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Economic Dispatch for Power System included Wind and Solar Thermal energy

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Abstract

With the fast development of technologies of alternative energy, the electric power network can be composed of several renewable energy resources. The energy resources have various characteristics in terms of operational costs and reliability. In this study, the problem is the Economic Environmental Dispatching (EED) of hybrid power system including wind and solar thermal energies. Renewable energy resources depend on the data of the climate such as the wind speed for wind energy, solar radiation and the temperature for solar thermal energy. In this article it proposes a methodology to solve this problem. The resolution takes account of the fuel costs and reducing of the emissions of the polluting gases. The resolution is done by the Strength Pareto Evolutionary Algorithm (SPEA) method and the simulations have been made on an IEEE network test (30 nodes, 8 machines and 41 lines).

Keywords

economic dispatch, total cost, active losses, multi objectives optimization, evolutionary algorithms, SPEA, renewable energy

Introduction

The economic and environmental problems in the power generation have received considerable attention. The apparition of the energy crisis and the excessive increase of the consumption have obliged production companies to implant renewable sources. However, this production poses many technical problems for their integration in the electric system.

The economic dispatch [8, 16] is a significant function in the modern energy system. It consists in programming correctly the electric production in order to reduce the operational cost [4, 7, 10, 15]. Recently, the wind power and solar thermal power attracted much attention like promising renewable energy resources [1, 6, 11, 18, 19, 22].

The problem is formulated as a multiobjective optimization problem [3, 5, 9, 24, 25]. It consists in distributing the active and renewable productions between the power stations of the most economic way, to reduce the emissions of the polluting gases and to maintain the stability of the network after penetration of renewable energy. The number of decision variables of the problem is related to all the nodes of the network.

Renewable energy

In this study, it is interested in two types of energies; wind power and thermal solar energy.

Wind energy

The mechanical power recovered by a wind turbine can be written in the form [6, 17, 23]:

$$P_W = \frac{1}{2} C_P . \rho . \pi . R_P^2 . V_W^3 \tag{1}$$

where C_P, is the aerodynamic coefficient of turbine power (it characterizes the aptitude of the aerogenerator to collect wind power), ρ is the air density, R_p the turbine ray and V_W wind speed. The power coefficient value C_P, depends on the rotation speed of turbine and wind speed.

Mechanical adjustment of the wind power

Wind turbine is dimensioned to develop a nominal power P_n from a nominal wind speed V_n. For wind speeds higher than V_n, the wind mill must modify these aerodynamic parameters in order to avoid the mechanical overloads, so that the power recovered by the turbine does not exceed the nominal power for which the wind mill was designed.

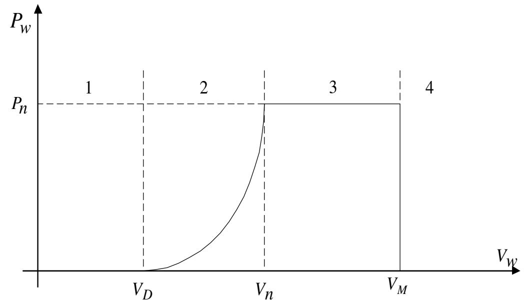

Figure 1. *Diagram of the useful power according to the wind speed.*

According to the figure1, the characteristic of power according to the wind speed comprises four zones. Zone 1, where $P_w = 0$, zone 2, in which useful power depends on wind speed. V_w, zone 3, generally where provided power P_w remains appreciably equal to P_n and finally zone 4,$P_w = 0$

Solar energy

Solar energy is energy produced by the solar radiation, directly or in a diffuse way through the atmosphere. Thanks to various processes, it can be transformed into another form of useful energy for the human activity, in particular in electricity or heat [14, 17, 23].

The maximum power provided by a solar panel is given by the following characteristic [14, 17]:

$$P_S = P_1.E_c.[1 + P_2.(T_j - T_{jref})] \quad (2)$$

E_c is solar radiation, T_{jref} is the reference temperature of the panels of 25°C, T_j is the cells junction temperature (°C), P_1 represent the characteristic dispersion of the panels and the value for one panel is included enters 0.095 to 0.105 and the parameter P_2=-0.47%/C°; is the drift in panels temperature [14].

