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Optimum Power Dispatch Management in Presence of Renewable Energy and Energy Storage

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SUMMARY

Since functioning and wellbeing of modern society depends on uninterrupted supply of electricity, its demand has been growing very rapidly in modern civilization. Therefore, civilization management and urban planning should include proper electricity management for increased number of conventional and renewable plants in order to meet the huge demand of electricity. An efficient operating policy for committed units (CUs) in order to meet the load demand is very important for power utility operators. Optimum Power Dispatch Management (OPDM) problems help to find such suitable operating policies for CUs without violating system and unit constraints. Minimization of fuel cost or reduction of amount of pollutant emissions or optimization of both fuel cost and pollutant emissions are the objectives of OPDM problems. Based on these objectives, OPDM problems are classifieds and discussed in this paper. The OPDM problems of hybrid power systems with renewable sources and energy storage facilities are suggested in this paper since the use of renewable and clean energy is essential for sustainable and environmentally acceptable energy supply system. Optimum dispatch can be obtained by extracting maximum renewable energy during its availability period and then using it for both available and unavailable periods with the aid of energy storage devices. MATLAB simulations are performed using IEEE-30 test bus data with 6 generators to illustrate the benefits of renewable energy storage in reducing the fuel cost and unwanted pollutants emissions. This strategy can help to bring sustainable and clean energy supply for civilization and to improve the urban environmental conditions.

Keywords: economic dispatch, economic environmental dispatch, environmental friendly dispatch, energy storage, multi-objective optimization, renewable energy.

1. INTRODUCTION

With the current trends in population growth, industrialization, urbanization, modernization and income growth, electricity consumption is expected to continue increasing substantially in years to come. World consumption of energy was about 84 million barrels per day (MBD) in 2008. According to International Energy Agency it will reach 113 MBD by year 2030. It is expected that the world energy demand could even double by

2050 [1]. This implies that enormous new conventional and renewable power plants will be needed to meet the rapid growth of electricity demand. Well planned electricity management and operating policies are essential for these power plants in order to reduce the fuel cost and the amount of pollutants while meeting the demand [1]. Electrical power generation is one of the major sources of pollutant emissions. Burning oil, natural gas and coal at power plants produce pollutants such as nitrogen oxide, sulfur dioxide, and carbon dioxide, etc. The emission of such gases can lead to smog, haze and acid rain. In addition, such emissions may increase the risk of climate change and global warming. Thus the proper planning of electricity supply system has a direct influence on the civilization management and urban planning. Pollution control devices on fossil fuel based power plants and use of available renewable energy resources can help to reduce the amount of such unwanted emissions. In such situations, the operating policies for such hybrid plants to minimize the amount of emission along with the reduction of fuel cost are very important.

The optimum power dispatch problem attempts to find efficient operating policy for the committed units in order to meet the load demand while satisfying the entire unit and the system constraints [2, 3]. The existing energy production is not clean. About 63% of world electricity is obtained by burning fossil fuels; 40% of which is from coal-fired electric power stations. Most of the coal-fired power stations were built two decades ago and emit 80-85% of NO_x generated by utilities. Some older power plants operate with pollution rates of up to 70 to 100 % greater than the newer plants [4]. Due to the increased cost and dwindling supplies of fossil fuels, awareness on carbon footprint and effect of global warming, the utilities have been forced to use renewable energy sources in hybrid power systems and to modify their operation strategies in order to reduce fuel cost, fuel demand, and atmospheric pollution by power plants. OPDM is a suitable tool for this purpose. Economic Dispatch (ED), Environmental Friendly Dispatch (EFD) and Economical and Environmental Dispatch (EED) are some of the important OPDM methods that are discussed in this paper. Minimizing the fuel cost is the objective of ED [3] problems while the minimization of pollutants emission is the objective of EFD [4]. The EED problem attempts to minimize both the fuels cost and the amount of emissions [5].

Methods for reducing fuel cost and pollutants emission by the power plants with or without the use of renewable sources haves been discussed in literatures [6, 7]. Most of the literatures formulated the power dispatch problems with common constraints in presence of renewable power only. But in this chapter, the authors introduced and discussed some additional constraints due to the presence of storage facilities. Reference [7] discussed methods to minimize cost only whereas [4, 8] discussed methods to minimize emission only while references [6, 9] outlined methods for reducing both fuel cost and pollutants emissions. Economic environmental dispatch (EED) is one of the best methods for optimizing both fuel cost and total amount of emissions. EED distributes conventional and renewable power production among the available power stations to minimize both fuel cost and pollutant emissions simultaneously. The amount of renewable power to be dispatched is calculated based on the data available with the Environmental Information Systems and Load Dispatch Centers and using any commercially available software package [10]. It is better to treat ED and EFD as single objective problems while EED as a multi-objective problem. Some reports have described EED as a multi-objective problem with renewable solar and wind power [5, 9, 11]. The applicability of EED becomes more effective in the areas that have high availability of renewable sources. Fuel cost for conventional production is not a big issue in countries like Saudi Arabia since these countries are blessed with abundant oil and natural gas resources [12]. Hence the reductions of pollutant emission should be the main objective of power dispatch problems in such countries and EFD offers a suitable approach for this objective [13].

The potential of renewable energy depends on the data such as the wind speed, solar radiation level, and temperature. The uncertainty and variation of the renewable resources complicates OPD problems. Different methodologies were illustrated in several articles to overcome these challenges. One of the methods is to treat renewable power as a negative load and formulate the demand equation on this basis [9]. The uncertainty in the availability of solar irradiation is less in some areas. The Kingdom of Saudi Arabia is one of the examples of such high potential solar areas. The country is part of a vast, rainless region that receives about 6-7 kWh/m^2/day [12]. The global solar radiation in the Kingdom varies between a minimum of 4493 W/m^2/day to a maximum of 7014 W/m^2/day with the minimum and maximum duration of sunshine varying between 7.4 and 9.4 hours. Other Middle East countries, some part of India, and Australia etc., also have high potential of solar power [1]. In many countries, there is considerable cloud activity. However in the Kingdom, there is less uncertainty due to cloud formation. Another renewable source i.e. wind also has uncertainty due to the availability of required wind speed. Wind does not blow with a steady speed or in a fixed direction. Installing a number of inter connected wind turbines in the passage of wind can improve the availability of wind power to some extent. Even though installing off shore wind turbines is a little bit complicated, it provides more efficient and steady wind speed than the on shore installations.

