Economic/Environmental Power Dispatch for Power Systems including wind farms

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Abstract: -This paper presents the problem of the Economic/Environmental Dispatching (EED) of hybrid power system including wind energies. 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 EED problem is a nonlinear constrained multi-objective optimization problem, two competing fuel cost and pollutant emission objectives should be minimized simultaneously while satisfying certain system constraints. In this paper, the resolution is done by Algorithm multi-objective particle swarm optimization (MOPSO). The effectiveness of the proposed method has been verified on IEEE 6-generator 30-bus test system and using MATLAB software package.

Key-Words: - EED, Wind farm, SR-FSWG, Power flow, Newton–Raphson algorithm, MOPSO.

1 Introduction

The main objective of the Environmental Economic power Dispatch (EED) consists in the schedule of the power generator units outputs with load demand at minimum operating cost, emissions and pollution while satisfying operational constraints of the generators. A lot of different strategies have been reported in the literature pertaining to the reduction of the atmospheric emissions in power plants [1,2]. These include the use of alternative fuels with a low emission potential, replacement of the existing technologies with energy-efficient ones and emission dispatching [3,4] which is an attractive short-term alternative. In recent years, the environmental and economic concerns lead to the use of renewable energy resources such as wind power and solar radiation. The use of wind energy conversion systems (WECS) has been considered the most growing renewable energy source [5]. However, the integration of wind generation into the electric power network requires more attention while planning and operating an electrical power system. In the last few decades, different Power Flow (PF) solution techniques such as Gauss-Seidel, Newton-Raphson and Fast decoupled load flow [6] have been developed in order to operate and control the power system. The Newton-Raphson technique is a fundamentally approach for modeling the wind energy systems. This method simultaneously combines the state variables corresponding to the wind generators and the network in a single frame-of-reference.

In the literature, several techniques [3,4,7] have been reported in order to handle the EED problem. In the recent direction, both fuel cost and emission are considered simultaneously as competing objectives. Stochastic search and Fuzzy-based multi-objective optimization techniques have been proposed for the EED problem [7,8]. However, these algorithms are unable to provide a systematic framework for directing the search toward Pareto-optimal front and the extension of these approaches to include more objectives is a very involved question. The EED problem can be also solved by using genetic algorithm based multi-objective techniques [9].

In recent years, multi-objective evolutionary algorithms [18] like NPGA and SPEA algorithm have been used for the EED problem optimization in order to find the optimal solution. Recently, modern meta-heuristic algorithms are used for nonlinear optimization problems. The multi-objective particle swarm optimization (MOPSO) [15] is a typical population-based optimization method. Unlike other heuristic techniques such as genetic algorithm (GA), MOPSO has a flexible mechanism to carry out both global and local search in each iteration process within a short calculation time.

In this paper, MOPSO is proposed to solve the EED problem. In addition, a fuzzy-based mechanism is used in order to extract the best compromise solution. To illustrate the effectiveness and potential of the proposed approach to solve the multi-objective EED problem, several runs are carried out on the IEEE 6-generator 30-bus test system and the results are compared to the recently reported methods. The results show that the proposed approach is efficiently used to solve the EED problem and is superior to other multi-objective methods.

2 Modeling of Wind Generator

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

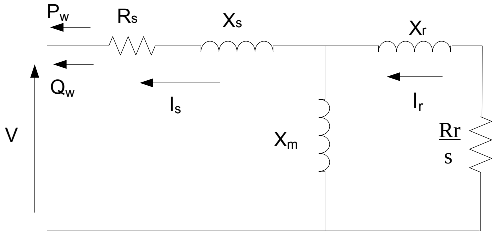

Fig.1. Induction machine equivalent circuit.

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).

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

Where, R_r is the rotor resistance, s is the slip of the induction generator and I_r is the rotor current given by the following equation .

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

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

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

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

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 [11] can be written as

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

Where, ρ [kg/m3] is the density of air, V_w [m/s] is the wind speed, $\mathrm{A}\,[\mathrm{m}^2]$ 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.

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

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

$$\lambda = \frac{W_r \eta R}{V_w} \tag{7}$$

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

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

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.

3 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.

3.1 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 [12].