The addition of one parameter P_3 to the characteristic, gives more satisfactory results:

$$P_S = P_1.[1 + P_2.(T_j - T_{jref})].(P_3 + E_c) \quad (3)$$

This simplified model makes it possible to determine the maximum power provided by a group of panels for solar radiation and panel temperature given, with only three constant parameters P_1, P_2 and P_3 and simple equation to apply.

A thermal solar power station consists of a production of solar system of heat which feeds from the turbines in a thermal cycle of electricity production.

Formulation of problem

The control system problem can be treated as follows:

Of absence of the auxiliary elements, the problem consists in extracting the maximum of power from the renewable sources. Then, we slice this power of the total demand P_D. the remaining total demand $P_D^{'} = P_D - (P_S + P_W)$, will distributed between the thermal power stations. The problem is reduced for a speed wind V_w and solar radiation E_c given to minimize the thermal cost functions and the emissions of polluting gases.

To approach to the reality, it is obvious that to must take account of the variation of the wind and solar radiation that can be done by using the techniques of the neurons networks which consists in forming a data base for various wind speed V_w, solar radiation E_c and total power demand P_D. The neurons network is composed of three layers, the entries layer is formed by V_w, E_c et P_D; the hidden internal layer which the number of neurons is variable and the exit layer which consists of 10 neurons which represent the minimal cost F_1, the emissions of polluting gases F_2, the generating nodes powers . The structure of this network is given by the figure (2).

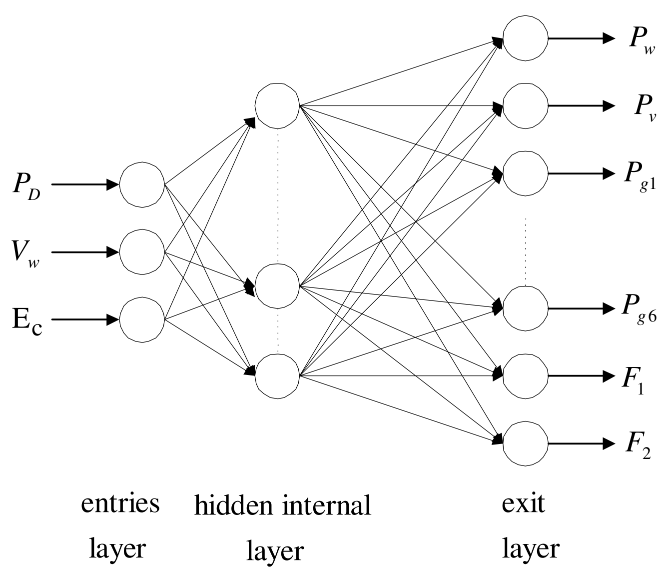

***Figure 2.** Structure du réseau de neurones utilisé*

Objective functions

Fuel cost function

The fuel cost function $F_{TH}(\underline{P}_g)$ in \$/h is represented by a quadratic function as follow [2, 5, 19]:

$$F_{TH}\left(\underline{P}_g\right)=\sum_{i=1}^{N_g} a_i + b_i P_{gi} + c_i P_{gi}^2 \qquad (4)$$

The coefficients a_i, b_i and c_i are appropriate to every production unit, P_{gi} is the real power output of *i-th* generator and N_g is the number of thermal generators.

Emission fonction

The atmospheric emission can be represented by a function that links emissions with the power generated by every unit. The emission of SO_2 depends on fuel consumption and has the same form as the fuel cost [8, 13].

The emission of NOx is difficult to predict and his production is associated to many factors as the temperature of the boiler and content of the air [12].

The emission function in *ton/h* which represents SO2 and NOx emission is a function of generator output and is expressed as follow [20]:

$$F_2\left(\underline{P}_g\right) = \sum_{i=1}^{N_g} \alpha_i + \beta_i P_{gi} + \gamma_i P_{gi}^2 + \xi_i \exp\left(\lambda_i P_{gi}\right) \qquad (5)$$

Where α_i, β_i and γ_i are the coefficients of emission function corresponding to the *i-th* generator. These three parameters are determined by adjustment techniques of curves based on reel tests [13].