The renewable power generation technologies and energy storage systems are being developed and widely used for clean power production. In such applications, the renewable generations and energy storage systems are effectively interconnected with the existing power plants. Some of the energy storage systems are described in [14-16]. Production and storage of renewable energy at off-peak times or at times when there would be a surplus of its availability and reuse of such stored energy during its unavailable periods will make the OPD optimization more effective and energy management system more useful, as shown in this paper.

For thermal generating units considered here, the fuel cost increases with the increase of the outputs of the units. Moreover, the amount of emission is also high for both lower and higher values of the power output [17]. Thus, distributing the optimal values of renewable power throughout the operating periods instead of using them only during their available periods can help to reduce both the cost and pollution emission to some extent. However, such an approach will require using suitable energy storage devices. The storage also helps to overcome the day-night weather based approach for economic dispatch. This chapter presents ED and EFD formulation as a single objective problems and EED as a multi-objective problem with renewable sources and storages.

2. RENEWABLE ENERGY

This paper considers solar and wind power as typical renewable sources. Wind power is harvested by wind turbine and solar power can be produced either by solar panels or by solar thermal plants or by both. The maximum solar power P_s (W) produced by a solar panel is proportional to solar irradiation *S* (W/m^2) and is given as;

$$P_s = P_m \frac{S}{1000\ {}^{W}\!/\!_{m^2}} \left[1 - \tau\left(T_{cell} - 25\right)\right] \tag{1}$$

where, P_m is the panel power rating and τ is the drift in panel output due to temperature per ^{0}C

The approximate solar power developed by solar thermal plant is also proportional to S and is given as;

$$P_s = \eta A_c S \tag{2}$$

where, η is the collector efficiency and A_c is the collector area in m^2.

For wind power the mechanical power produced by a wind turbine P_w (W) can be written as;

$$P_w = \frac{1}{2} a_c \rho A_s V_w^3 \qquad (3)$$

where, a_c is the aerodynamic coefficient of wind turbine which depends on the turbine speed and the wind speed, ρ is the air density, A_s is the surface swept in m^2 and V_w is the wind speed in m/s.

In order to limit the variance in the useful power produced due to the varying wind speed, the wind power production is designed so that it is constant over a certain wind speed range. Wind turbines are normally designed to develop a nominal power P_n with nominal wind speed V_n. Wind speed higher than V_n causes mechanical overloading of the turbine. To avoid such overloading and to limit the variance in the power output, the variation of power verses wind speed is shown in Fig. 1, where V_1, V_2 and V_3 are the different level of wind speed available and P_{w1}, P_{w2} and P_{w3} are the corresponding values of useful power developed.

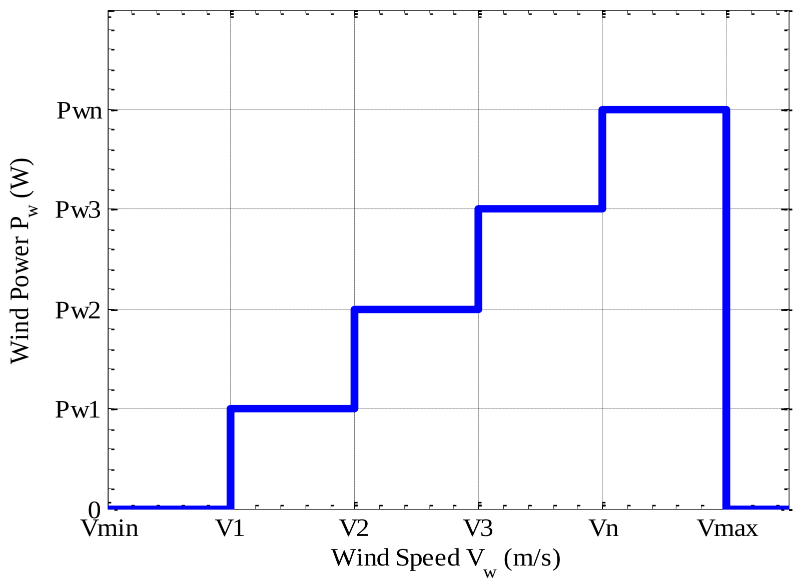

Fig. 1: Output Power versus Wind Speed

3. Problem Formulation

A general optimization problem refers to the selection of a best set of element from some sets of available alternatives. It consists of one or multi objective functions to be optimized and is associated with a number of equality and inequality constraints [18]. Mathematically, it can be formulated as follows;

$$\text{Minimize } F(x) = \left[f_1(x_1, x_2, \ldots\ldots x_n), f_2(x_1, x_2, \ldots\ldots x_n), \ldots \right] \quad (4)$$

$$\text{Subject to } \begin{cases} g_i(x_1, x_2, \ldots\ldots x_n) & i = 1,2,\ldots\ldots,I \\ h_j(x_1, x_2, \ldots\ldots x_n) & j = 1,2,\ldots\ldots,J \\ l_k(x_1, x_2, \ldots\ldots x_n) & k = 1,2,\ldots\ldots,K \end{cases} \quad (5)$$

Here, (4) is the objective function while (5) constitutes the set of constraints imposed on the solution. The variables x_1, x_2, . . ., x_n, represent the set of decision variables, and f_1 (x_1, x_2, . . ., x_n) and f_2 (x_1, x_2, . . ., x_n) are the objective functions expressed in terms of these decision variables.

For problem at hand, the objective functions are minimization of fuel cost and reduction of the total amount of pollutants emissions. The constraints are formulated in the presence of both renewable and stored energies. The ED and EFD are single objective problems with objective of minimization of fuel cost or reduction of amount of emissions, respectively while EED is a multi-objective problem which minimizes both the fuel cost and the amount of emissions simultaneously.

The fuel cost function $F_f(P_{gi})$ in \$/h is represented by a quadratic equation of the type;

$$F_f\left(P_{gi}\right) = \sum_{i=1}^{N_g} a_i + b_i P_{gi} + c_i P_{gi}^2 \quad (6)$$

In equation (6), the coefficients a_i, b_i and c_i are the appropriate cost coefficients for individual generating units, P_{gi} is the real power output of the i^{th} generator and N_g is the number of generators.