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

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

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:

$$\begin{bmatrix}\Delta P \\ \Delta Q\end{bmatrix} = \begin{bmatrix}\frac{\delta P_i}{\delta \alpha_j} & \frac{\delta P_i}{\delta V_j} \\ \frac{\delta Q_i}{\delta \alpha_j} & \frac{\delta Q_i}{\delta V_j}\end{bmatrix}\begin{bmatrix}\Delta \alpha \\ \Delta V\end{bmatrix} \tag{11}$$

3.2 Power Flow Analysis with Wind Farm [13]

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

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

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

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

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

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

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).

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

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

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

4 Problem Formulation

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

4.1 Objective Functions

The economic/environmental power dispatch problem is to minimize two competing objective functions, fuel cost and emission, while satisfying several equality and inequality constraints.
The multi-objective problem is formulated as a nonlinear problem as follows [9,14].

$$Min(F) = \left[F_1(Pg), F_2(Pg) \right] \qquad (18)$$

4.1.1 Cost Function

$$F_1(Pg) = \sum_{i=1}^{N_g} a_i + b_i Pg_i + c_i Pg_i^2 \text{ \$/h} \qquad (19)$$

Where a_i, b_i and c_i are the cost coefficients of the i-th generator and N_g is the number of generators committed to the operating system. Pg_i is the power output of the i-th generator.

4.1.2 Emission Function

$$F_2(Pg) = \sum_{i=1}^{N_g} \left(\alpha_i + \beta_i Pg_i + \gamma_i Pg_i^2 \right) 10^{-2} \text{ ton/h} + \xi_i \exp\left(\lambda_i Pg_i \right) \qquad (20)$$

Where α_i, β_i, γ_i, ξ_i and λ_i are the emission coefficients of i-th generator.

4.2 Problem Constraints

In this study, the equality and inequality constraints of the problem are as follows.

4.2.1 Production capacity constraints

The generated real power of each generator at the bus i is restricted by lower limit $P_{g_i}^{\max}$ and upper limit $P_{g_i}^{\min}$:

$$P_{g_i}^{\min} < P_{g_i} < P_{g_i}^{\max}, i = 1...N_g \qquad (21)$$

4.2.2 Active power loss constraint

Active power loss of the transmission and transport liens, are positives:

$$p > 0 \qquad (22)$$

4.2.3 Load flow constraints

$$P_{Gi} - P_{Di} = P_i \qquad (23)$$

$$Q_{Gi} - Q_{Di} = Q_i \qquad (24)$$

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

4.2.4 Line flow constraints

This constrains can be described as:

$$\left|P_{ij,l}\right| < P_{ij,l}^{\max}, l = 1 \ldots N_L \tag{25}$$

Where $P_{ij,l}$ the real power flow of line l. $P_{ij,l}^{\max}$ is the power flow up limit of line l and N_L is the number of transmission lines.

5 The MOPSO Technique

This approach is population-based, it uses an external memory, called repository, and a geographically-based approach to maintain diversity. MOPSO is based on the idea of having a global repository in which every particle will deposit its flight experiences after each flight cycle. The general algorithm of MOPSO can be described in steps as follows [15]:

Step 1: Initialize an array of particles with random positions POP and their associated velocities VEL.

Step 2: Evaluate the fitness function of each particle.

Step 3: Store the positions of the particles that represent nondominated vectors in the repository REP.

Step 4: Generate hypercubes of the search space explored so far, and locate the particles using these hypercubes as a coordinate system.

Step 5: Initialize the memory of each particle.

Step 6: Compute the speed of each particle using the following expression:

$$\begin{aligned} VEL(i) = \chi[VEL(i) + \varphi_1 r_1 (PBEST(i) - POP(i)) \\ + \varphi_2 r_2 (REP(h) - POP(i))] \end{aligned} \tag{26}$$

Here φ_1 and φ_2 are weights affecting the cognitive and social factors, respectively; r_1 and r_2 are random numbers in the range [0-1]. χ is the constriction factor that ensures convergence which is calculated as in (27):

$$\chi = \begin{cases} \dfrac{2k}{\left|2 - \phi - \sqrt{\phi^2 - 4\phi}\right|} & \text{if } \phi \geq 4 \\ k & \text{if } 0 \prec \phi \prec 4 \end{cases} \tag{27}$$

Where $0 \prec k \prec 1$ and

$$\phi = \varphi_1 + \varphi_2 \tag{28}$$

$PBEST(i)$ is the best position that the particle i has had; $REP(h)$ is a value that is taken from the repository; the index h is selected by applying roulette-wheel selection

Step 7: Update the position for each particle

$$POP(i) = POP(i) + VEL(i) \tag{29}$$

Step 8: Maintain the particles within the search.

