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Optimization of Pollution Emission in Power Dispatch including Renewable Energy and Energy Storage

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Abstract: Electric power dispatch with minimal pollutants emission is a major challenge for power system operators. One of the main objectives of Economic/Environmental Dispatch (EED) and Environmental Friendly Dispatch (EFD) is to optimize the amount of pollutants emitted from the hybrid power plants. The optimization problems determine the amount of optimum generation to be allocated to each generating unit including renewable sources without violating system constraints while minimizing the pollutants. EED is an important multi objective problem which minimizes both the fuel cost of generation and the amount of pollutants emission while EFD has the single objective of optimizing the amount of pollutants emission only. EED and EFD are especially more useful tools in areas that have high potential of renewable energy. Optimum EED and EFD can be obtained by extracting maximum renewable energy during their availability periods and then using this renewable energy for both available and unavailable periods with the aid of energy storage. This study illustrates the optimization of EED and EFD with renewable energy and energy storage. MATLAB simulations are performed using IEEE-30 test bus data with 6 generators to illustrate the benefits of renewable energy and energy storage in reducing the unwanted pollutants emission.

Keywords: Economic/environmental dispatch, energy storage, environmental friendly dispatch, renewable energy

INTRODUCTION

Electrical power generation is one of the major sources of pollutant emissions. Burning of oil, natural gas and coal at power plants produces 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 increase the risk of climate change. Pollution control devices on fossil fuel based plants and use of available renewable energy resources can help to reduce the amount of unwanted emissions. In such situations, the operating policy for such hybrid plants to minimize the amount of emissions is very important.

The power dispatch problem attempts to find the optimum operating policy for the committed units in order to meet the load demand while satisfying all unit and system constraints. Minimizing the fuel cost is the objective of traditional Economic Dispatch (ED) problem. At present about 63% of world electricity is generated by burning fossil fuels; 40% of which is from coal-fired power plants. Most of the coal-fired power plants were built two decades ago and account for 80-85% of NO_x emitted by electric utilities. Some older power plants operate with pollution rates of 70 to 100 higher than the newer plants (Rahman and Castro, 1995; Palanichamy and Babu, 2002). Due to the increased public awareness regarding the environmental issues, the utilities are being forced to use hybrid power systems including renewable sources and to modify their operation strategies in order to reduce the pollutants emission to the atmosphere.

Methods for reducing pollutants emission by the power plants with or without the use of renewable sources have been discussed in various literatures. Gent and Lamont (1971), Kumarappan and Mohan (2003) and Xian and Xu (2010) discussed methods to minimize emission only while Zahavi and Eisenberg (1977) and Al-Awami *et al*. (2009) outlined methods for reducing both fuel cost and pollutants emissions. Comparative analysis of methods for reducing both fuel cost and pollutants were

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reported by Brini *et al*., 2009; Le and Ilic, 2009; Chen and Wang, 2010. 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 plants to minimize both fuel cost and pollutant emissions simultaneously (Brini *et al*., 2009; Le and Ilic, 2009; Pazheri *et al*., 2012). In EED, the amount of renewable power to be dispatched is calculated based on the data available with the Environmental Information Systems and Load Dispatch Centers, by using any commercially available software package (Rahman and Castro, 1995). It is better to treat EED as a multi objective optimization problem instead of treating it as a single objective problem (Abido, 2003). Some reports have described EED as a multi objective problem with both solar and wind sources of renewable power (Al-Awami *et al*., 2009; Brini *et al*., 2009).

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. Hence the reduction of pollutant emission should be the main objective of power dispatch problems in such countries and EFD offers a suitable approach. The main objective of EFD is to minimize the emissions as it allocates the conventional and renewable power production among different generating stations to meet this objective without disturbing the constraints.

