Conférence Internationale des Energies Renouvelables (CIER'13) Sousse, Tunisie - 2013

Vol.2
ISSN : 2356-5608

Economic/Reactive Power Dispatch for Power systems including wind farms

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Abstract— **This paper is concerned with developing the mathematical model of wind generator, and proposes a solution approach of the power flow (PF) problem and the solution of optimal power flow (OPF). The power flow model for a stall regulated fixed speed wind generator (SR-FSWG) system is discussed to assess the steady-state condition of power systems with wind farms.**

Modified Newton-Raphson algorithm including SR-FSWG is used to solve the load flow equations. In which the state variables of the wind generators are combined with the nodal voltage magnitudes and angles of the entire network.

The OPF is formulated as a multi objective problem (MOP). This nonlinear MOP involves the simultaneous optimization of three objective functions. The first function is the total real power loses in transmission lines. While, the second one is the voltage deviation at load buses and the third is the sum generation cost of the active power. Non-dominated sorting genetic algorithm II (NSGA-II) technique is employed to solve the MOP.

The simulation results are performed on the IEEE-14 bus test system and using MATLAB software package.

Keywords— **Wind farm, SR-FSWG, Power flow, Newton–Raphson algorithm, NSGA-II.**

I. INTRODUCTION

During these years, there has been a growth in the world in the use of renewable energy, particularly wind power [1].The wind generation has been added to many power systems as energy source. Therefore, studying the impact of wind power to the grid is an important topic. Power flow calculation of power system including wind farm is an important foundation for the wind farm planning, operation distribution, and other theoretical research.

In this article, the study of the problem of power flow of a meshed network with a wind power plant, equipped with an asynchronous generator operating under conditions similar to those reported in [2].

In [3,4] models for power injection of fixed speed wind flow is propose. The active and reactive power outputs of the models are completely expressed in terms of generators and variable parameters without using approximations.

This paper presents an approach to solve the Economic/Reactive Power Dispatch (E/RPD) for Power systems including wind farms. This problem consists to minimize the transmission losses, voltage deviation at load buses and generation cost after integration of wind farm.

Many approximated methods have been proposed to solve the multi objective evolutionary algorithm (MOEA) as the Vector Evaluated Genetic Algorithm (VEGA) and Vector Optimized Evolution Strategy (VOES) but these two algorithms are non-Pareto approaches. In the MOEA, there is no single optimal solution, but a set of nondominated solutions. They are called the Pareto optimal solutions. Recently, the Pareto-based approaches are interested by the researchers. Multiple Objective Genetic Algorithms, such as, niched Pareto genetic algorithm (NPGA), Nondominated Sorting Genetic Algorithm (NSGA-II), are proposed for solving MOP. In this work, the NSGA-II [5] is proposed to solve the E/RPD problem. An algorithm to solve the power flow for power systems including wind farm is proposed. Therefore, this manuscript is organized as follows. Section II shows a brief review of the model of the wind generator. Then, the power flow method including wind farm is presented. In section III, we investigate the problem formulation of the E/RPD, where, the NSGA-II is presented. While section IV presents numerical results. Finally, conclusion is drawn in section V.

II. MODELING OF WIND GENERATOR

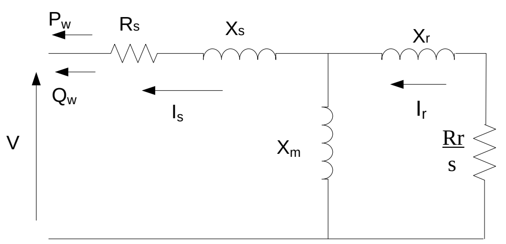


Fig.1 Induction machine equivalent circuit.

Currently, different types of wind turbine generating units were installed and they can be classified into three categories, namely fixed, semi-variable and variable speed types. This paper addresses the mathematical representation of directly grid-connected wind generators such as SR-FSWG. The idea of this machine is based on an asynchronous squirrel-cage motor generator shown in Fig.1, which is driven by a wind turbine with the stator directly connected to the grid through a power transformer. In this SR-FSWG a fixed shunt capacitor is used to provide reactive power compensation.