Step 9: Evaluate each of the particles in POP.

Step 10: Update the contents of REP together with the geographical representation of the particles within the hypercubes.

Step 11: Update the particle's position using Pareto dominance.

Step 12: Repeat Step 6-11 until a stopping criterion is satisfied or the maximum number of iterations is reached.

6 Results and Discussion

The effectiveness of the proposed algorithms is tested using IEEE 30 bus system including wind farms comprising ten wind generators. Data and results of system are based on 100 MVA. Bus 30 is the slack bus. The test system data can be found in [16].

The values of fuel cost and emission coefficients corresponding to the generators G_i are shown in [17]. The bounds of generated powers are: $P_{gi}^{\min} = 0.05\,p.u$ and $P_{gi}^{\max} = 1.5\,p.u$.

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 $\rho = 1.225\ \text{kg/m}^3$.

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 [13].

6.1 Power Flow 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 ten SR_FSWG is 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 283.4 MW.

The convergence characteristic of the power flow program without and with wind farm is given infig. 2.

6.2 Optimal Solutions

6.2.1 Without wind farm

The MOPSO technique is implemented with all constraints have been taken into account. The best cost and best emission solutions obtained are given in table 2 and table 3. In this table the proposed method it is compared with the NPGA, SPEA [18], which have been applied to the EED problem. The convergence of fuel cost and emissions are depicted in fig. 3.

Table 1. Solution 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	0.9568	-18.4720	0.9569	-11.5578
2	0.9697	-17.5551	0.9698	-11.5578
3	1.0067	-11.9744	1.0105	-5.7516
4	0.9878	-16.1597	0.9880	-9.2461
5	0.9608	-17.1391	0.9617	-9.7909
6	0.9792	-16.6855	0.9801	-9.3381
7	0.9796	-17.0775	0.9822	-9.0301
8	0.9920	-17.1170	0.9955	-8.5782
9	0.9935	-16.7448	0.9959	-8.6576
10	0.9930	-16.7642	0.9954	-8.6738
11	1.0028	-17.1434	1.0057	-8.8268
12	0.9992	-17.7798	1.0022	-9.2322
13	1.0002	-17.6750	1.0033	-9.0559
14	1.0047	-16.4141	1.0072	-8.2195
15	1.0133	-16.2660	1.0171	-7.5764
16	1.0078	-16.8697	1.0121	-7.9755
17	1.0133	-16.7887	1.0189	-7.7447
18	1.0293	-15.8452	1.0351	-6.6557
19	1.0064	-16.2977	1.0087	-8.2003
20	1.0264	-14.5852	1.0290	-6.4553
21	1.0025	-13.1126	1.0055	-7.1430
22	1.0113	-11.3614	1.0162	-5.3686
23	1.0169	-9.6984	1.0251	-4.5893
24	1.0245	-8.0293	1.0318	-3.7798
25	1.0710	-15.8452	1.0710	-4.1010
26	1.0820	-14.5852	1.0820	-4.5152
27	1.0100	-12.0944	1.0100	-5.5252
28	1.0100	-14.3647	1.0100	-8.5163
29	1.0450	-5.5222	1.0450	-2.3737
30	1.0600	0	1.0600	0
s	-		-0.0029	
10.P_w MW	-		6.3291	
10.Q_w MVAR	-		-1.5165	