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 create issues in EED and EFD problems. Different methodologies were illustrated in several studies to overcome these issues. One of the methods is to treat renewable power as a negative load and formulate the demand equation on this basis (Anderson and Leach, 2004; Brini *et al*., 2009; Le and Ilic, 2009). The uncertainty in the availability of solar irradiation is less in high potential solar areas. The Kingdom of Saudi Arabia is one of the examples of such areas. The country is part of a vast, rainless region that receives about 6-7 kWh/m^2/day (Pazheri *et al*., 2011). 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 h. Other Middle Eastern countries, some part of India, Australia, etc are also examples of high potential solar areas. In many countries, there is considerable cloud activity which creates some uncertainty about available solar power output. 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 the 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 will ensure 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 from on shore installations.

The renewable power generation technologies and energy storage systems are being developed and widely used for economic and environmental friendly power dispatch. In such applications, the renewable power generators and energy storage systems are effectively interconnected with the existing power plants. Some of the energy storage systems are described by Kyung-Hee *et al*. (1996), Schoenung and Burns (1996) Rau and Short (1996) Feak (1997). 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 the unavailable periods of renewable power will make the EED and EFD optimization more effective.

For thermal generating units the fuel cost increases with the increase of the outputs of the committed units. Moreover, the amount of emission is usually high for both lower and higher values of the power output (Kockar *et al*., 2009). Thus, distributing the optimal values of renewable energies throughout the operating periods instead of using them only during their respective available period can help to reduce both the fuel cost and the pollution emissions to some extent. However, such an approach will require using suitable energy storage devices. The storage can also help to overcome the day-night weather based approach for economic dispatch.

The objective of this study is to present mathematical formulations of EED and EFD problems using hybrid power systems employing coal/oil/gas fired thermal plants and solar/wind based renewable plants, in addition to energy storage devices. The purpose of energy storage is to store part of the renewable power generated during its available period and use it during its unavailable period. This strategy can help in reducing the overall fuel cost as well as pollution emission. Thus, the study presents EED as a multi objective problem and EFD formulation as a single objective problem. The study presents the problem formulation, solution techniques and discussions on the results and findings of the study.

RENEWABLE ENERGY

In this study only solar and wind power are considered for 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) provided by a solar panel is proportional to solar irradiation S (W/m^2) and is given as:

Table 1: Wind power variation with wind speed

Wind speed V_w (m/s)	Wind power P_w (W)
$V_w \leq V_{min}$	0
$V_{min}\ V_w\ V_n$	useful power
$V_1 \leq V_w\ V_2$	P_{w1}
$V_2 \leq V_w\ V_3$	P_{w2}
$V_3 \leq V_w\ V_n$	P_{w3}
$V_n \leq V_w \leq V_{max}$	P_n
$V_w \geq V_{max}$	0

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

where, P_m is the panel power rating and τ is the drift in panel output due to temperature per ºC

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.

The mechanical power produced by a wind turbine P_w (W) can be written as:

$$P_w = \frac{1}{2} a_c \rho A_s V_w^3 \tag{3}$$

where, a_c is the aerodynamic coefficient of the wind turbine which depends on the turbine and the wind speeds, 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 under varying wind speed, the system is designed in such a way that the output power is constant for a certain range of wind speeds. Also, wind turbines are designed to develop a nominal power P_n with a nominal wind speed V_n. Wind speeds higher than V_n cause mechanical overloading of the turbine. To avoid such overloading and to limit the variance in the power output, the output power versus wind speed characteristic is summarized in Table 1. Here V_1, V_2 and V_3 ($V_{min} < V_1 < V_2 < V_3 < V_n < V_{max}$), are different wind speed levels available per day and P_{w1}, P_{w2} and P_{w3} are the corresponding power outputs.