The main emissions in thermal power plants are SO_2 and NO_x. The emission of SO_2 depends on fuel consumption. Many factors such as the temperature of the boiler and content of the air determine the emission of

NO_x. In general, the emission $F_e(P_{gi})$ in ton/h of SO_2 and NO_x pollutants is a function of generator output power and can be expressed by an equation of the type;

$$F_e\left(P_{gi}\right)=\sum_{i=1}^{N_g}\alpha_i+\beta_i P_{gi}+\gamma_i P_{gi}^2 \ +\lambda_i e^{\delta_i P_{gi}} \tag{7}$$

where, α_i, β_i, γ_i, λ_i and δ_i are emission coefficients of the i^{th} generating unit.

The availability of both wind power as well as solar power is not constant over the 24 hour period. Thus, in the presence of such variability, our aim is to extract maximum amount of power from renewable sources during the available period (T_a). Some part of the renewable energy thus generated is stored using some storage devices. This stored energy is used during the unavailable period (T_u) of renewable sources.

Assume that total power demand is $\left(P_D^t\right)$whereas power produced by the renewable sources is (P_r). Furthermore, let the stored renewable power be (P_{st}) during the available period T_a which is utilized in the unavailable period T_u. Thus, the net actual demand $\left(P_D^a\right)$ can be expressed as;

$$P_D^a = P_D^t - P_r \pm P_{st} \tag{8}$$

In this equation, the positive sign is applicable during the storage period whereas the negative sign is used during the delivery period of the stored power.

The constraints applicable for this case are as follows:

- The total power generation, renewable power and stored power must cover the actual net demand and the power loss (P_L) in transmission system in order to ensure power balance. Thus we must have;

$$P_D^a + P_L - \sum_{i=1}^{N_g} P_{gi} = 0 \tag{9}$$

- The power output of the i^{th} generator is usually restricted by the lower limit P_{gi}^{min} and the upper limit P_{gi}^{max}:

$$P_{gi}^{min} \le P_{gi} \le P_{gi}^{max}\text{, i=1, 2, ….., Ng} \tag{10}$$

- The power loss of the transmission system is positive, i.e.,

$$P_L = \sum_{i=1}^{N_g}\sum_{j=1}^{N_g} P_{gi}B_{ij}P_{gj} + \sum_{i=1}^{N_g} B_{0i}P_{gi} + B_{00} > 0 \quad (11)$$

where B_{ij}, B_{0i} and B_{00} are loss coefficients

- The amount of renewable power to be dispatched is limited to x times the actual demand in order to keep acceptable penetration of renewable sources into the network.

$$\begin{aligned} &(P_r)_d \le xP_D^a \\ &P_r = \begin{cases} P_s + P_w & \text{during} T_a \\ P_w & \text{during} T_u \end{cases} \end{aligned} \quad (12)$$

In equation (12) P_s and P_w are the solar power and wind power respectively and x is the renewable energy penetration level. Here it is assumed that $x \le 0.3$ pu .

- The stored power is the difference between the total power extracted from renewable sources and the dispatched renewable power during the period T_a. However, during period T_u, it must not exceed y times the total stored renewable power of period T_a. Moreover, the sum of total energy delivered by the storage devices during T_u must not exceed the total energy stored during T_a. Thus:

$$P_{st} \le \frac{\int_i \left[(P_s + P_w)_g - (P_s + P_w)_d\right]dt}{\int_i dt}\text{; during } T_a \quad (13)$$

$$i = t_1, t_{2,}. . . .,t_n \in T_a$$

and,

$$P_{st} \le y\frac{\int_i \left[(P_s + P_w)_g - (P_s + P_w)_d\right]dt}{\int_i dt} \text{ during } T_u \quad (14)$$

$$\text{Where } y \propto \frac{T_a}{T_u} P_D^a \text{ and selected such that } \sum_{T_u} P_{st} \leq \sum_{T_a} P_{st} \tag{15}$$

Thus, the optimization problems for economic dispatch (ED), environmental friendly dispatch (EFD) and economical/environmental (EED) can be formulated as follows:

3.1.ED Formulation

The objective of ED problem is to minimize the fuel cost while extracting maximum power from the renewable sources while satisfying the applicable constraints. Thus we can write:

$$\text{Minimize } \left(F_f\left(P_{gi}\right)\right)$$

Subjected to:

$$P_D^a + P_L - \sum_{i=1}^{N_g} P_{gi} = 0$$

$$P_{gi}^{\min} \leq P_{gi} \leq P_{gi}^{\max}$$

$$P_L > 0$$

$$\left(P_r\right)_d \leq x P_D^a$$

$$P_{st} \leq \begin{cases} \dfrac{\int_i \left[\left(P_s + P_w\right)_g - \left(P_s + P_w\right)_d\right] dt}{\int_i dt}; during T_a \\ y\dfrac{\int_i \left[\left(P_s + P_w\right)_g - \left(P_s + P_w\right)_d\right] dt}{\int_i dt}; during T_u \end{cases}$$

$$\sum_{T_u} P_{st} \leq \sum_{T_a} P_{st}$$

3.2. EFD Formulation

The characteristics of thermal plants are usually such that the total amount of emission is high at lower and higher values of power output. Thus, it is normally not advisable to use renewable power for low power demand periods since the addition of renewable power during such times will further lower the net demand on the thermal units and hence will result in an increase in the emissions. Thus, during low demand periods it may be more useful to store all of the produced renewable energy. The main objective in EFD is to minimize the emission levels of polluting gases by extracting the maximum power from the renewable sources in order to meet the actual demand as in (8) without violating the applicable constraints. Therefore, the objective function is the emission of conventional generators given in (7) and the constraints are the same as given in (9) to (15).

Thus, the EFD problem can be summarized as;

$$\text{Minimize } \left[F_e\left(P_{gi}\right)\right]$$

Subjected to the constraints given in (9) – (15)

3.3. EED Formulation

The objectives of EED are to minimize both the fuel cost and the emission levels of pollutants using renewable sources and the storage devices. Thus the objective function should include fuel cost and emission functions. EED problem can thus be summarized as;

$$\text{Minimize } \left(F_f\left(P_{gi}\right), F_e\left(P_{gi}\right)\right)$$

Subjected to the constraints given in (9) – (15)

The simulations of OPD problems with the specified constraints are performed using Sequential Quadratic Programming (SQP) algorithm in MATLAB and the results are discussed next.