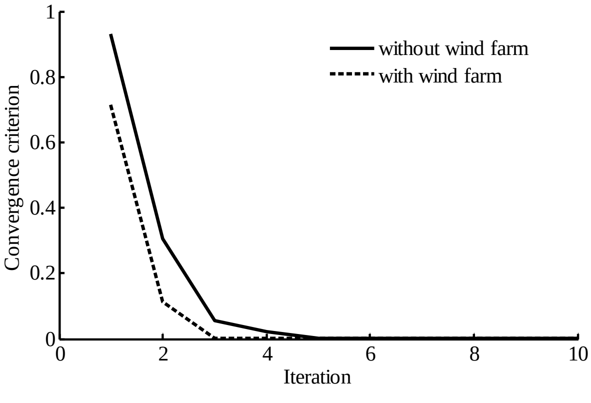

Fig. 2 . Convergence criterion of the power flow algorithm

Table 2 . The best cost solution without wind farm

	Best Cost		
	NPGA	SPEA	MOPSO
cost [$/h]	620.46	619.60	607.52
Emission[ton/h]	0.2243	0.2244	0.2198
Pg1 [pu]	0.1127	0.1319	0.1117
Pg2 [pu]	0.3747	0.3654	0.3097
Pg3 [pu]	0.8057	0.7791	0.5954
Pg4 [pu]	0.9031	0.9282	0.9778
Pg5 [pu]	0.1347	0.1308	0.5227
Pg6 [pu]	0.5331	0.5292	0.3486

Table 3 . The best emission solution without wind farm

	Best Emission		
	NPGA	SPEA	MOPSO
cost [$/h]	657.59	651.71	644.33
Emission[ton/h]	0.2017	0.2019	0.1942
Pg1 [pu]	0.4753	0.4419	0.4110
Pg2 [pu]	0.5162	0.4598	0.4583
Pg3 [pu]	0.6513	0.6944	0.5438
Pg4 [pu]	0.4363	0.4616	0.3933
Pg5 [pu]	0.1896	0.1952	0.5502
Pg6 [pu]	0.5988	0.6131	0.5072

Table 4 given the best compromise solution that has the maximum value of membership function can be extracted. The results of the proposed approach were compared to those reported using NPGA and SPEA algorithms [18].

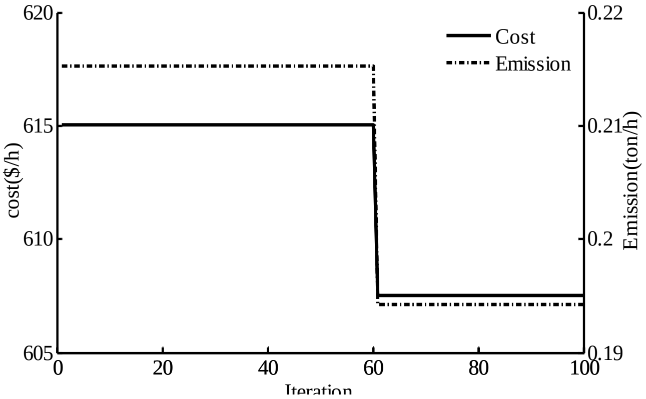

Fig. 3. Convergence of cost and emission objective functions without wind form

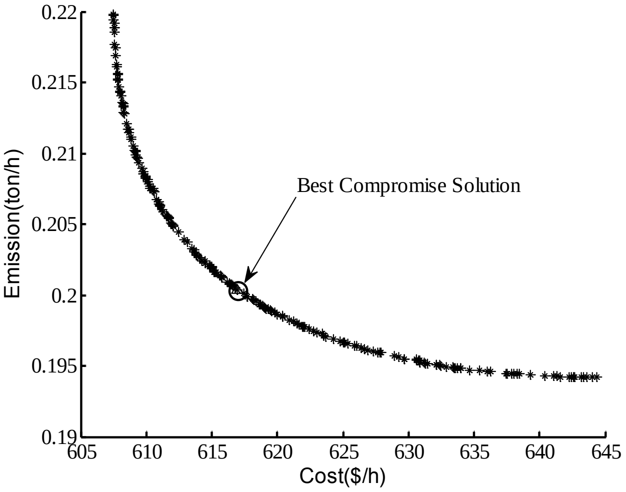

Fig. 4. Pareto front using MOPSO without wind farm

The distribution of the non-dominated solutions in Pareto optimal front using the proposed MOPSO is shown in fig. 4. In this figure the best compromise solution is also shown.