PROBLEM FORMULATION

EED formulation: The objectives of EED are to minimize both fuel cost and the emission of pollutant gases while extracting maximum power from the renewable sources. Thus, the objective functions should include fuel cost and the emission functions. The fuel cost function $F_f(P_{gi})$ in \$/h is represented by a quadratic equation of the type:

$$F_f\left(P_{gi}\right) = \sum_{i=1}^{N_g}\left(a_i + b_i P_{gi} + c_i P_{gi}^2\right) \tag{4}$$

In Eq. (4), 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 and can be represented by a function that has the same form as the fuel cost function. Many factors such as the temperature of the boiler and air content determine the emission levels 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 as:

$$F_e\left(P_{gi}\right) = \sum_{i=1}^{N_g}\left(\alpha_i + \beta_i P_{gi} + \gamma_i P_{gi}^2 + \lambda_i e^{\delta_i P_{gi}}\right) \tag{5}$$

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

Whereas wind is available throughout the day at different locations with varying speed, the sun light is available only for a particular duration of the day. Our aim is to extract maximum amount of power from solar generator during the available period (T_a). Some part of renewable power generated during the available period is stored using suitable storage devices. This stored energy is used during the unavailable period (T_u) of the sun light.

The power extracted from the renewable source varies and can be considered as a variable load. Assuming P_s and P_w are powers produced by sunlight and wind, the power (P_s+P_w) is deducted from the total demand $\left(P_D^t\right)$. Also the stored power (P_{st}) is added to it during period T_a or subtracted from it during period T_u in order to obtain the actual net demand $\left(P_D^a\right)$ on the conventional thermal generators. This demand is then distributed among the available thermal generating units for dispatch purposes. This net actual demand is expressed as:

$$P_D^a = P_D^t - \left(P_s + P_w\right)_g \pm P_{st} \tag{6}$$

In this equation, the positive sign is applicable during the energy storage period whereas the negative sign is used during the stored energy delivery period.
The applicable constraints are formulated as follows:

- The total power generation, renewable power and stored power must cover the actual demand and the transmission lines power loss (P_L) to ensure power balance. Thus:

$$P_D^a + P_L - \sum_{i=1}^{N_g} P_{gi} = 0 \tag{7}$$

- The output power of the i^{th} generating unit is restricted by the lower limit $P_{gi}^{\min}$ and the upper limit $P_{gi}^{\max}$:

$$P_{gi}^{\min} \le /P_{gi} \le P_{gi}^{\max}, \ i = 1, 2, \ldots, Ng \tag{8}$$

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

$$P_L > 0 \tag{9}$$

- The amount of renewable power to be dispatched is limited to x times the actual demand:

$$\left(P_s + P_w\right)_d \le xP_D^a \tag{10}$$

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 amount of renewable power during the period T_a. However, during the 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 from the storage devices during T_u must not exceed the total energy stored during T_a. Thus:

$$P_{st} \le \frac{\sum_{T_a}\int_i \left[\left(P_s + P_w\right)_g - \left(P_s + P_w\right)_d\right]dt}{\int_i dt} \text{ during } T_a \tag{11}$$

$i = t_1, t_2, \ldots, t_n \in T_a$

and,

$$P_{st} \le y\frac{\sum_{T_a}\int_i \left[\left(P_s + P_w\right)_g - \left(P_s + P_w\right)_d\right]dt}{\int_i dt} \text{ during } T_u \tag{12}$$

where, y is proportional to $\frac{T_a}{T_u}P_D^a$ and is selected so that:

$$\sum_{T_u} P_{st} \le \sum_{T_a} P_{st} \tag{13}$$

Thus, the optimization problem for EED can be summarized as follows:

Minimize $(F_f(P_{gi}), F_e(P_{gi}))$
Subjected to the following constraints:

$$P_D^a + P_L - \sum_{i=1}^{N_g} P_{gi} = 0$$
$$P_{gi}^{\min} \le P_{gi} \le P_{gi}^{\max}$$
$$P_L > 0$$
$$\left(P_s + P_w\right)_d \le xP_D^a$$
$$P_{st} \le \begin{cases} \dfrac{\sum_{T_a}\int_i \left[\left(P_s + P_w\right)_g - \left(P_s + P_w\right)_d\right]dt}{\int_i dt}; during\, T_a \\ y\dfrac{\sum_{T_a}\int_i \left[\left(P_s + P_w\right)_g - \left(P_s + P_w\right)_d\right]dt}{\int_i dt}; during\, T_u \end{cases}$$