Problem constraints

The problem constraints are five types:

- ***Production capacity constraints***

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

$$P_{gi}^{min} \le P_{gi} \le P_{gi}^{max}, \ i = 1,\ldots,N_g \qquad (6)$$

- ***Power balance constraint***

The total power generation and the wind power must cover the total demand $P_D^{'}$ and the power loss p in transmission lines, so we have:

$$P_D^{'} + p - \sum_{i=1}^{Ng} P_{gi} = 0 \quad (7)$$

- *Active power loss constraint*

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

$$p > 0 \quad (8)$$

- *Renewable power constraint*:

The renewable power used for dispatch should not exceed the 30% of total power demand:

$$P_W + P_S \le 0.3 P_D \quad (9)$$

Thus, the problem to be solved is formulated as follow:

- **Minimize:** $(F_{TH}(\underline{P}_g), F_2(\underline{P}_g))$

Under:

$$P_{gi}^{min} \le P_{gi} \le P_{gi}^{max}, \ i = 1,...,N_g$$
$$P_D^{'} + p - \sum_{i=1}^{Ng} P_{gi} = 0$$
$$p > 0$$
$$P_W + P_S \le 0.3 P_D$$

Multi objectives Optimization

Principle

The multi-objective optimization problem is formulated in general as follow:

$$\begin{cases} \text{Minimize } f(x) = \left(f_1(x), f_2(x), ..., f_{N_{obj}}(x) \right) \\ \text{Under :} \\ g_j(x) = 0 \quad , \quad j = 1,...,M \\ h_k(x) \le 0 \quad , \quad k = 1,...,K \end{cases} \quad (10)$$

with:

N_{obj} : number of objectives functions

M, K : number of equality and inequality respectively constraints

x : decision vector.

Two solutions x_1 and x_2 of such optimization problem, we could have one which dominates the other or none dominates the other.

In a minimization problem, a solution x_1 dominates other solution x_2 if the following two conditions are satisfied:

$$\begin{cases} \forall i \in \{1,2,...,N_{obj}\}, & f_i(x_1) \leq f_i(x_2) \\ \exists j \in \{1,2,...,N_{obj}\}, & f_j(x_1) \pi f_j(x_2) \end{cases} \quad (11)$$

Define by X_f the satisfiesability set, that is to say: $X_f = \{x \in X / \underline{g}(x) = 0 \text{ et } \underline{h}(x) \leq 0\}$

where

$\underline{g}(x) = (g_1(x), g_2(x), ..., g_M(x))^T$ and $\underline{h}(x) = (h_1(x), h_2(x), ..., h_K(x))^T$

A decision vector $x \in X_f$ is none dominated compared to a set $A \subset X_f$, if:

$$\nexists a \in A / a < x \quad (12)$$

The optimize solutions set that are non-dominated within the entire search space are denoted as Pareto-optimal and the set of objectives vectors corresponding constitute the Pareto-optimal set or Pareto-optimal front.

SPEA approach (Strength Pareto Evolutionary Algorithm)

In [18], Zitzler and Thiele propose an elitist evolutionary approach to solve a multi objective problem which is called Strength Pareto Evolutionary Algorithm (SPEA). The Elitism is introduced by an external Pareto set. This set stores the non-dominated solutions funded during the resolution of the problem. In order to reduce the size of the external set, an average linkage based on hierarchical clustering algorithm is used without destroying the characteristics of the trade-off front.

Noting by:

P *:* the current population.

P_t : the external population.

N_{pop} : the size of current population.

F_i the fitness of an individual *i*.

S_i the strength of an individual *i*.

The assignment procedure to calculate the fitness values is the following:

- **Step 1**: For each individual $i \in P_t$ is assigned a reel value $S_i \in [0, 1)$ called strength. S_i is proportional to the number of individuals in the current population dominated by the individual *i* in the external Pareto set. It can be calculated as follows:

For an individual $j \in P_t$

$$S_i = \frac{\left|\{j / j \in P_t \text{ and individual } j \text{ is dominated by } i\}\right|}{N_{pop} + 1} \tag{13}$$

The strength of a Pareto solution is also its fitness: $F_i = S_i$.