The power output of this SR-FSWG depends on the turbine and generator characteristics, wind speed, rotor speed and the terminal voltage.
From the equivalent circuit shown in Fig. 1, the power converted from mechanical to electrical form P_g can be represented by (1).

$$P_g = -I_r^2 R_r \left(\frac{1-s}{s}\right) \quad (1)$$

Where, I_r is the rotor current given by the following equation.

$$I_r^2(V,s) = V^2 \left[\frac{\left(Ks+Ls^2\right)^2 + \left(Ms-Ns^2\right)^2}{\left(\left(D-Es\right)^2+\left(F+Gs\right)^2\right)^2} \right] \quad (2)$$

The active and reactive powers, determined by equations (3) and (4), are dependent on the machine's slip s and the terminal voltage V.

$$P_W\left(V,s\right) = -V^2 \left[\frac{A+Bs+Cs^2}{\left(D-Es\right)^2+\left(F+Gs\right)^2} \right] \quad (3)$$

$$Q_W\left(V,s\right) = -V^2 \left[\frac{H+Js^2}{\left(D-Es\right)^2+\left(F+Gs\right)^2} \right] \quad (4)$$

Where the variables are defined as

$A = R_s R_r^{\,2}$, $B = R_r X_m^2$, $C = R_s\left(X_r+X_m\right)^2$, $D = R_s R_r$,
$E = X_r X_m$, $E = X_r X_m$, $F = R_r\left(X_s+X_m\right)$,
$G = R_s\left(X_s+X_m\right)$, $H = R_r^2\left(X_s+X_m\right)$,
$F = \left(X_r+X_m\right)\left[X_r X_m + X_s\left(X_r+X_m\right)\right]$,
$K = X_m R_r\left(X_s+X_m\right)$, $L = R_s X_m\left(X_r+X_m\right)$,
$M = R_r R_s X_m$, $N = X_m\left[X_r X_m + X_s\left(X_r+X_m\right)\right]$

The wind turbine mechanical power output P_m [W] extracted from the wind by this generator [6] can be written as

$$P_m = \frac{1}{2}\rho \mathrm{A} V_w^3 C_p\left(\lambda,\gamma\right) \quad (5)$$

Where, ρ [kg/m3] is the density of air, V_w [m/s] is the wind speed, A [m2] is the area swept by the rotor and $C_p\left(\lambda,\beta\right)$ is the power coefficient. The C_p given by (6) is a nonlinear function of the tip speed ratio λ and the pitch angle β.

$$C_p\left(\lambda,\beta\right) = c_1\left(\frac{c_2}{\mu} - c_3\beta - c_4\beta^{c_5} - c_6\right)\exp\left(-c_7/\mu\right) \quad (6)$$

Where,
λ depends on the wind speed V_w and the radius of the rotor R [m] as given in (7).

$$\lambda = \frac{W_r \eta R}{V_w} \quad (7)$$

W_r [rad/s] is the angular speed of the turbine

$$\mu = \frac{1}{\left[\left(\frac{1}{\lambda + c_8\beta}\right) - \left(\frac{c_9}{\beta^3+1}\right)\right]} \quad (8)$$

μ is represented by (8), β [degrees] is the pitch angle and the constants c_1 to c_9 are the parameters of design of the wind turbine.

III. POWER FLOW MODEL

The objective of this section is to give a power flow model for a power system without and with wind farm device.

A. Power flow analysis without wind farm

The injected real and reactive power flow at bus i, for power system with N buses, can be written as [7].

$$P_i = \sum_{j=1}^{N} V_i V_j Y_{ij} \cos\left(\alpha_i - \alpha_j - \theta_{ij}\right) \quad (9)$$

$$Q_i = \sum_{j=1}^{N} V_i V_j Y_{ij} \sin\left(\alpha_i - \alpha_j - \theta_{ij}\right) \quad (10)$$

Where V_i and α_i are respectively, modulus and argument of the complex voltage at bus i. Y_{ij} and θ_{ij} are respectively, modulus and argument of the ij-th element of the nodal admittance matrix Y.
The resolution of the problem of power flow uses iterative methods, since it is about a nonlinear problem. The Newton-Raphson method constitutes the universal method for the resolution of this problem. The nonlinear system is represented by the linearized Jacobian equation given by the following equation:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \frac{\delta P_i}{\delta \alpha_j} & \frac{\delta P_i}{\delta V_j} \\ \frac{\delta Q_i}{\delta \alpha_j} & \frac{\delta Q_i}{\delta V_j} \end{bmatrix} \begin{bmatrix} \Delta\alpha \\ \Delta V \end{bmatrix}$$

(11)

