Security and Stochastic Economic Dispatch of Power System Including Wind and Solar Resources with Environmental Consideration

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Abstract-With increasing concern of environmental protection, renewable energy sources are widely applied as a mean to reach emission reduction. In this paper, Dynamic Economic Emission Dispatch (DEED) model with security constraints is developed for a system incorporating wind, photovoltaic and non-convex thermal units. Weighted aggregation method is used to enable particle swarm optimization (PSO) to solve environmental/economic multiobjective (MO) problem. The optimization is aimed at minimizing the cost function and emissions of the system while satisfying all operational constraints considering both conventional and renewable energy generators. The model takes into account cost of modern thermal units with multiple valves and penalty costs due to mismatch between the actual and scheduled wind and PV power outputs. The costs include weighted cost depends on the stochastic nature of wind speed and solar irradiance. Moreover, the Newton Rapson optimal power flow is applied in order to maintain transmission line constraints without violation and calculate the total transmission losses depending on the square power flow. With the stochastic wind speed and solar irradiance based on weibull probability density function (pdf), the optimization problem is numerically solved for a scenario involving three conventional, two wind farms and two PV power plants. The simulation results show the feasibility and effectiveness of the proposed model.

Keywords-Dynamic economic emission dispatch; optimal power flow; Newton Raphson.

1. Introduction

Power systems should be operated under a high degree of economy for competition of deregulation. Additionally, the rising consciousness of environmental protection has forced power utilities to remedy their operational strategies to reduce pollution and atmospheric emissions of the thermal power plants [1]. Since generation dispatch is the fundamental issue during operational process, it should be an attractive concern to take both emission and operating cost into consideration. The dynamic economic and emission dispatch is an extension of the conventional economic dispatch problem [2-3]. It is used to determine the optimal generation schedule of on-line generators, so as to meet the predicted load demands without violating generator and security constraints over a certain period of time so as to operate the power system most economically and simultaneously reducing the emission level. Meanwhile, with the rapid development of renewable energy, wind and photovoltaic power generations (WPGs & PVs) have taken great penetration in the power systems to overcome the carbon emission of fossil-fuel type generators such as thermal units regardless of their higher electrical energy cost[4-6]. Unlike the conventional thermal units, wind and PV power generators have intermittent nature which results in a new challenge to the economical operation problems. One of the major difficulties in optimizing the operation problem is the uncertainty associated with weather profiles. Unpredicted weather variations cause fluctuations in the wind and solar power outputs. Such fluctuations can cause operational challenges to maintain the generation-load balance. In addition the system loads are also varying; thus even economic dispatch algorithms must rely on unconventional, stochastic optimization techniques [7-9]. In this paper, the weighted sum Particle Swarm Optimization technique is projected to address multiobjective economic dispatch with emission minimization (EED) problem by generating sets of the Pareto optimal solutions. These solutions provide many alternate dispatch options for reducing conflicting objectives like cost and emission. Different weights are assigned to the various objectives in accordance to their importance .Thus the different objectives are combined in to a single objective function. The main objective is to serve the load demand and satisfy equality and inequality constraints so that the total operating cost and total fuel combustion emission are minimized, simultaneously. In the conventional methods, the input-output characteristic of thermal generators is usually approximated by quadratic functions or piecewise quadratic functions, which are unfortunately far from the reality of a modern plant [1]. The input-output curves of modern generators are highly nonlinear due to the presence of valve point effect and ramp rate limits [10]. Moreover, the Newton Rapson optimal power flow is applied in order to maintain transmission line constraints without violation and calculate the total transmission losses [11]. To develop a complete model of the DEED problem, it is necessary to characterize the stochastic nature of the wind speed and solar irradiance in order to analyze the problem with numerical results. Therefore, the weibull probability density function (pdf) is utilized to represent their stochastic nature.