- **Step 2**: The fitness of an individual $j \in P_t$ is the sum of the strengths of all external Pareto individuals $i \in P_t$ dominated by $j \in P_t$. We add one in odder to guarantee that Pareto solutions are most likely to be produced.

$$F_j = 1 + \sum_{i \in \bar{P}t,\, i \text{ dominate } j} S_i \tag{14}$$

where $F_j \in [1, N_{pop})$

The clustering algorithm is described by the following steps:

- **Step 1**: To initialise clustering set *C*; each individual $i \in P_t$ constitutes a distinct cluster:

$$C = \bigcup_{i \in \bar{P}_t} \left\{ \{i\} \right\}. \tag{15}$$

- **Step 2**: if the number of cluster is lower or equal to maximum size of external set (N_{pop}), go to step 5. Else, go to step 3.
- **Step 3**: Calculate the distance between each pair of clusters. The distance d_c between two clusters c_1 and $c_2 \in C$ is defined as the average distance between two pairs of individuals from each cluster:

$$d_c = \frac{1}{n_1 n_2} \sum_{i_1 \in c_1,\, i_2 \in c_2} d_{i_1 i_2} \tag{16}$$

n_1 and n_2 are respectively the numbers of individuals in clusters c_1 and c_2 .

- **Step 4**: Find the pair of clusters corresponding to the minimal distance d_c between them. Combine into a large one $C = \{c_1 \bigcup c_2\}$. and return to step 2.
- **Step 5**: Find the centroid of each cluster. Select the nearest individual in this cluster to the centroid as a representative individual and remove all other individuals from the cluster.
- **Step 6:** Thus, the reduced Pareto set P_{t+1} is computed by uniting these representatives: $P_{t+1} = \bigcup_{c \in C} c$.

Numeric Simulations and Comments

Presentation of the test network

The structure of the test system is shown in fig.1.Appendix A1. It was derived from the standard IEEE 30-bus 6-generator test system while adding to him two renewable generators. The characteristics of the wind mill are presented in table 1. The values of the fuel and emission coefficients are given in table2. The lines data and bus data are given respectively in tables 1 and 2 in Appendix A1.

Table 1. Wind mill Data

Characteristics of the wind mill				
propeller Diameter	blades number	Surface swept	chechmate Height	Nominal wind speed V_n
34 m	3	1480 m^2	45 m	15 m/s
Nominal characteristics of the asynchronous generator				
Interlinked voltage	Current	Frequency	power P_n	Cos φ
660 V	760 A	50 Hz	790 Kw	0.91
R_s	R_r	L_σ	X_m	R_m
0.00374 Ω	0.00324 Ω	0.23 mH	5.8 mH	83.85 Ω

Table 2: Generator cost and emission coefficients

		G1	G2	G3	G4	G5	G6
Cost	a	10	10	20	10	20	10
	b	200	150	180	100	180	150
	c	100	120	40	60	40	100
Emission	α	4.091	2.543	4.258	5.326	4.258	6.131
	β	-5.554	-6.047	-5.094	-3.550	-5.094	-5.555
	γ	6.490	5.638	4.586	3.380	4.586	5.151
	ξ	$2.0\ 10^{-4}$	$5.0\ 10^{-4}$	$1.0\ 10^{-6}$	$2.0\ 10^{-3}$	$1.0\ 10^{-6}$	$1.0\ 10^{-5}$
	λ	2.857	3.333	8	2	8	6.667

Lower limit and upper limit of the generated real power of each generator at the bus it is shown by (17):

$$0.05 \le P_{gi} \le 1.5,\ i = 1,...,N_g \tag{17}$$

Results and Comments

Implementation and test of the neurons network

The neurons network is used to calculate in real time the active production in the thermal generating nodes and of the renewable origins. The structure of this network is given by the figure (2).

To ensure a good training of the neurons network, the base data is formed by 600 random solutions calculated by method SPEA and corresponding at a wind speed included enters 8 and 12 ms^{-1}, solar radiation vary between $0w/m^2$ and $1000w/m^2$ and the total power demand vary between 0.8 and 4 pu.