4. Results And Discussion

The MATLAB simulations were carried out for OPD problems using the data of the 30 bus IEEE standard test system [9, 19]. Here, two case studies are discussed: Case A, during T_a period and Case B, during the T_u period. During T_a period, high intensity of solar radiation provides P_s and variable wind power P_w is available. One must extract the maximum renewable power from these two sources during this period. About 30% of the total demand is dispatched using this extracted renewable power while the remaining part of renewable power is stored. Therefore, the emissions are independent of stored energy during this period. During T_u, both wind power and renewable stored power are available. Due to the uncertainty of the wind speed, the dispatch amount of renewable power is less (e.g. about 10% of the total demand) when compared to case A. Assuming that almost 0.75 pu of stored power is available throughout T_u period, the amount of stored dispatched power is related to the demand and the T_u duration. The maximum value of power that can be stored per hour is taken as almost 2 pu.

Three sub cases considered were; (i) without renewable & storage, (ii) with renewable only but without storage and (iii) with both renewable and storage. Let C_m^k and E_m^k be the values of cost and emission per hour respectively, where m= N, R and R&S corresponding to these three sub cases and k =1, 2 and 3 for ED, EFD and EED problems respectively. The values of the fuel and emission coefficients used for simulations are given in Table 1. The values of loss coefficients [3]are given as ;

$$B = \begin{bmatrix} 0.0218 & 0.0103 & 0.0009 & -0.0010 & 0.0002 & 0.0027 \\ 0.0103 & 0.0181 & 0.0004 & -0.0015 & 0.0002 & 0.0030 \\ 0.0009 & 0.0004 & 0.0417 & -0.0131 & -0.0153 & -0.0107 \\ -0.0010 & -0.0015 & -0.0131 & 0.0221 & 0.0094 & 0.0050 \\ 0.0002 & 0.0002 & -0.0153 & 0.0094 & 0.0243 & -0.0000 \\ 0.0027 & 0.0030 & -0.0107 & 0.0050 & -0.0000 & 0.03580 \end{bmatrix} \tag{16}$$

$$B_0 = \begin{bmatrix} -0.000003 & 0.000021 & -0.000056 & 0.000034 & 0.000015 & 0.000078 \end{bmatrix}$$

$$\text{and} \quad B_{00} = \begin{bmatrix} 0.0014 \end{bmatrix}$$

The lower and upper limits of generator output powers are assumed as;

$$0.05\,pu \le P_{gi} \le 1.5\,pu \text{ ; i=1, 2, ….., 6} \tag{17}$$

Table 1: Generator Cost and Emission Coefficients [9]

		Cost				Emission		
Gen.	a	b	c	α	β	γ	λ	δ
1	10	200	100	4.091	-5.554	6.490	2x10-4	2.857
2	10	150	120	2.543	-6.047	5.638	5x10-4	3.333
3	20	180	40	4.258	-5.094	4.586	1x10-6	8
4	10	100	60	5.326	-3.55	3.380	2x10-3	2
5	20	180	40	4.258	-5.094	4.586	1x10-6	8

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6	10	150	100	6.131	-5.555	5.151	1x10-5	6.667

4.1. ED Results

When comparing fuel cost with and without renewable power, the fuel cost per hour is always higher in case of dispatch without using renewable sources. Reasonable power production is available during T_a. Therefore the value of fuel cost/hour is less during this period. The use of renewable power, during the period T_u reduces the fuel cost below the value of C_N^1 while the use of stored power along with renewable power during this period reduces the value of cost/hour almost equal to the values obtained during the period T_a. Figure 2 shows the variation of fuel cost/hour with power demand. The fuel cost always increases with increase in power demand. The variation of percentage reduction in fuel cost $\%\Delta C_m^k \left(1-\frac{C_m^k}{C_N^k}x100\right)$ is shown in Fig. 3. The ratio of $\%\Delta C_{R\&S}^1$ to $\%\Delta C_R^1$ is almost 0.75 during T_u for most of the demand range.

Table 2 gives the results of ED problem with variation of load per 24 hours day and Fig. 4 shows the variation of percentage reduction in cost with load curve. Almost 35 % of fuel cost is saved during T_a while this saving is less than 10 % during T_u with renewable sources only. However, the % saving of fuel cost becomes more than 30% for peak demand during T_u with the use of both renewable and storage power.