2. Wind Energy Stochastic Model

The wind speed distribution for selected sites as well as the power output characteristic of the chosen wind turbine is the factors that have to be considered to determine the WPG output. It is assumed that the wind speed profile ' v ' at a given location most closely follows a weibull distribution over time with a scale parameter ‘c’ and a shape parameter k [12]. The probability density function (pdf), $f_v(v)$, for a weibull distribution is given in [13] as:

$$f_v(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{(k-1)} e^{-(v/c)^k} \tag{1}$$

There are several methods used to calculate the weibull factors [14], [15]. In this paper, the factors k and c are calculated approximately using the mean wind speed v_m and the standard deviation σ as follows

$$k = \left(\frac{\sigma}{v_m}\right)^{-1.086} \tag{2}$$

$$c = \frac{v_m}{\Gamma\left(1+{}^{1}/_{k}\right)} \tag{3}$$

The output power of a wind turbine is dependent on the wind speed at the site as well as the parameters of the power performance curve. Therefore, once the Weibullpdf is generated for a specific time segment, the output power during the different states is calculated for this segment using the following equation

.

$$w = \begin{cases} 0 & 0 \le v \le v_i \\ w_r * \frac{(v-v_i)}{(v_r-v_i)} & v_i \le v \le v_r \\ w_r & v_r \le v \le v_o \\ & g \\ 0 & v_o \le v \end{cases} \tag{4}$$

The probability density function, $f_w(w)$, for the power output of the wind turbine can be obtained using Eqs. (1) and (4) by the application of the transformation theorem [13]

$$f_w(w) = \begin{cases} \left(\frac{klv_i}{c}\right)\left(\frac{(1+\rho l)v_i}{c}\right)^{k-1} \exp\left(-\left(\frac{(1+\rho l)v_i}{c}\right)^k\right) \; for\ 0 < w < w_r \\ 1 \\ 1 \\ 1-\exp\left[-\left(\frac{v_i}{c}\right)^k\right] + \exp\left[-\left(\frac{v_o}{c}\right)^k\right] w = 0 \\ 1 \\ 1 \\ 1 \\ \exp\left[-\left(\frac{v_r}{c}\right)^k\right] - \exp\left[-\left(\frac{v_o}{c}\right)^k\right] w = w_r \end{cases} \tag{5}$$

where $\rho = \frac{w}{w_r}$ and $l = \frac{v_r - v_i}{v_i}$, v_r is rated wind speed, w_r is rated wind power, v_i and v_o are the cut in and cut out speeds, respectively.

3. PV Stochastic Model

The amount of solar radiation that reaches the ground, besides the daily and yearly apparent motion of the sun depends on the geographical location (latitude and altitude) and on the climatic conditions (e.g., cloud cover). To account for the difference betweenthe values of solar radiation measured outside the atmosphere and on earthly surface an hourly clearness index, k_t,has been defined as the ratio of the irradiance on a horizontal plane, I_t [kW/m^2], to the extraterrestrial total solar irradiance I_o [kW/m^2], i.e.

$$k_t = \frac{I_t}{I_0} \tag{6}$$

In this work, the clearness index pdf [16] shown in (7), is utilized to model the hourly solar irradiance.

$$f_{kt}(k_t) = c'(1 - k_t/k_{tmax})exp(\lambda k_t) \tag{7}$$

Where $c'$and λ are functions of the maximum value of clearness index, k_{tmax}, and the mean value of clearness index,k_{tm}, as follows [17]:

$$c' = \frac{\lambda^2 k_{tmax}}{((\exp(\lambda k_{tmax}))-1-\lambda k_{tmax})} \tag{8}$$

$$\lambda = \frac{(2\gamma - 17.519\exp(-1.3118\gamma) - 1062\exp(-5.0426\gamma))}{k_{tmax}} \tag{9}$$

$$\gamma = \frac{k_{tmax}}{k_{tmax} - k_{tm}} \tag{10}$$

Therefore, once λ is determined from (9) for a specific value of k_{tmax}, the corresponding value of c' can be determined from (8). From the hourly clearness index, the solar irradiance on a surface with inclination β can be calculated as in (11):

$$I_\beta = \left[R_b + \left(\frac{1+cos\beta}{2} - R_b\right).k + \rho_r.\frac{1-cos\beta}{2}\right].I_t \tag{11}$$

where

R_b : ratio of beam radiation on a tilted surface to that on a horizontal surface;

k: fraction of the hourly radiation on horizontal plan which is diffused;

ρ: reflectance of the ground.