Training curves of wind speed, solar radiation and the total power demand are given by figures (3, 4 and 5).

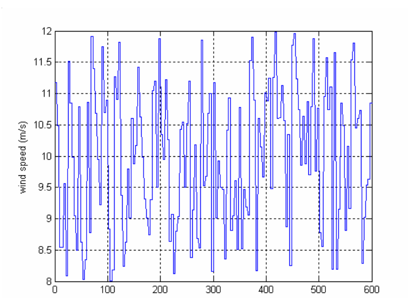

Figure 3. *Training curve of wind speed*

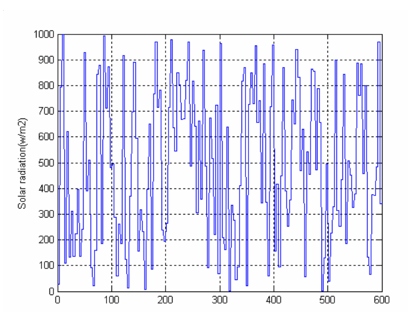

Figure 4. *Training curve of solar radiation*

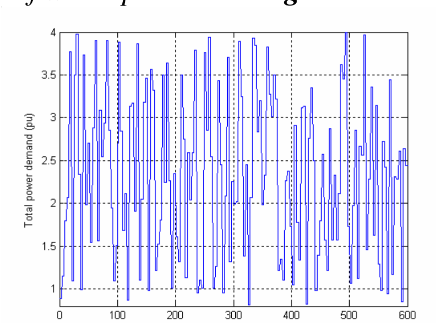

Figure 5. *Training curve of total power demand*

During this phase, some of new examples are presented to the neurons network. The same examples were already simulated by SPEA method and we studied the quality of these answers given to table 3.

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Table 3. Results of test neurons network

		Test exemple									
		P_w (pu)	P_s (pu)	P_{g1} (pu)	P_{g2} (pu)	P_{g3} (pu)	P_{g4} (pu)	P_{g5} (pu)	P_{g6} (pu)	Emiss (ton/h)	Coût ($/h)
P_{D1}	2.35	0.6156	0.0475	0.3242	0.4352	0.4363	0.2052	0.3871	0.3795	0.1934	499.5495
P_{D2}	3.43	0.7059	0.0175	0.4095	0.5220	0.5516	0.3635	0.5071	0.4846	0.1866	643.0993
P_{D3}	3.35	0.8423	0.0385	0.3708	0.4870	0.5054	0.3575	0.4714	0.4605	0.1874	598.0519
P_{D4}	1.16	0.3039	0.0252	0.3051	0.4284	0.4116	0.0939	0.3786	0.3598	0.1973	468.1725
P_{D5}	0.93	0.2315	0.0412	0.3204	0.4743	0.4537	0.1231	0.3774	0.3504	0.1950	500.7442
P_{D6}	1.25	0.3392	0.0301	0.3107	0.4249	0.4091	0.1017	0.3630	0.3410	0.1977	461.6945
P_{D7}	2.65	0.4445	0.0266	0.3786	0.4834	0.5146	0.2245	0.4519	0.4197	0.1901	569.3929
P_{D8}	3.10	0.5576	0.0388	0.4071	0.5251	0.5541	0.3173	0.5067	0.4879	0.1871	638.1037
		Response of neurons network									
		P_w (pu)	P_s (pu)	P_{g1} (pu)	P_{g2} (pu)	P_{g3} (pu)	P_{g4} (pu)	P_{g5} (pu)	P_{g6} (pu)	Emiss (ton/h)	Coût ($/h)
P_{D1}	2.35	0.6156	0.0475	0.3202	0.4351	0.4317	0.2163	0.3874	0.3767	0.1932	499.6342
P_{D2}	3.43	0.7059	0.0175	0.4105	0.5289	0.5448	0.3633	0.5111	0.4931	0.1864	643.0030
P_{D3}	3.35	0.8423	0.0385	0.3711	0.4872	0.5114	0.3614	0.4711	0.4611	0.1872	598.8744
P_{D4}	1.16	0.3039	0.0252	0.3054	0.4126	0.4144	0.1013	0.3814	0.3437	0.1995	466.2881
P_{D5}	0.93	0.2315	0.0412	0.3199	0.4759	0.4538	0.1001	0.3633	0.3543	0.1951	501.1572
P_{D6}	1.25	0.3392	0.0301	0.3106	0.4276	0.4097	0.1081	0.3665	0.3403	0.1972	463.4970
P_{D7}	2.65	0.4445	0.0266	0.3652	0.4882	0.5168	0.2244	0.4543	0.4282	0.1901	569.3759
P_{D8}	3.10	0.5576	0.0388	0.4019	0.5132	0.5537	0.3083	0.4982	0.4800	0.1875	637.9193

