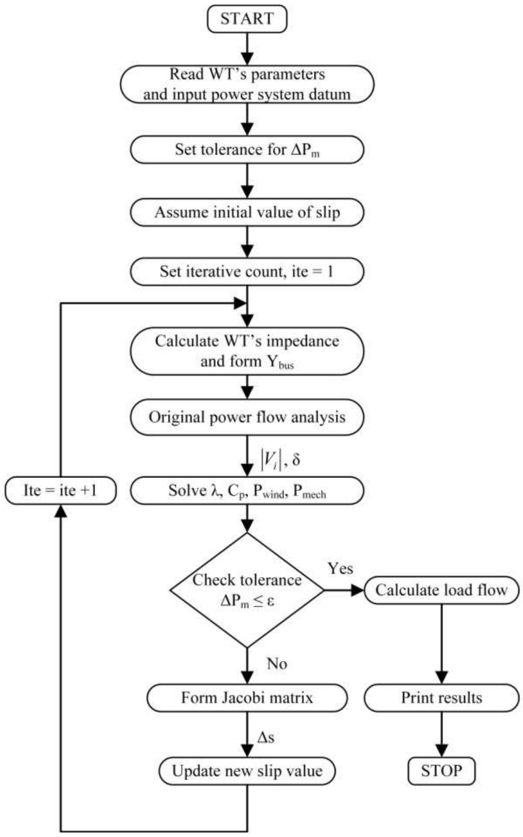

Fig.8. Flow chart of the main PF calculating program.

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NOMENCLATURE

Z_{wt}	Equivalent impedance of AG
R_s, R_r	Stator and rotor windings resistances
X_s, X_r	Stator and rotor windings reactances
X_m	Magnetizing reactance
R_1	Real element of Z_{wt} in case A
X_1	Imaginary element of Z_{wt} in case A
Z_{eq}	Thevenin's equivalent impedance
R_{p-eq}	Parallel equivalent resistance of rotor windings
X_{p-eq}	Parallel equivalent reactance of rotor windings
s	Asynchronous generator's slip
P_{mech}	WT's mechanical power
P_{wind}	Power extracted from the wind of WT
P_{gen}	Generated power from rotor windings
P_g, Q_c	Generated and consumed power from AG
$[J]$	Jacobi matrix
A	Swept area of blades
ρ, λ	Air density and tip speed ratio
C_p	Power coefficient
ω_r, R	Rotor speed and blade length

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