Regarding R_b, it is calculated as in [12]. The diffuse fraction (k), the correlation between it, and the clearness index can be approximated with a piecewise linear function as follows [15]

$$k = p - qk_t \tag{12}$$

Further, I_t can be expressed as a function of H_o, $r_d$and k_t as follows:

$$I_t = \frac{H_o}{3600} r_d k_t \tag{13}$$

Where, r_d and H_o are the ratio, diffuse radiation in hour/diffuse in day and extra-terrestrial radiation on a horizontal surface (MJ m_2) respectively. Substituting (6) and (13) in (12), the final formula of I_β as a function of clearness index assumes the following:

$$I_\beta = \left[\left(R_b + \rho.\frac{1-cos\beta}{2}\right) + \left(\frac{1+cos\beta}{2} - R_b\right).p\right].r_d.\frac{H_0}{3600}k_t - \left(\frac{1+cos\beta}{2} - R_b\right).q.r_d.\frac{H_0}{3600} \tag{14}$$

$$I_\beta = Tk_t - T'k_t^2 \tag{15}$$

where,

$$T = \left[\left(R_b + \rho.\frac{1-cos\beta}{2}\right) + \left(\frac{1+cos\beta}{2} - R_b\right).p\right].r_d.\frac{H_0}{3600} \tag{16}$$

$$T' = \left(\frac{1+cos\beta}{2} - R_b\right).q.r_d.\frac{H_0}{3600} \tag{17}$$

The output power of the PV module is dependent on the solar irradiance and ambient temperature of the site as well as the characteristics of the module itself. Therefore, once the clearness index pdf is generated for a specific time segment, the output power during the different states is calculated according to the following:

$$T_c = T_A + I_\beta\left(\frac{N_{OT}-20}{0.8}\right) \tag{18}$$

$$I = I_\beta[I_{SC} + K_i(T_c - 25)] \tag{19}$$

$$V = V_{OC} - K_V * T_c \tag{20}$$

$$pv = N * FF * V * I \tag{21}$$

$$FF = \frac{V_{MPP} * I_{MPP}}{V_{OC} * I_{SC}} \tag{22}$$

FF is the fill factor. T_c is the cell temperature in ^{o}C. T_A *is* the ambient temperature in ^{o}C. N_{OT} is normal operating cell temperature in ^{o}C. I is the cell current. V is the cell voltage in V. I_{sc} is the short circuit current in A. K_i *is the* current temperature coefficient (A/^{o}C). K_V is the voltage temperature coefficient (V/^{o}C). V_{oc} is the open circuit voltage in V and N is the number of cells.V_{MPP} and I_{MPP} are the voltage and the current at maximum power point in V and I, respectively. pv is the output power of the PV module.

If the probability density function $f_{kt}(k_t)$ for the random variable k_t is known, it is possible to obtain its value for pv, $f_{pv}(pv)$, by applying the fundamental theorem for function of a random variable [18]. Depending on the sign of parameters T and T ' that depend on inclination β, reflectance of the ground ρ, latitude, hour angle, sunset hour angle and day of the year [19], the probability density function $f_{pv}(pv)$ has four different expressions but only two have physical meaning [18] ,in particular, if T>0 and T'<0 then:

$$f_{pv}(pv) = \begin{cases} \frac{c'(k_{tmax} - 0.5(\alpha + \alpha'))}{k_{tmax} A_c \eta T' \alpha'} exp^{\frac{\lambda(\alpha+\alpha')}{2}} & if\ P_{pv} \in [0, P_{pv}(k_{tu}) \\ 0 & otherwise \end{cases} \tag{23}$$