B. Power flow analysis with wind farm [2]

When the SR-FSWG is connected at terminal f of the system, the set of mismatch power flow equations is

$$\Delta P_f = P_f^{inj} - P_W\left(V,g\right) - P_{lf} = 0 \quad (12)$$

$$\Delta Q_f = Q_f^{inj} - Q_W\left(V,g\right) - Q_{lf} = 0 \quad (13)$$

Where P_{lf} and Q_{lf} represent the active and reactive powers drawn by the load at bus f.

$$P_f^{inj} = V_f^2 G_{ff} + V_f \sum_{i\in f} V_i\left[G_{fi}\cos\left(\alpha_f - \alpha_i\right) + B_{fi}\sin\left(\alpha_f - \alpha_i\right)\right] \quad (14)$$

$$Q_f^{inj} = -V_f^2 B_{ff} + V_f \sum_{i\in f} V_i\left[G_{fi}\sin\left(\alpha_f - \alpha_i\right) - B_{fi}\cos\left(\alpha_f - \alpha_i\right)\right] \quad (15)$$

P_f^{inj} and Q_f^{inj} are active and reactive power injections at bus f , G_{fi} and B_{fi} are transfer conductance and susceptance between buses f and i , respectively.

The power balance inside the induction machine is represented by (16)

$$\Delta P_{T1,f} = -Pm + Pg = 0 \tag{16}$$

Finally, the modified power flow equations can be solved with the Newton-Raphson method by using equation (17).

$$\begin{bmatrix} \Delta P_f \\ \Delta Q_f \\ \Delta P_{T1,f} \end{bmatrix} = \begin{bmatrix} \dfrac{\delta P_f^{inj}}{\delta \alpha_f} & \left(\dfrac{\delta P_f^{inj}}{\delta V_f} - \dfrac{\delta P_W}{\delta V_f}\right) & \dfrac{\delta P_W}{\delta s} \\ \dfrac{\delta Q_f^{inj}}{\delta \alpha_f} & \left(\dfrac{\delta Q_f^{inj}}{\delta V_f} - \dfrac{\delta Q_W}{\delta V_f}\right) & \dfrac{\delta Q_W}{\delta s} \\ 0 & \dfrac{\delta P_{T1,f}}{\delta V_f} & \dfrac{\delta P_{T1,f}}{\delta s} \end{bmatrix} \begin{bmatrix} \Delta \alpha_f \\ \Delta V_f \\ \Delta s \end{bmatrix} \tag{17}$$

IV. Problem formulation

The OPF is a mathematical optimization problem set up to minimise a multi-objective function subject to equality and inequality constraints.

A. *Objective functions*

The optimal Economic /reactive power dispatch (OE/RPD) problem is defined to minimize the real power losses, voltage deviation and the generation cost of the active power under several constraints.

1) *Real Power Losses:* they can be presented by the following equation [8].

$$F_1 = \sum_{i=1}^{N}\sum_{j=1}^{N} Y_{ij} V_i V_j \cos(\delta_i - \delta_j - \theta_{ij}) \tag{18}$$

N is the buses number.

2) *Voltage Deviation:* this objective consists to minimize the deviation in voltage magnitude at load buses. It can be expressed as follows [9]

$$F2 = \sum_{i=1}^{N_L} \left(V_i - V_i^{ref}\right)^2 \tag{19}$$

Where N_L is the number of load buses, V_i^{ref} the Pre-specified reference value of the voltage magnitude at the *i*-th load bus. In this application, $V_i^{ref} = 1pu$.

3) *Generation cost function:* the total generation cost function C_{p_g} [\$/h] is represented by a quadratic function as given by (20).

$$C_{p_g} = \sum_{j=1}^{N_g} G_j\left(P_{gj}\right) \tag{20}$$

Where,

$$G_j\left(P_{g_j}\right) = a_j + b_j P_{gj} + c_j P_{gj}^2 \tag{21}$$

G_j and P_{gj} are cost function and electrical output of the *j*-th machine, respectively.

a_j , b_j and c_j are cost coefficients of the *j*-th generator. N_g is the number of generators.

B. *Problem constraints*

In this study, the equality and inequality constraints of the OE/RPD are as follows.

1) *Security Limits :* These constraints are represented by:

- Voltage limits at load buses as shown in (22).

$$V_{Li}^{\min} < V_{Li} < V_{Li}^{\max} \qquad i = 1,...,N_L \tag{22}$$

Where:

$V_{Li}^{\min}$ and $V_{Li}^{\max}$ are respectively, lower and upper voltage limits at load buses.