Figures (6, 7 and 8) present respectively the forecasts of wind speed, solar radiation and total power demand.

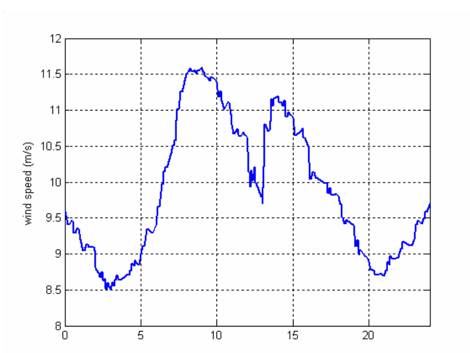

***Figure 6**. Forecast of wind speed*

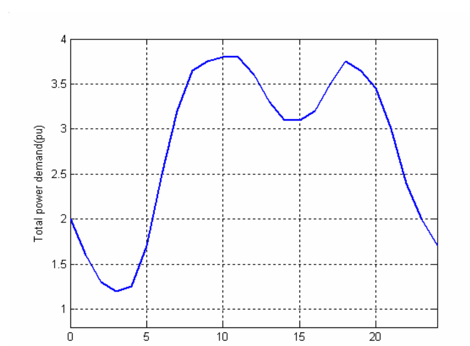

***Figure 7.** Forecast of total power demand*

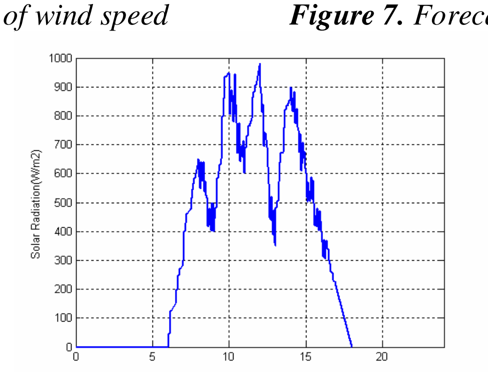

***Figure 8.**Forecast of solar radiation*

After the training phase of the neurons network, the simulation results are presented in the figures 9, 10, 11 and 12.

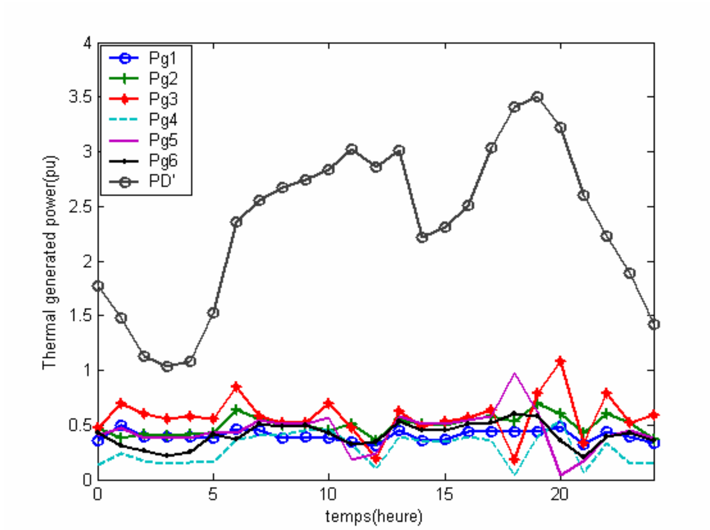

***Figure 9.** Power of the thermal generated nodes and P_D'*

According to figure 9, we notice that the bus thermal generators powers remain variable within their limits.