If T>0 and T'>0, it gives

$$f_{pv}(pv) = \begin{cases} \frac{c'(k_{tmax} - 0.5(\alpha - \alpha'))}{k_{tmax} A_c \eta T' \alpha'} exp^{\frac{\lambda(\alpha-\alpha')}{2}} & if\ P_{pv} \in [0, P_{pv}(k_{tu}) \\ 0 & otherwise \end{cases} \tag{24}$$

$$\alpha = \frac{T}{T'} \tag{25}$$

$$\alpha' = \sqrt{\alpha^2 - 4.\frac{pv}{\eta.T'.A_c}} \tag{26}$$

Where, A_c is the array surface area [m^2], η is the efficiency of the PVs in realistic reporting conditions (RRC).

4. Problem Formulation

In the DEED problem, the main objective is to efficientlyminimize two competing objective functions, total generation cost and emission. Furthermore, this should satisfy generation units and system constraints in a scheduling horizon over one day. However, incorporating wind and PV generators into the existing DEED problem adds further complexity to the solution methodology. The formulation of each problem objectives and constraints is considered are:

4.1. Objective Functions

4.1.1. Total operating costs

The cost functional associated to DEED running costs includes costs of fuel, wind and PV power generators. The problem is formulated as follows.

4.1.1.1. Fuel cost function

Generally, the generation cost function is usually expressed as a quadratic polynomial or piecewise functions [20], which are unfortunately far from the reality of a modern plant. The non-smooth electrical energy cost function considering multiple valve-point effects is shown in "Fig. (1)" [4].

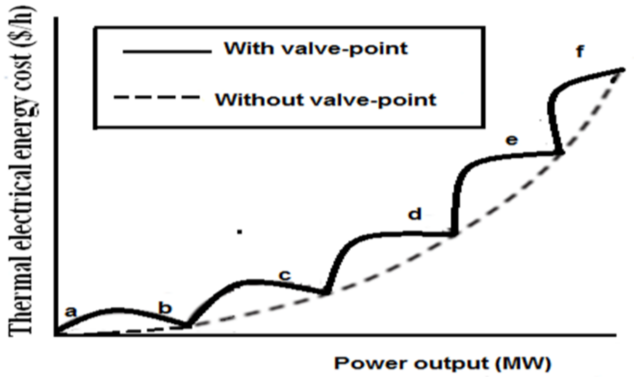

Fig.1. Thermal electrical energy cost function of a thermal unit with and without valve-points [4].

To model the valve-point effect, an additional sinusoidal term is added to the quadratic electrical energy cost function, the fuel cost function of i^{th} thermal generating unit is expressed as:

$$oc(P_{ij}) = a_i + b_i P_{ij} + c_i P_{ij}^2 + \left| e_i \sin\left(f_i\left(P_{ij}^{min} - P_{ij}\right)\right)\right| \quad (27)$$

Where, P_{ij} is the power of the i^{th} generating thermal unit at j^{th} hour, a_i, b_i, and c_i are cost coefficients of generator *i* and e_i, f_i are the coefficients of generator *i* reflecting valve-point effects.

4.1.1.2. operational cost function for wind power generator

$$oc(w_{ij}) = c_{wi}(w_{ij}) + c_{p,wi}(W_{ij,av} - w_{ij}) + c_{r,wi}(w_{ij} - W_{ij,av}) \quad (28)$$

Where, w_{ij} is the scheduled output of i^{th} wind farm in j^{th} hour. Eq. (28) includes three parts; the first part is the weighted cost function representing the cost based on wind speed profile. Where the cost coefficient is multiplied by Weibull pdf of wind power, $f_w(w)$, and is represented by:

$$c_{wi}(w_{ij}) = d_i f_w(w) w_{ij} \quad (29)$$

Where d_i is the cost coefficient for i^{th} wind farm. The second part is the penalty cost for not using all the available wind power and it is assumed to be linearly proportional to the difference between the actual and scheduled wind powers. It can be formulated as [21]:

$$c_{p,wi=k_{P,wi}}(W_{ij,av} - w_{ij}) = k_{P,wi} \int_{w_i}^{w_{ri}} (w - w_{ij}) f_w(w) dw \quad (30)$$