- The line flow limits given by (23).

$$P_{Li} < P_{Li}^{\max} \qquad i = 1,...,N_L \tag{23}$$

P_{Li} is the real power flow in each transmission line i .

2) *Load flow constraints*

$$P_{Gi} - P_{Di} = P_i \tag{24}$$

$$Q_{Gi} - Q_{Di} = Q_i \tag{25}$$

Where P_{Gi} and Q_{Gi} are generated real and reactive powers at bus i , respectively. P_{Di} and Q_{Di} are respectively, real and reactive power loads at bus i ,.

C. *NSGA-II Approach*

Deb et al. [10] proposed a version of the algorithm NSGA-II, which is considered more efficient than its predecessor. The NSGA-II procedure is outlined as follows [11].

Step 1: Create the population of children Q_t from current population P_t by applying the genetic operators for selected individuals.

Step 2**:** Combine the two populations Q_t and P_t to form R_t : $R_t = P_t \cup Q_t$.

Step 3: Find the all non-dominated fronts F_i of R_t .

Step 4: Initiate the new population $P_{t+1} = \varnothing$ and the counter of front for inclusion $i = 1$.

Step 5: While $|P_{t+1}| + |F_i| < N_{pop}$

$$P_{t+1} \leftarrow P_{t+1} \cup F_i \quad i \leftarrow i+1 \tag{26}$$

Step 6: Sort the last front F_i using the crowding distance in descending order and choose the first $\left(N_{pop} - |P_{t+1}|\right)$ elements of F_i **.**

Step 7: Use selection, crossover and mutation operators to create the new offspring population Q_{t+1} of size N_{obj}.

To estimate the density of solution surrounding a particular solution $\underline{X}_i$ in a non-dominated set F, we calculate the crowding distance as follows:

Step 1: Let's suppose $q = |F|$. For each solution $\underline{X}_i$ in F, set $d = 0$. Initiate $m = 1$.

Step 2: Sort F in the descending order according to the objective function of rank m, f_m.

Let's consider $\mathrm{I}^m = sort_{[f_{m,>}]}(F)$ the vector of indices; i.e I_i^m is the index of the solution $\underline{X}_i$ in the sorted list according to the objective function f_m.

Step 3: For each solution $\underline{X}_i$ which verifies $2 \le I_i^m \le (q-1)$, update the value of d_i as follows:

$$d_i \leftarrow d_i + \frac{f_m^{I_i^{m+1}} - f_m^{I_i^{m-1}}}{f_m^{\max} - f_m^{\min}} \tag{27}$$

Then, the boundary solutions in the sorted list (solutions with smallest and largest function) are assigned an infinite distance value, i.e. if, $I_i^m = 1$ or $I_i^m = q$, $d_i = \infty$.

Step 4: If $m = M$, the procedure is finished.

Else, $m = (m+1)$ and return to step 2.

V. NUMERICAL RESULTS

The effectiveness of the proposed algorithm is tested using IEEE 14 bus system including wind farms comprising five wind generators as it is depicted in Fig. 2. Data and results of system are based on 100 MVA. Bus 14 is the slack bus. The test system data can be found in Tables IV and V [12].

The constant values c_1 to c_9, pitch angle β, rotor radius R and the gear ratio η for this turbine are as follows.

$c_1 = 0.5$, $c_2 = 116$, $c_3 = 0.4$, $c_4 = 0$, $c_5 = 0$, $c_6 = 5$, $c_7 = 21$, $c_8 = 0.08$, $c_9 = 0.035$, $\beta = 0$, $R = 28.5m$ and $\eta = 1/65.27$.

The air density is taken to be $\rho = 1.225$ kg/m^3.

The initial value for the slip of the induction generator to execute simulations is given by $s(0) = s_{nom}/2$.

$s_{nom} = -0.005$. The value of fixed capacitors installed at each wind generator is 30% of rated power.

The induction generator circuit parameters are given in Table VI [13].