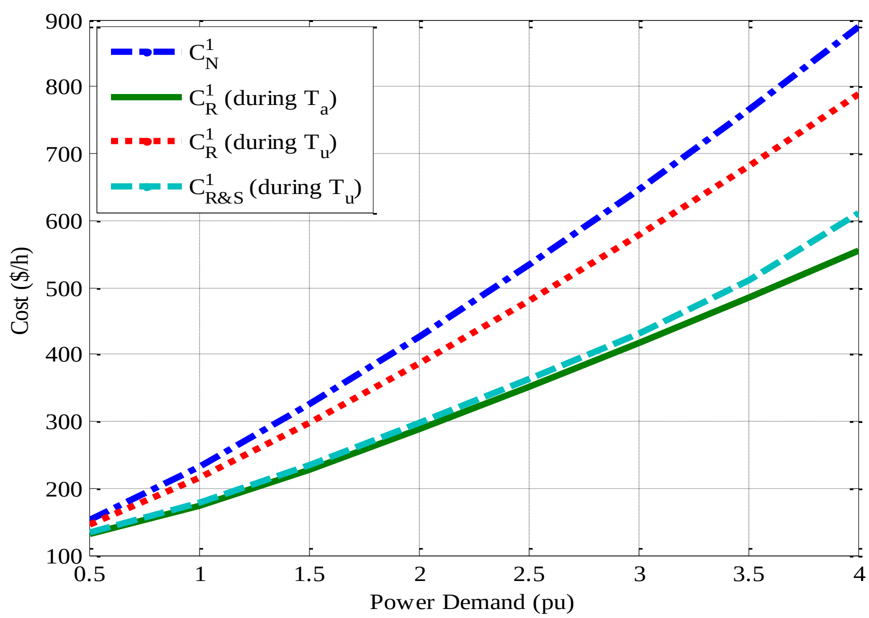

Fig. 2 Variation of Cost with Demand for ED

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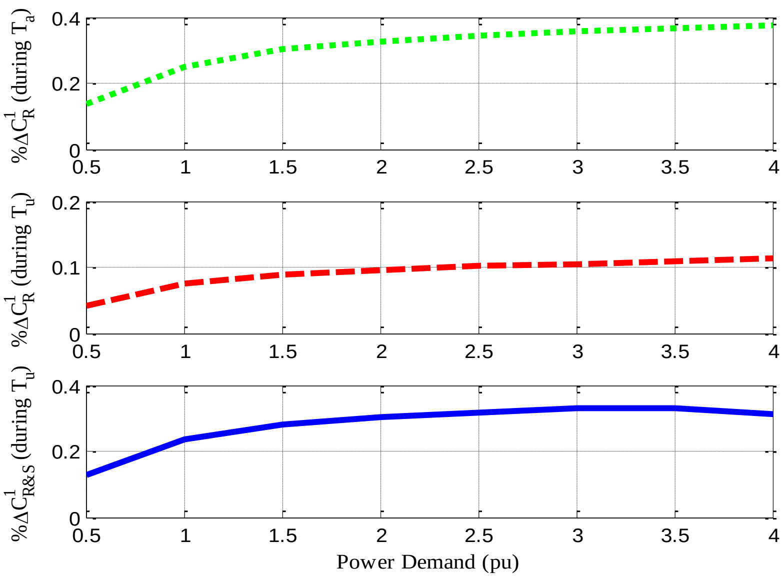

Fig. 3: Variation of Percentage Reduction in Cost for ED

Table 2: Results of ED problems with power demands of 24 hours

Time (h)	P_D^t (pu)	P_{g1} (pu)	P_{g2} (pu)	P_{g3} (pu)	P_{g4} (pu)	P_{g5} (pu)	P_{g6} (pu)	P_r (pu)	P_{st} (pu)	Cost ($/h)
0	1.5	0.05	0.116	0.05	0.62	0.05	0.136	0.15	0.338	234.742
2	1	0.05	0.05	0.05	0.429	0.05	0.05	0.1	0.225	177.971
4	1.5	0.05	0.116	0.05	0.62	0.05	0.136	0.15	0.338	234.742
6	2.5	0.05	0.195	0.236	0.773	0.22	0.23	0.25	0.563	363.31
8	2.5	0.05	0.189	0.217	0.761	0.203	0.222	0.875	1.125	350.907
10	3	0.05	0.222	0.318	0.824	0.296	0.261	1.05	0.95	416.493
12	2.5	0.05	0.189	0.217	0.761	0.202	0.222	0.875	1.125	350.907
14	3	0.05	0.222	0.318	0.824	0.296	0.261	1.05	0.95	416.493
16	3	0.05	0.222	0.318	0.824	0.296	0.261	1.05	0.95	416.493
18	3.5	0.078	0.264	0.451	0.905	0.418	0.31	0.35	0.75	511.692
20	3	0.05	0.229	0.342	0.838	0.318	0.269	0.3	0.675	432.013
22	2	0.05	0.162	0.131	0.708	0.122	0.19	0.2	0.45	297.517
24	1.5	0.05	0.116	0.05	0.62	0.05	0.136	0.15	0.338	234.742

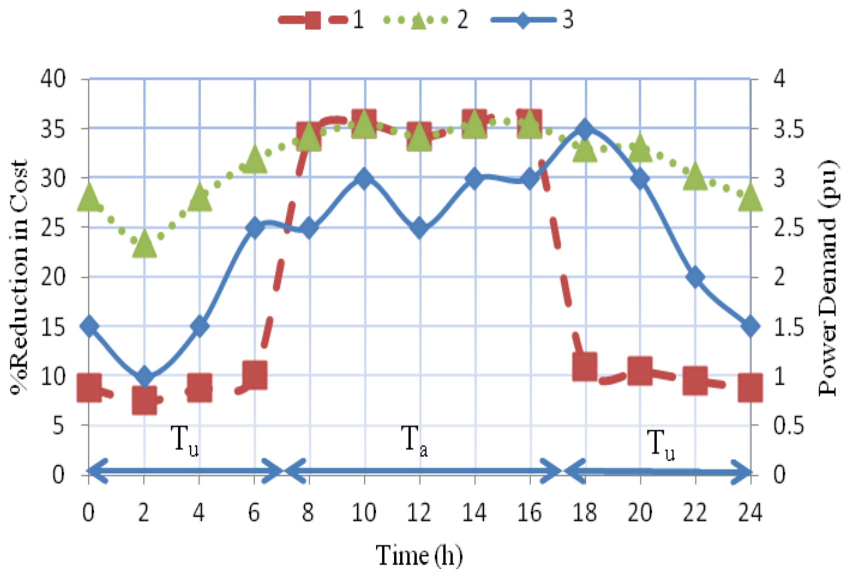

Fig. 4: Percentage change in Cost with daily Load Curve for ED

1. $\%\Delta C^1_R$ and 2. $\%\Delta C^1_{R\&S}$ and 3. Load curve

4.2. EFD Results

The variation of emissions/hour with demand for EFD case is shown in Fig. 5. The amounts of pollutant emissions per hour in all cases are equal for low demand period. However, for higher demand period, E^2_R during T_a is almost equal to $E^2_{R\&S}$ during T_u. Also, the emission per hour is related as $E^2_{R\&S} < E^2_R < E^2_N$ at higher demands during period T_u. The optimum values of emission/hour for low demands are obtained without the use of renewable sources and the storage, while for higher demands it is obtained by using renewable sources. In other words, adding renewable power for low demand periods increases the net emission while increased use of renewable power during the higher demand periods the net emission reduces. Therefore, it is advisable to store maximum renewable energy during the low demand periods and use it during peak load periods. The percentage reduction in emission is shown in Fig. 6. The power output of each generator unit with variations of load per day and corresponding amount of emissions are tabulated in Table 3. The percentage change in emission with load curve is shown in Fig. 7.