Where $k_{P,wi}$ is the penalty cost coefficient for over generation of i^{th} wind farm, $W_{ij,av}$ is actual or available wind power from i^{th} wind farm and w_{ri} is the rated output of i^{th} wind farm. The third part is the penalty reserve requirement cost which is due to that the actual or available wind power is less than the scheduled wind power. It is assumed that the difference between the available wind power and the scheduled wind power, multiplied by the wind power output probability function is linearly related to the reserve cost and is given by:

$$c_{r,wi} = k_{r,wi}(w_{ij} - W_{ij,av}) = k_{r,wi} \int_0^{w_i} (w_{ij} - w) f_w(w) dw \quad (31)$$

Where, $k_{r,wi}$ is the reserve cost coefficient for under generation of i^{th} wind farm [21].

4.1.1.3. Operational cost function for pv power plant

The operating cost of PV power plant, oc(pv_{ij}), includes three parts as below:

$$oc(pv_{ij}) = c_{pvi}(pv_{ij}) + c_{p,pvi}(PV_{i,av} - pv_{ij}) + c_{r,pvi}(pv_{ij} - PV_{i,av}) \quad (32)$$

The first part is the weighted cost function which represents the cost based on solar irradiance profile; the weight is the pdf of PV power and can be expressed as:

$$c_{pvi}(pv_{ij}) = h_i f_{pv}(pv)(pv_i) \quad (33)$$

Where, h_i, and pv_i are the cost coefficient and the scheduled output from i^{th} PV plant in j^{th} hour. The second part is the penalty cost for not using all the available solar power which is linearly related to the difference between available or actual solar power and scheduled solar power. It can be formulated as:

$$c_{p,pvi=k_{P,pvi}}(PV_{ij,av} - pv_{ij}) = k_{P,pvi} \int_{pv_i}^{pv(k_{tmax})} (pv - pv_{ij}) f_{pv}(pv) dpv \quad (34)$$

Where $k_{P,pvi}$ is the penalty cost coefficient for over generation of i^{th} PV plant, $PV_{ij,av}$ is the actual or available PV power from the i^{th} PV power plant which is a random variable and $pv(k_{tmax})$ is the maximum output of i^{th} PV plant. The third part is the penalty reserve requirement cost which is due to that the actual or available PV power is less than the scheduled PV power and can be given by:

$$c_{r,pvi} = k_{r,pvi}(pv_{ij} - PV_{ij,av}) = k_{r,pvi} \int_0^{pv_i} (pv_{ij} - pv) f_{pv}(pv) dpv \quad (35)$$

Where $k_{r,pvi}$ is the reserve cost coefficient for under generation of the i^{th} PV generator.

4.1.2. Emissions

The emission function can be presented as the sum of all types of emission considered, such as sulpher oxides,SO2, nitrogen oxides, NOx, and thermal emission, with suitable pricing or weighting on each pollutant emitted. In the present study, only one type of emission (NOx) is taken into account without loss of generality. The amount of NOx emission is given as a function of generator output, that is, the sum of a quadratic and exponential function [22].

$$E(P_{ij}) = \sum_{i=1}^{N} \alpha e_i + \beta e_i P_{ij} + \gamma e_i P_{ij}^2 + \zeta e_i \exp(\lambda e_i P_{ij}) \quad (36)$$

Where $\alpha e_i, \beta e_i, \gamma e_i, \zeta e_i$ and λe_i are coefficients of the i^{th} generator emission characteristics.

4.2. Constraints

The following are the system and unit constraints which are taken into account in this work:

1. Real power balance constraint:

The total thermal, wind and PV power must match the total load demand (P_{Dj}), the power loss (P_{lossj})in transmission lines thus

$$\sum_{i=1}^{N} P_{ij} + \sum_{i=1}^{M} w_{ij} + \sum_{i=1}^{S} pv_{ij} = P_{Dj} + P_{loss\,j} \qquad (37)$$

In this work, the transmission power losses (P_{lossj})are computed using Newton Rapson optimal power flow.