Bus generator 2 has a remarkable participate by its active power P_{g2} when total power demands $P'_D$is significant because it is the machine which has the more high cost.

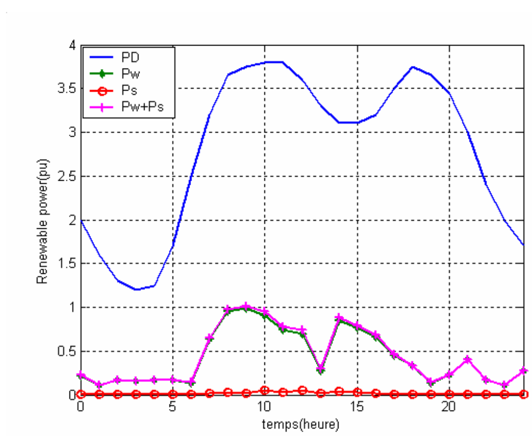

***Figure 10.**Total power demand and renewable power*

Figure 10; show the variation of solar thermal power, wind power and their resultant which remains lower than 30%of the total power demand P_D.

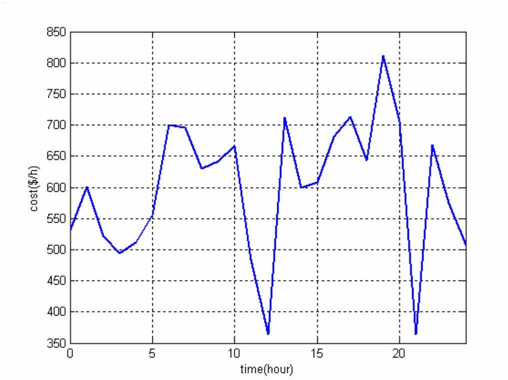

Figure 11. *Total cost function*

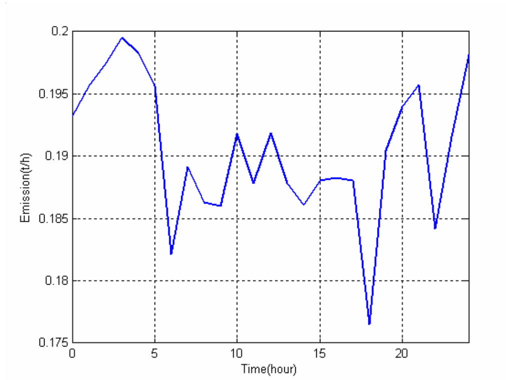

Figure 12. *Emissions function*

Figures 11 and 12 who represent respectively the variations of the total cost function and emissions of polluting gases function show that if the emissions of polluting gases decrease in the course of time then the total cost increases and conversely.

Conclusion

In this study we presented a method allowing the resolution of the problem of the Environmental Economic Dispatching of an electrical network including renewable energy sources. We made an optimization without auxiliary elements and the problem consists to extract the maximum of power from the renewable sources and to distribute the remainder of the power on the power stations. To have the solutions of the problem in real time we established them on a neurons network.