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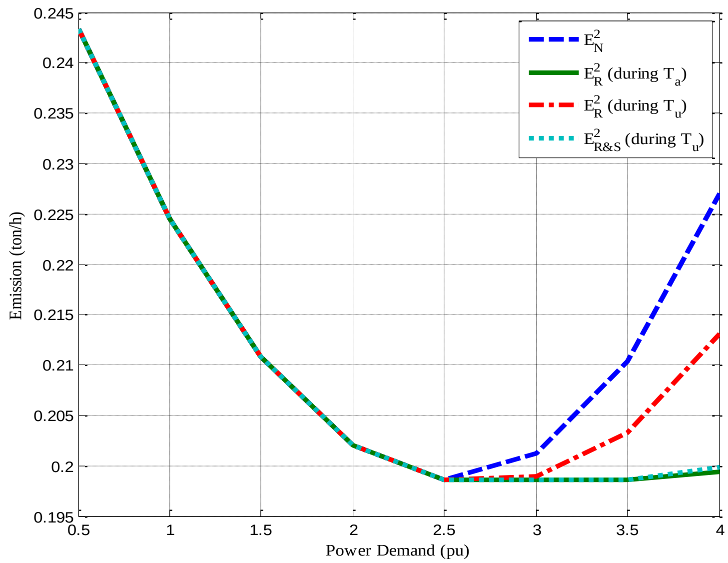

Fig. 5: Variation of Emission with Power for EFD

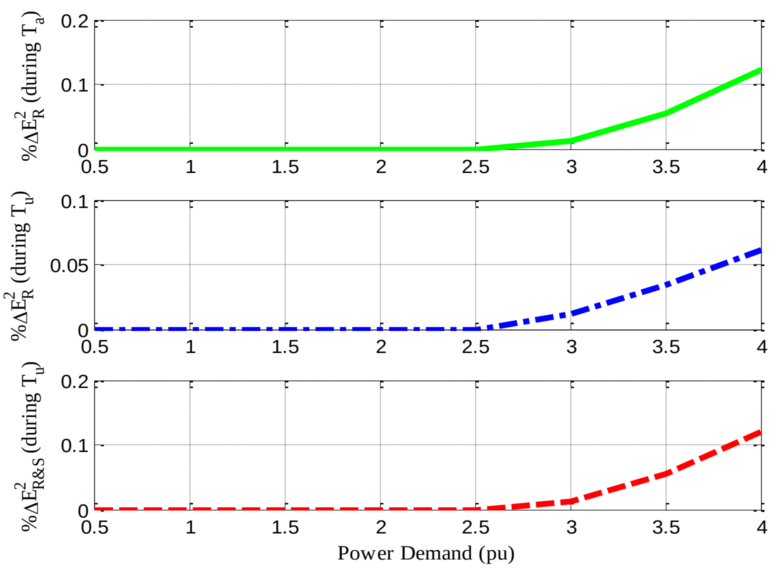

Fig. 6: Variation of Emission with Power Demand for EFD

Table 3: Results of EFD problems with daily power demands

Time (h)	P_D^t (pu)	P_{g1} (pu)	P_{g2} (pu)	P_{g3} (pu)	P_{g4} (pu)	P_{g5} (pu)	P_{g6} (pu)	P_r (pu)	P_{st} (pu)	Emission (ton/h)
0	1.5	0.248	0.3	0.247	0.185	0.248	0.282	0	0	0.211

2	1	0.177	0.225	0.172	0.05	0.173	0.207	0	0	0.225
4	1.5	0.248	0.3	0.247	0.185	0.248	0.282	0	0	0.211
6	2.5	0.405	0.46	0.373	0.494	0.373	0.421	0	0	0.199
8	2.5	0.406	0.456	0.372	0.499	0.37	0.423	0	2	0.199
10	3	0.414	0.466	0.377	0.509	0.377	0.427	0.458	1.542	0.199
12	2.5	0.406	0.456	0.372	0.499	0.372	0.423	0	2	0.199
14	3	0.414	0.466	0.377	0.509	0.377	0.427	0.458	1.542	0.199
16	3	0.414	0.466	0.377	0.509	0.377	0.427	0.458	1.542	0.199
18	3.5	0.415	0.469	0.378	0.507	0.378	0.426	0.35	0.606	0.199
20	3	0.415	0.466	0.377	0.509	0.377	0.427	0.253	0.205	0.199
22	2	0.324	0.378	0.314	0.334	0.315	0.354	0	0	0.202
24	1.5	0.248	0.3	0.247	0.185	0.248	0.282	0	0	0.211