2. Real power operating limits of thermal, wind and PV generating units are:

$$P_i^{min} \le P_i \le P_i^{max}$$
$$0 \le w_i \le w_{ri} \qquad (38)$$
$$0 \le pv_i \le pv(k_{tmax})$$

3. The ramp rate constraints for thermal generating units are:

$$P_{ij} - P_{ij-1} \le UR_i \qquad (39)$$
$$P_{ij-1} - P_{ij} \le DR_i \qquad (40)$$

Where UR_i and DR_i are the ramp up and down rate limits of i^{th} unit, respectively.

4. The transmission line constraints are:

$$-P_l^{max} \le P_{lj} \le P_l^{max} \qquad l = 1 \ldots\ldots L \qquad (41)$$

Where, P_l^{max} is the maximum transmission capacity of line l and P_{lj} is the load flow on line l at j^{th} period.

5. Overall Formulation

The main objective of generation dispatch is to minimize the total generation cost and emission of specific operating intervals, while satisfying all inequality/equality constraints, as stated below:

Minimize

$$\left[\begin{array}{c} w_1\left(\sum_{i=1}^{N} \mathrm{OC}(P_{ij}) + \sum_{i=1}^{M} \mathrm{OC}(w_{ij}) + \sum_{i=1}^{S} \mathrm{OC}(pv_{ij})\right) \\ + w_2 \sum_{i=1}^{N} \mathrm{E}(P_{ij}) \end{array}\right] \qquad (42)$$

Where,

N, M and S are the number of thermal units, wind farm and PV power plants, respectively;

$W_1$and W_2 are non-negative weights, such that $W_1 + W_2 = 1$.

$W_1$and W_2 are used to make a trade-off between emission and total cost. Many studies use this weight setting to convert a multi-objective problem into a single-objective one [23, 24].

6. Multiobjective Optimization

Particle Swarm Optimization (PSO) is one of the modern heuristic algorithms, which can be effectively used to solve nonlinear and non-continuous optimization problems. It is a population-based search algorithm and searches in parallel using a group of particles similar to other artificial intelligence based optimization techniques [25].

In this paper weighted Aggregation (WA) method is used to enable PSO to solve environmental/economic MO problem [26]. The weighted aggregation method scalarizes a set of objectives into a single objective by pre-multiplying each objective with a user-specified weight. The weight of each objective is usually selected in proportion to its relative importance in the overall problem. When such objectives are weighted to form a single aggregated objective function, quite often they need to be scaled (normalized) appropriately in order to fall into the identical order of magnitude. After the objectives are normalized, an aggregated objective function can be formed by summing up the weighted normalized objectives. It should be noted that, to obtain the Pareto-optimal solutions, the simulation needs to run multiple times by varying the weight between 0 and 1 [27].

7. Simulation Results and Discussion

6 bus system with three thermal generating units of multi-valve steam turbines, two wind farms, two PV power plants and 11 transmission lines is used to illustrate the proposed method. The data of the transmission line parameters are provided in [1] while those concerned with thermal, wind, PV power generators and loads are provided in [19]. The three thermal generating units are placed on buses 1, 2 and 3. One of the wind farm and PV power plant are placed on bus 2 while the other two units are placed on bus 3.

Transmission losses play an important role in the economic operations of power systems and will affect the DEED problem. The Newton Rapson optimal power flow is utilized for economic dispatch in order to maintain transmission line constraints without violation and calculate the total transmission losses depending on the square power flow [11]. In order to study the effect of line flow limits on the DEED, flow limits on all lines are reduced to 250 MW. Two cases are considered. In both cases the problem is solved as MO optimization problem where both operation cost and emission are optimized simultaneously. WA method is used to enable PSO to solve environmental/economic MO problem. In the first case, the problem of DEED was solved taken into consideration system and unit constraints Eqs. (37-40) without considering line flow limits. The expected power of the thermal units, wind and PV power plants, the total operating and emission costs are shown in "table 1". Unfortunately, this resulted in an overflow on line which connects between bus 2 and bus 4 with 529.8Mw.