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

EFD formulation: The characteristics of the thermal plants are normally such that the total amount of emission is high at lower and higher values of power output. Thus, it is 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 lower demand periods it may be helpful to store all of the produced renewable energy. In EFD, the fuel cost is assumed to be very small and is not considered and thus, the main objective is to minimize the emission levels of polluting gases by extracting the maximum power from the renewable sources in order to meet the actual net demand without violating the applicable constraints. Therefore, the objective function is the emission of conventional generators given in (5) and the constraints are the same as given in (7) to (13). Here, the EFD problem can be summarized as:

Minimize $\lfloor F_e(P_{gi}) \rfloor$
Subjected to the constraints given in (7)-(13)

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

RESULTS AND DISCUSSION

The MATLAB simulations were carried out for both EED and EFD formulations using the data of the 30 bus IEEE standard test system (Abido, 2003; Brini *et al*., 2009). Here, two case studies are discussed: Case A, during period T_a and Case B, during period T_u. During T_a period, high intensity of solar radiation provides P_s and variable wind power P_w is available also. 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 and the remaining part of renewable power is stored. During period 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 20% of the total demand) when compared to case A.

Table 2: Generator cost and emission coefficients (Abido, 2003)

	Cost			Emission				
	a	b	c	α	β	γ	λ	δ
P_{g1}	10	200	100	4.091	-5.554	6.490	2x10-4	2.857
P_{g2}	10	150	120	2.543	-6.047	5.638	5x10-4	3.333
P_{g3}	20	180	40	4.258	-5.094	4.586	1x10-6	8.000
P_{g4}	10	100	60	5.326	-3.55	3.380	2x10-3	2.000
P_{g5}	20	180	40	4.258	-5.094	4.586	1x10-6	8.000
P_{g6}	10	150	100	6.131	-5.555	5.151	1x10-5	6.667

Table 3: Amount of dispatched power and emission of each generator units without the use of renewable sources

	P_D^t (pu)	Emission (ton/h)	P_{g1} (pu)	P_{g2} (pu)	P_{g3} (pu)	P_{g4} (pu)	P_{g5} (pu)	P_{g6} (pu)
EED	0.5	0.2479	0.0500	0.0500	0.0500	0.2503	0.0500	0.0500
	1.0	0.2400	0.0500	0.1032	0.0500	0.6232	0.0500	0.1239
	1.5	0.2278	0.0500	0.1749	0.1496	0.7664	0.1496	0.2098
	2.0	0.2191	0.0500	0.2239	0.2967	0.8644	0.2967	0.2687
	2.5	0.2177	0.0746	0.2705	0.4365	0.9577	0.4365	0.3246
	3.0	0.2279	0.1272	0.3144	0.5681	1.0454	0.5681	0.3772
	3.5	0.2658	0.1799	0.3582	0.6996	1.1331	0.6996	0.4299
	4.0	0.3740	0.2325	0.4021	0.8312	1.2208	0.8312	0.4825
	4.5	0.6748	0.2851	0.4459	0.9628	1.3085	0.9628	0.5351
	5.0	1.5000	0.3378	0.4898	1.0944	1.3963	1.0944	0.5878
EFD	0.5	0.2435	0.0859	0.1284	0.0666	0.0500	0.0666	0.1029
	1.0	0.2246	0.1759	0.2231	0.1732	0.0500	0.1732	0.2052
	1.5	0.2110	0.2456	0.2975	0.2472	0.1838	0.2472	0.2792
	2.0	0.2022	0.3244	0.3725	0.3122	0.3265	0.3122	0.3527
	2.5	0.1987	0.4010	0.4579	0.3701	0.4848	0.3701	0.4165
	3.0	0.2008	0.4890	0.5388	0.4194	0.6537	0.4194	0.4799
	3.5	0.2091	0.5836	0.6235	0.4617	0.8348	0.4617	0.5350
	4.0	0.2242	0.6851	0.7082	0.4968	1.0291	0.4968	0.5842
	4.5	0.2466	0.7912	0.7938	0.5281	1.2321	0.5281	0.6271
	5.0	0.2767	0.9031	0.8764	0.5571	1.4425	0.5571	0.6642

Three sub cases considered were:

- Without renewable and storage
- With renewable only but without storage
- With both renewable and storage

Let E_N^k, E_R^k and $E_{R\&S}^k$ be the values of emission per hour and C_N^k, C_R^k and $C_{R\&S}^k$ the fuel cost per hour corresponding to these three sub cases, where k = 1 and 2 apply to EED and EFD problems, respectively. The values of the fuel and emission coefficients used for simulations are given in Table 2.