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Appendix

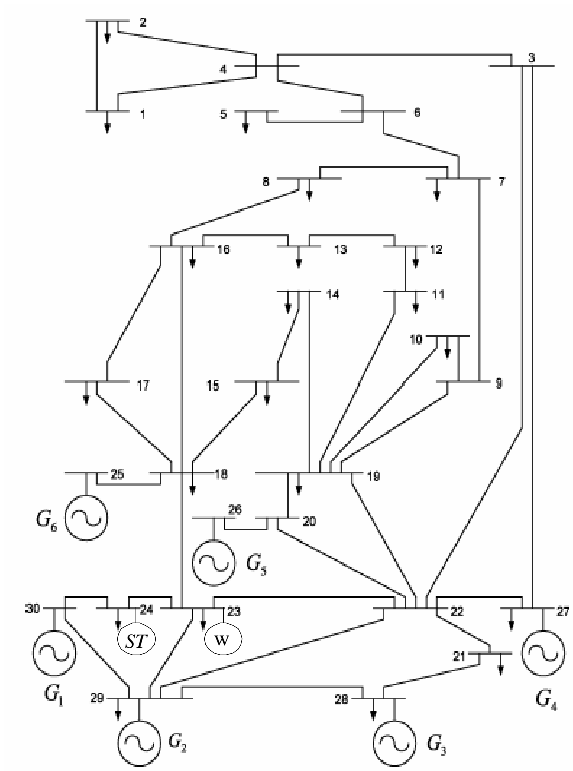

Figure 1. *Single-line diagram of IEEE 30-bus test system with two renewable power stations*

Table 1. Line data

Line N°	Connection	Impedance (p.u.)	Line N°	Connection	Impedance (p.u.)
1	30-29	0.0192 + j0.0575	22	13-12	0.0192 + j0.0575
2	30-24	0.0452 + j0.1852	23	12-11	0.0452 + j0.1852
3	29-23	0.0570 + j0.1737	24	19-11	0.0570 + j0.1737
4	24-23	0.0132 + j0.0379	25	19-14	0.0132 + j0.0379
5	29-28	0.0472 + j0.1983	26	19-10	0.0348 + j0.0749

6	29-22	0.0581 + j0.1763	27	19-9	0.0727 + j0.1499
7	23-22	0.0119 + j0.0414	28	10-9	0.0116 + j0.0236
8	28-21	0.0460 + j0.1160	29	16-8	0.1000 + j0.2020
9	22-21	0.0267 + j0.0820	30	9-7	0.1150 + j0.1790
10	22-27	0.0120 + j0.0420	31	8-7	0.1320 + j0.2700
11	22-20	j0.2080	32	7-6	0.1885 + j0.3292
12	22-19	j0.5560	33	6-5	0.2544 + j0.3800
13	20-26	j0.2080	34	6-4	0.1093 + j0.2087
14	23-18	j0.2560	35	3-4	j0.3960
15	18-25	j0.1400	36	4-2	0.2198 + j0.4153
16	18-17	0.1231 + j0.2559	37	4-1	0.3202 + j0.6027
17	18-16	0.0662 + j0.1304	38	2-1	0.2339 + j0.4533
18	18-15	0.0945 + j0.1987	39	27-3	0.0636 + j0.2000
19	17-16	0.2210 + j0.1997	40	22-3	0.0169 + j0.0599
20	15-14	0.0824 + j0.1923	41	20-19	j0.1100
21	16-13	0.1070 + j0.2185			

Table 2. Bus data

Line N°	**Type**	**Active power (p.u)**	**Reactive power (p.u)**	**Bus voltage (p.u)**	**Line N°**	**Type**	**Active power (p.u)**	**Reactive power (p.u)**	**Bus voltage (p.u)**
1	P-Q	0.106	0.019	—	16	P-Q	0.082	0.025	—
2	P-Q	0.024	0.009	—	17	P-Q	0.062	0.016	—
3	P-Q	0.000	0.000	—	18	P-Q	0.112	0.075	—
4	P-Q	0.000	0.023	—	19	P-Q	0.058	0.020	—
5	P-Q	0.035	0.000	—	20	P-Q	0.000	0.000	—
6	P-Q	0.000	0.000	—	21	P-Q	0.228	0.109	—
7	P-Q	0.087	0.067	—	22	P-Q	0.000	0.000	—
8	P-Q	0.032	0.016	—	23	P-Q	0.076	0.000	1.010
9	P-Q	0.000	0.000	—	24	P-Q	0.024	0.000	1.010
10	P-Q	0.175	0.112	—	25	P-V	0.000	0.000	1.071
11	P-Q	0.022	0.007	—	26	P-V	0.000	0.000	1.082
12	P-Q	0.095	0.034	—	27	P-V	0.300	—	1.010
13	P-Q	0.032	0.009	—	28	P-V	0.942	—	1.010
14	P-Q	0.090	0.058	—	29	P-V	0.217	—	1.045
15	P-Q	0.035	0.018	—	30	Bilan	0.000	0.000	1.060