Table 1. Optimum solution obtained from DEED without line flow limits

Pg_1(MW)	Pg_2(MW)	Pg_3(MW)	PV_1(MW)	PV_2(MW)	W_1(MW)	W_2(MW)	Cost($/h)	Emissions(kg/h)
100.03	212.07	66.87	0	0	3.78	17.25	4420.00	226.98
135.90	243.91	50.02	0	0	10.42	4.74	4830.38	283.54
129.36	165.84	174.41	0	0	6.21	24.18	5390.99	327.19
109.56	270.04	64.93	0	0	1.77	3.71	5002.42	218.10
209.86	161.19	97.85	0	0	5.10	5.99	5055.61	263.24
207.92	232.42	61.48	0	0	16.55	11.63	5439.65	297.33
352.17	250.95	136.43	0.41	0	10.05	0.00	7633.27	678.25
264.41	207.79	136.54	0.43	1.20	7.10	2.52	6633.19	431.51
239.04	298.35	80.26	2.77	4.03	7.98	9.58	6748.94	479.28
109.72	206.35	157.35	1.45	10.56	6.23	8.34	5299.70	266.66
168.23	187.26	127.33	11.39	11.90	10.64	3.24	5502.05	355.64
100.00	194.97	185.39	18.58	3.54	7.84	19.68	5332.61	341.79
142.41	168.79	89.37	5.67	9.13	2.12	2.50	4698.90	241.30
103.36	112.73	108.34	15.45	12.52	9.90	14.70	3889.83	163.85
382.57	174.87	128.24	23.00	15.96	5.05	0.30	7095.80	587.25
152.92	157.98	125.77	6.69	4.26	18.89	8.49	5186.17	260.37
145.38	138.52	72.68	0.50	0.95	7.22	9.75	4529.40	178.65
192.65	223.26	117.28	0	0	15.33	14.49	5795.18	401.01
128.34	293.79	119.72	0	0	8.71	12.44	6080.35	363.06
137.77	262.68	127.73	0	0	4.26	9.56	5908.86	337.02
114.57	190.59	116.81	0	0	9.78	1.25	4839.00	191.57
133.29	115.40	85.50	0	0	5.07	2.75	4187.81	176.31
182.33	279.72	71.53	0	0	3.53	4.89	5890.62	343.25
101.18	135.23	154.45	0	0	8.43	0.70	4472.90	286.11

Table 2. Optimum solution obtained from DEED with line flow limits

Pg_1 (MW)	Pg_2 (MW)	Pg_3 (MW)	PV_1 (MW)	PV_2 (MW)	W_1 (MW)	W_2 (MW)	Cost ($/h)	Emissions (kg/h)
139.43	125.31	121.69	0	0	1.96	11.60	4761.41	253.08
154.49	190.89	82.07	0	0	6.72	10.83	5042.84	239.47
190.93	110.18	182.81	0	0	0.43	15.65	5340.39	304.42
136.15	221.11	67.88	0	0	17.23	7.62	5070.84	224.19
139.26	175.19	139.24	0	0	7.99	18.32	5129.80	268.76
107.19	202.04	182.02	0	0	20.47	18.28	5518.32	341.93
234.26	244.03	248.85	1.35	0	12.39	9.13	7546.38	692.26
222.25	131.60	244.83	1.62	0.60	9.08	10.04	6550.38	532.81
174.87	226.46	221.06	6.43	3.23	2.88	7.06	6804.22	481.86
106.42	120.78	236.72	19.42	5.97	3.188	7.51	5310.25	296.49
206.88	103.74	176.45	12.50	11.98	8.38	0.09	5334.61	282.78
101.76	241.11	127.17	15.48	23.48	9.45	11.54	5179.76	334.45
212.13	102.61	57.91	21.04	14.35	6.69	5.28	4271.41	293.84
129.04	146.74	60.18	5.24	11.37	18.13	6.31	4248.76	164.25
166.32	245.12	248.96	19.75	21.04	7.67	21.15	7025.19	612.80
124.36	144.73	170.69	7.13	11.31	9.81	6.98	5223.45	224.05
115.82	151.94	90.62	0.88	1.31	11.01	3.42	4294.56	200.46
152.21	242.94	156.03	0	0	0.73	11.08	6000.19	396.97
242.80	127.72	169.88	0	0	5.83	16.77	6138.20	357.26
138.98	144.50	229.70	0	0	20. 19	8.62	5986.60	349.69
238.82	114.58	57.05	0	0	13.08	9.47	4811.96	216.52
169.01	112.55	51.84	0	0	3.08	5.53	4041.26	166.696
230.79	150.09	135.20	0	0	14.86	11.06	5816.30	378.58
104.14	236.99	50.098	0	0	2.94	5.82	4322.71	191.21