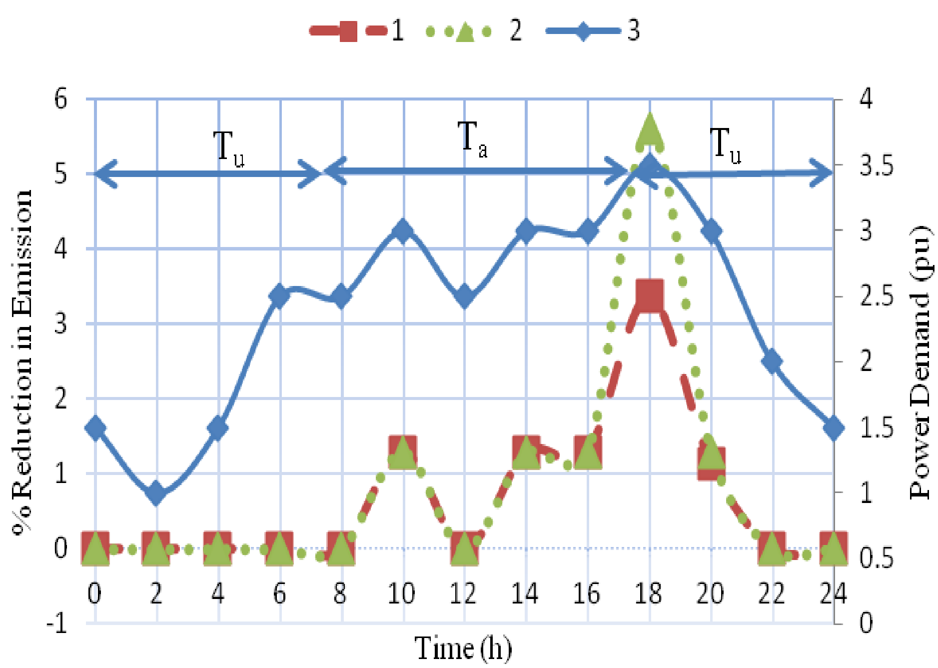

Fig. 7: Percentage change in Emission with daily Load Curve for EFD

1. $\%\Delta E_R^1$ and 2. $\%\Delta E_{R\&S}^1$ and 3. Load curve

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4.2. EED Results

The variations of emission/hour with cost/hour for the demand varying from 0.5 pu to 4 pu are shown in Fig. 8. Without the use of renewable sources, both emission and cost increase with increase in power demand while the use of renewable power during T_a and renewable and stored power during T_u reduces both values. The variation of cost/hour and emission/hour with power demand are shown in Figs. 9 and 10, respectively. Comparing Figs. 9 and 10, it is clear that the cost for a demand of 3 pu with renewable only during T_u is almost 600 $/h and during T_a is almost 410 $/h while use of storage energy in the T_u period along with renewable power reduces this cost to around 425 $/h. But the amount of emissions in all these cases is almost 0.22 ton/h.

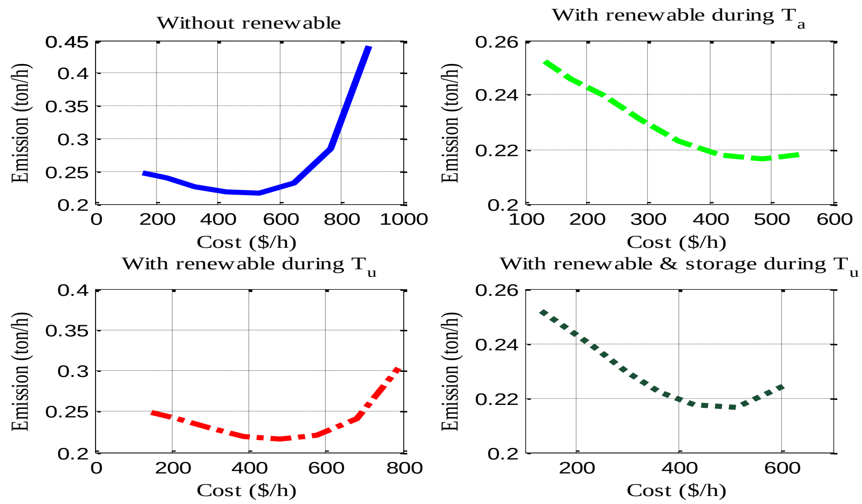

Fig. 8: Variations of Emissions with Cost for EED

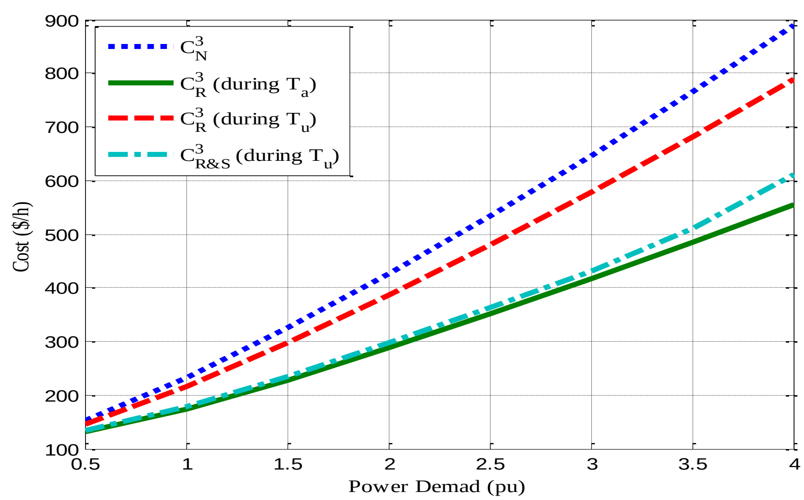

Fig. 9: Variation of Cost with Power Demand for EED

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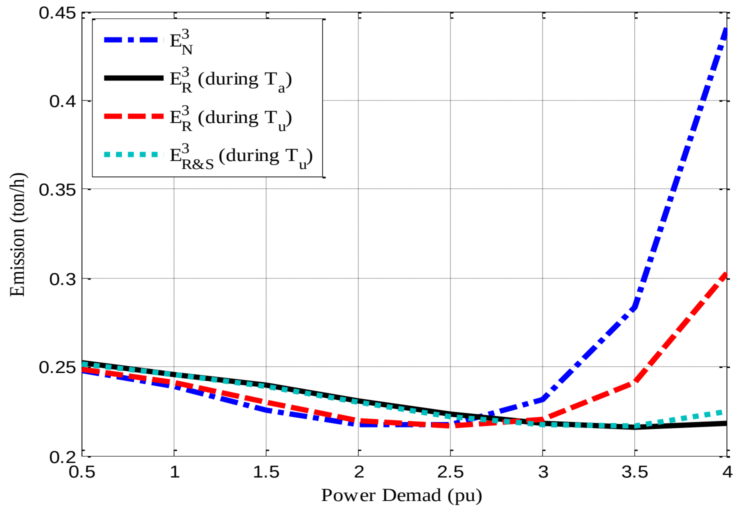

Fig. 10: Variation of Emissions with Power Demand for EED

For low demands the amount of emissions while using renewable power is slightly more than the amount of emissions produced without the use of renewable sources. However the value of emission decreases with increase in demand when renewable power is utilized. The cost/hour for a specified demand always follows a relation $C_{R\&S}^3 < C_R^3 < C_N^3$ during T_u and the values of $C_{R\&S}^3$ and $E_{R\&S}^3$ during T_u period are almost equal to the values of C_R^3 and E_R^3 during T_a period for a specific demand. The results of EED problem for varying demand in a whole day are given in Table 4. The percentage reduction in cost and emission with power demand are shown in Fig.11 and these variations with load curve are shown in Fig. 12. The percentage savings of both cost and amount of emissions are increased at peak load with the use of storage power along with renewable power during T_u period.