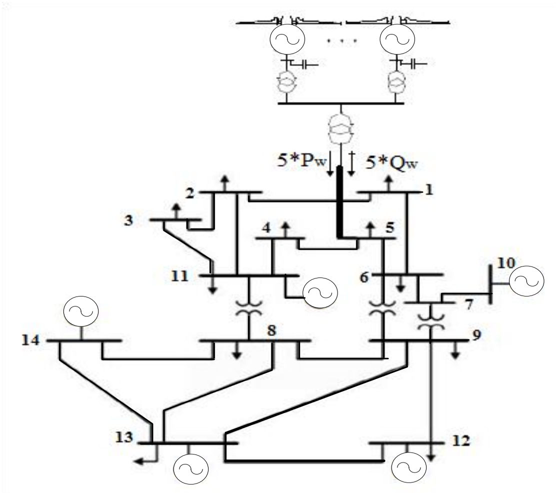


Fig.2 IEEE-14 bus test system with wind farm

A. *PF OF BASE Case*

Table 1 shows the voltage magnitudes and angles given by the power flow program for the system without and with wind farm. However, slip, active and reactive powers given by five SR_FSWG are also the outputs of power flow program of the system with wind farm.

The results assuming that wind speed is $V_w = 10 m/s$ at all wind farms and the active power requested (PD) equal to 259 MW.

The convergence characteristic of the power flow program with wind farm is given in Fig.3

TABLE I

SOLUTIONS OF THE POWER FLOW PROGRAM FOR THE BASE CASE

	Without wind farm		**With wind farm**	
Bus No	V [pu]	α [Degree]	V [pu]	α [Degree]
1	1.0174	-16.3940	1.0175	-16.0389
2	1.0462	-15.7383	1.0463	-15.4311
3	1.0530	-15.7197	1.0530	-15.4194
4	1.0449	-15.2134	1.0452	-14.8140
5	1.0275	-15.3181	1.0279	-14.8137
6	1.0276	-15.0699	1.0277	-14.6774
7	1.0448	-13.4503	1.0450	-13.1359
8	1.0326	-8.9467	1.0331	-8.8021
9	1.0261	-10.3659	1.0266	-10.2018
10	1.0900	-13.4503	1.0900	-13.1359
11	1.0700	-14.8794	1.0700	-14.5858
12	1.0100	-12.6328	1.0100	-12.5048
13	1.0450	-4.9565	1.0450	-4.8808
14	1.0600	0	1.0600	0
s	___		-0.0029	
$5*P_W$ [MW]	___		3.1660	
$5*Q_W$ [MVAR]	___		-0.7473	

B. *Optimal solutions*

To optimize the three functions, cost, voltage deviation and active power losses, the NSGA-II algorithm is used.
The population size and the maximum number of iterations have the same value, which is 100. The probabilities of crossover and mutation are respectively, 0.9 and 0.01.
To demonstrate the effectiveness of the NSGA-II, three different cases have been considered as follows.

Base case: $PD_{tot} = PD_0$

Light case : $PD_{tot} = 0.8PD_0$

Heavy case : $PD_{tot} = 1.2PD_0$

The decision parameters of the MOP for cases without and with wind farm are active productions of the two generators G13 and G14, P_{g13} and P_{g14}.

After convergence of the NSGAII program, The Pareto-optimal fronts of the MOP with wind farm for the three cases can be illustrated in Fig.4

Tables II and III show optimum values of P_{g13} and P_{g14}. The corresponding values of the fitness functions are given in these tables.

TABLE II
THE MINIMUM SOLUTION FOR THE THREE FUNCTIONS WITHOUT WIND FARM

	without wind farm		
	BASE CASE	Light case	Heavy case
Minimum cost [$/h]	957.0176	762.7006	1.1779e+003
Minimum Voltage Deviation[pu]	0.3200	0.3786	0.2579
Minimum Power losses [pu]	0.0904	0.0582	0.1312
Pg13 [pu]	0.9251	0.6899	1.1665
Pg14 [pu]	1.7762	1.4541	2.1022