Table 4 . Best compromise solutions without wind farm

	NPGA	SPEA	MOPSO
cost [$/h]	630.06	629.59	616.95
Emission[ton/h]	0.2079	0.2079	0.2004
Pg1 [pu]	0.2998	0.3052	0.2483
Pg2 [pu]	0.4325	0.4389	0.3841
Pg3 [pu]	0.7342	0.7163	0.5776
Pg4 [pu]	0.6852	0.6978	0.6747
Pg5 [pu]	0.1560	0.1552	0.5375
Pg6 [pu]	0.5561	0.5507	0.4403

6.2.2 With wind farm

In this study, the wind farms comprising ten wind generators is connected in bus 24 of the IEEE 30 bus system . The convergence of fuel cost and emissions are depicted in fig. 5.The results of simulation are given in table 4.

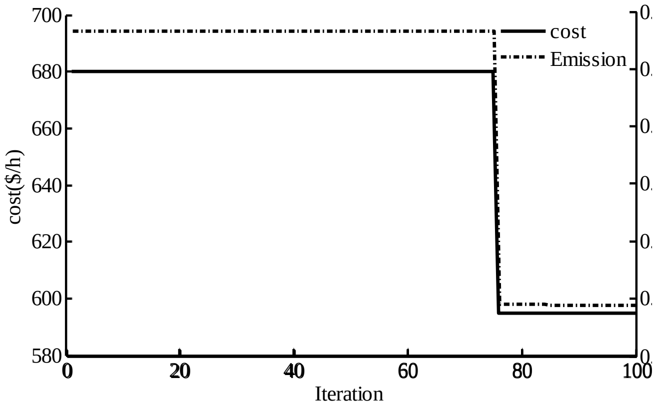

Fig. 5. Convergence of cost and emission objective functions without wind form

Table 4. The best solution with wind farm of MOPSO

	Best cost	Best Emission
cost [$/h]	594.6563	630.2102
Emission [ton/h]	0.2203	0.1945
Pg1 [pu]	0.1009	0.3951
Pg2 [pu]	0.2963	0.4431
Pg3 [pu]	0.7140	0.5914
Pg4 [pu]	0.9318	0.3642
Pg5 [pu]	0.4335	0.5226
Pg6 [pu]	0.3224	0.4828

Table 5 gives the best compromise solution that has the maximum value of membership function can be extracted. The best compromise solution is also shown in fig. 6.

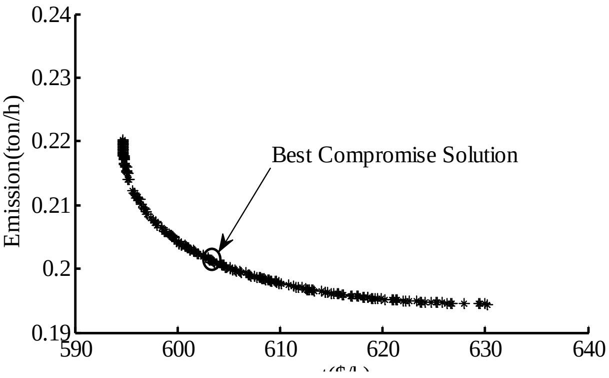

Fig. 6. Pareto front using MOPSO with wind farm

Fig. 6 shows the distribution of the non-dominated solutions in Pareto optimal front using the proposed MOPSO.

Table 5. Best compromise solutions with wind farm of MOPSO

Cost[$/h]	603.0989
Emission[ton/h]	0.2014
Pg1 [pu]	0.2459
Pg2 [pu]	0.3551
Pg3 [pu]	0.6582
Pg4 [pu]	0.6451
Pg5 [pu]	0.5072
Pg6 [pu]	0.3851

7 CONCLUSION

This paper presents the mathematical model of wind generator and the modified Newton-Raphson algorithm for power system including SR_FSWG. In addition, this paper presents an approach to solve the economic/environmental dispatch of electric energy power including wind farms. The problem has been formulated as multiobjective optimization problem with competing fuel cost and environmental impact objectives. We have used the MOPSO approach to solve the MOP.

The efficiency of the proposed MOPSO algorithm to solve multi-objective EED problem are verified by means of the IEEE-30-bus 6-generators. The comparable studied that of the recent represented algorithms show the effectiveness of the proposed MOPSO technique.

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