Table 4: Results of EED problems with daily power demands

Time (h)	P_D^t (pu)	P_{g1} (pu)	P_{g2} (pu)	P_{g3} (pu)	P_{g4} (pu)	P_{g5} (pu)	P_{g6} (pu)	P_r (pu)	P_{st} (pu)	Cost ($/h)	Emission (ton/h)
0	1.5	0.05	0.116	0.05	0.62	0.05	0.136	0.15	0.338	234.742	0.239
2	1	0.05	0.05	0.05	0.429	0.05	0.05	0.1	0.225	177.971	0.246
4	1.5	0.05	0.116	0.05	0.62	0.05	0.136	0.15	0.338	234.742	0.239
6	2.5	0.05	0.195	0.236	0.773	0.22	0.23	0.25	0.563	363.31	0.222

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8	2.5	0.05	0.189	0.217	0.761	0.202	0.222	0.875	1.125	350.907	0.223
10	3	0.05	0.222	0.318	0.824	0.296	0.261	1.05	0.95	416.493	0.218
12	2.5	0.05	0.189	0.217	0.761	0.202	0.222	0.875	1.125	350.907	0.223
14	3	0.05	0.222	0.318	0.824	0.296	0.261	1.05	0.95	416.493	0.218
16	3	0.05	0.222	0.318	0.824	0.296	0.261	1.05	0.95	416.493	0.218
18	3.5	0.078	0.264	0.451	0.905	0.418	0.310	0.35	0.75	511.692	0.216
20	3	0.05	0.23	0.342	0.838	0.318	0.269	0.3	0.675	432.013	0.218
22	2	0.05	0.162	0.131	0.708	0.122	0.190	0.2	0.45	297.517	0.23
24	1.5	0.05	0.116	0.05	0.63	0.05	0.136	0.15	0.338	234.742	0.239

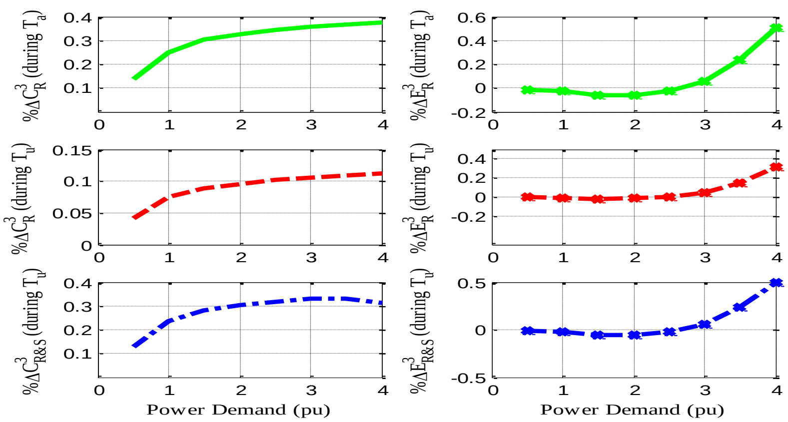

Fig. 11: Variations of Percentage Reduction in Cost and Emission with Power Demand for EED

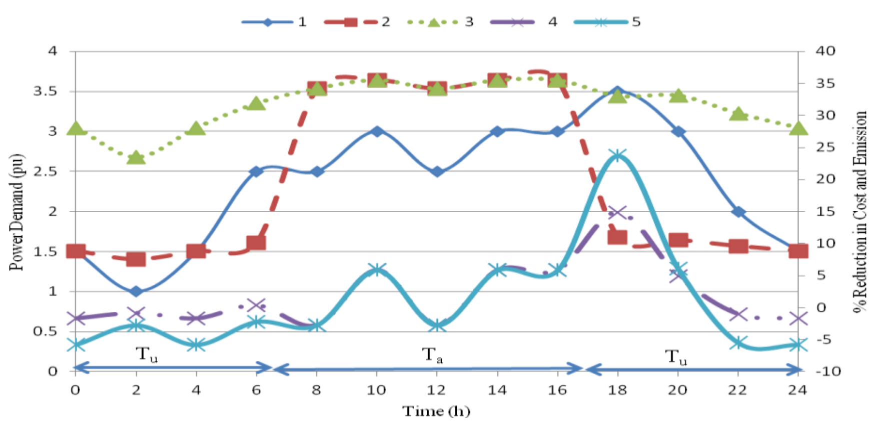

Fig. 12: Percentage change in Emission and Cost with daily Load Curve of EED

1. Load Curve, 2. $\%\Delta C_{R}^{1}$, 3. $\%\Delta C_{R\&S}^{1}$ 4. $\%\Delta E_{R}^{1}$ and 5. $\%\Delta E_{R\&S}^{1}$ s

For sustainable and environmentaly acceptable energy supply system, the use of renewable and clean energy is essential. Hence, optimum power dispatch methods for a hybrid power system with renewable sources and energy storage facilities have to ensure most reliable, economic and environmental friendly dispatch while managing the supply of available fuels. The selection of OPD problems depends on the availability of fuel sources as well as the priority of the objectives. The amount of fuel cost obtained from ED and EED problems are same while the amount of pollutants emission from EFD problem is always less than the amount of emissions from EED for a specific value of demand. Due to the carbon footprint, high cost and dwindling supplies of fuel, most of the countries have the objectives of reducing both fuel cost and amount of emission while meeting the power needs. EED is the best tool for such a dispatch. For countries which are blessed with renewable and non-renewable energy sources and have the main objective of reducing the amount of emissions only, EFD is the best option.

5. Conclusions

OPD problems are formulated for a hybrid system which includes thermal generating units, solar, wind and renewable storage. Analysis is carried out using MATLAB simulations for various operating strategies. Results show that, the renewable storage helps to take advantage of clean energy sources during unavailable periods. The optimized results are compared for both available and unavailable periods of sun light. From the analysis it is concluded that, if EED is adopted at low demand, it consumes less amount of extracted renewable power while for EFD, the renewable power consumption for optimal dispatch is almost zero at low demand periods. Thereby large values of energy can be stored at low demand during the solar power available periods. Also the amount of emission is always less in the EFD optimization than in the EED optimization. A strategy based on storage and reuse of renewable power can help in optimizing both the cost and the pollutants emissions. Thus, power utilities should examine the storage option seriously.

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