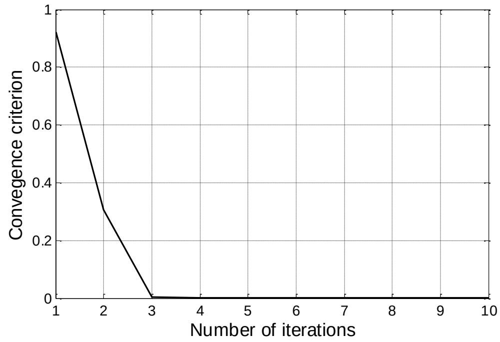


Fig.3 Convergence criterion of the power flow algorithm

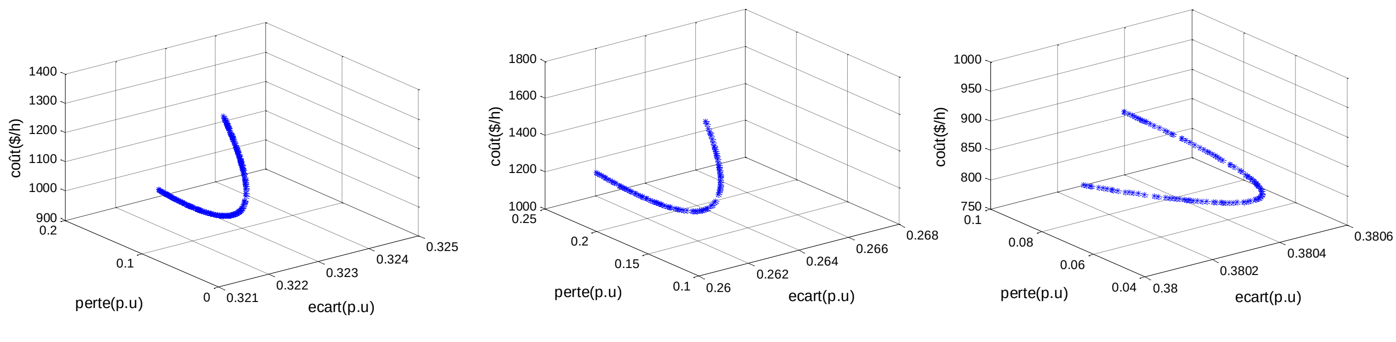
TABLE III
THE MINIMUM SOLUTION FOR THE THREE FUNCTIONS WITH WIND FARM

	with wind farm		
	BASE CASE	Case1	Case 2
Minimum Cost [$/h]	944.4749	751.7213	1.1637e+003
Minimum Voltage Deviation [pu]	0.3220	0.3801	0.2603
Minimum Power losses [pu]	0.0883	0.0566	0.1286
Pg13 [pu]	0.9108	0.6759	1.1517
Pg14 [pu]	1.7564	1.4346	2.0822

From Tables II and III, it can be seen that the generation cost and the power losses are decreased after integration of the wind farm.

CONCLUSION

This paper presents the mathematical model of wind generator and the modified Newton-Raphson algorithm for power system including SR_FSWG.



(a) (b) (c)

Fig.4 Pareto solutions with wind farm: (a):base case ,(b) Light case, (c) Heavy case

In addition, this paper presents an approach to solve the economic/reactive power dispatch for Power systems including wind farms. Three objective functions are considered. They are total transmission losses, voltage deviation at load buses and generation cost.
The simulations results obtained for the IEEE-14 bus system without and with wind farms showed the effectiveness of the proposed method. These solutions are presented by Pareto-optimal front.

APPENDIX:

TABLE IV
LINE DATA FOR IEEE-14 BUS.

Number Of line	***Line***	***R* [pu]**	***X* [pu]**	***B* [pu]**	**Pmax [MW]**
1	1-2	0.17093	0.34802	0	45
2	1-6	0.12711	0.27038	0	45
3	2-3	0.22092	0.19988	0	45
4	2-11	0.06615	0.13027	0	45
5	3-11	0.12291	0.25581	0	45
6	4-5	0.08205	0.19207	0	45
7	4-11	0.09498	0.1989	0	60
8	5-6	0.03181	0.0845	0	45
9	6-7	0	0.11001	0	60
10	6-9	0	0.55618	0	36
11	7-9	0	0.20912	0	60
12	7-10	0	0.17615	0	45
13	8-9	0.01335	0.04211	0	150
14	8-11	0	0.25202	0	80
15	8-13	0.05695	0.17388	0.03460	150
16	8-14	0.05403	0.22304	0.04920	150
17	9-12	0.06701	0.17103	0.01280	150
18	9-13	0.05811	0.17632	0.03400	150
19	12-13	0.04699	0.19797	0.04380	150
20	13-14	0.01938	0.05917	0.0528	300

TABLE V

GENERATION DATA AND COST FUNCTION FOR IEEE 14 BUS SYSTEM

Gi	***N° Bus***	***ai***	***bi***	***ci***	P_{gi}^{min}	P_{gi}^{max}	Q_{gi}^{min}	Q_{gi}^{max}
G1	14	100	1.5	0.006	0	332.4	0	10
G2	13	130	2.1	0.009	0	140	-40	50

TABLE VI
INDUCTION GENERATOR CIRCUIT PARAMETERS

Rating [kW]	*900*
Rated [V]	690
Rs [Ω]	0.0027
Xs [Ω]	0.025
Rr [Ω]	0.0022
Xr [Ω]	0.046
Xm [Ω]	1.38

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