"Table 2" shows the result of the second case which take into consideration the line flow limits on the DEED using the aforementioned technique. In this case, all the constraints listed above are considered and, no transmission lines violation reported. "Figure 2" illustrates the comparison between the hourly costs of the DEED problem for the two cases. The diversity of the Pareto optimal set over the trade-off is shown in "Fig. 3" which shows that the operating cost, for both scenarios, of the non-dominated solutions are inversely proportional to their emissions. The graphical results clearly reveal that the solutions found were well distributed and covered the entire Pareto front of the problem.

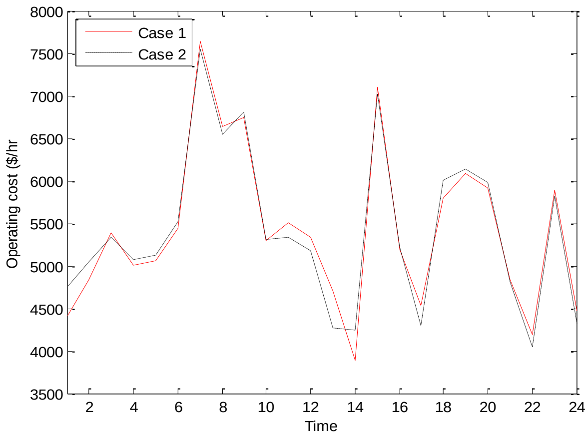

Fig. 2. Comparison between the hourly costs of the SDEED problem with and without considering line flow limits.

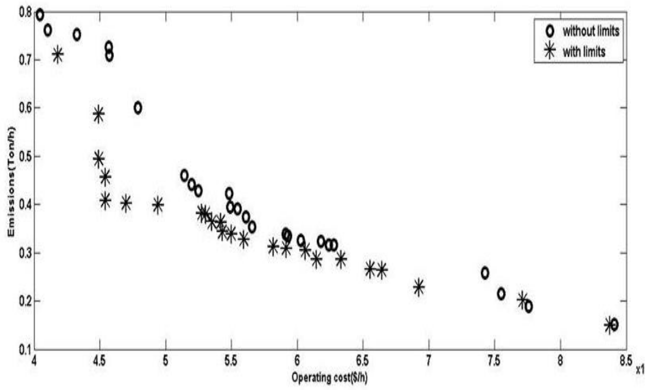

Fig. 3. Trade-off in cost and emission

8. Conclusion

An optimal dispatch model with considerations of security, economy and environment protection is proposed. The effectiveness of employing PSO approach solving a DEED problem for achieving a global solution is verified using weighted aggregation method. A very well distributed Pareto optimal fronts has been obtained which presents a large number of trade off solutions for the power system operator. The proposed technique was tested on 6 bus system with three thermal generating units, two wind farms and two PV power plants taking into account imbalance charges due to possible mismatch between scheduled and actual wind and PV power outputs. In addition, the uncertainty of wind speed and PV solar irradiance are characterized by weibullpdf. The results demonstrate the effectiveness of the proposed model to operate the system optimally and securely.

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