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

$$0.05\ pu \leq P_{gi} \leq 1.5\ pu\ ;\ i = 1, 2, \ldots, 6 \tag{14}$$

The optimum amount of power dispatch and emission of each generating units without using renewable sources for EED and EFD cases are given in Table 3. Although the given loads are the same in both EED and EFD, the outputs of thermal units in these cases are different. This is due to the fact that the generation in EED is based on optimum values of both cost and emission while in EFD, it is based on the optimum amount of emissions only. These results further show that, the amount of emission is always higher in the case of EED than in the case of EFD.

EED results: The results of EED during T_a are summarized in Figs. 1 and 2. Figure 1 shows that, E_R^1 decreases with the increase in demand while E_N^1 decreases up to a certain level of the total demand and then it increases rapidly with further increase in the demand. Also C_R^1 for a given demand is always less than C_N^1. The variation of emission with respect to cost is shown in

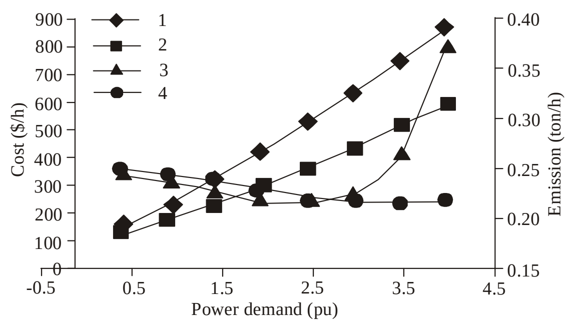

Fig. 1: Variation of emission & cost with power demand in EED during T_a, 1: C_N^1; 2: C_R^1; 3: E_N^1; 4: E_R^1

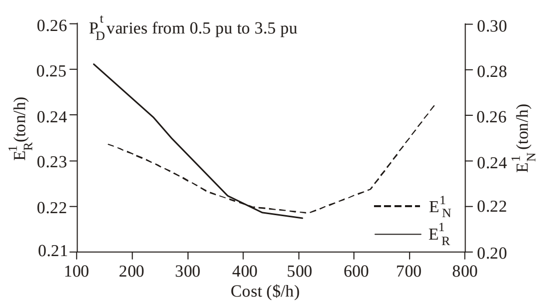

Fig. 2: Variation of emission with cost in EED during T_a

Fig. 2. Comparing Figs. 1 and 2, it is clear that 3 pu demand can be met with a cost of 450 $/h with renewable sources while only 2 pu can meet without the use of renewable sources when the amount of emission is about 0.22 ton/h in both cases.

Assuming that 1 pu of stored power is available throughout T_u period, then the amount of stored dispatched power is related to the demand and the T_u duration. The results are summarized in Figs. 3 and 4. It

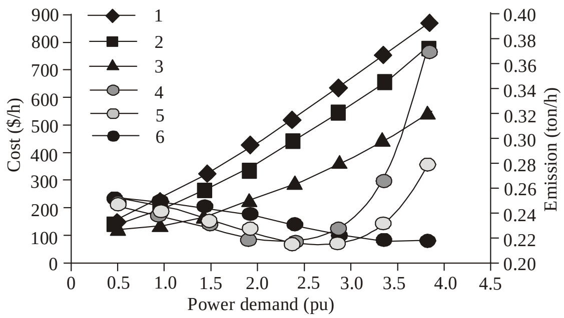

Fig. 3: Variations of emission & cost with power demand during Tu, 1: $E^1_{R\&S}$; 2: E^1_R; 3: E^1_N; 4: $C^1_{R\&S}$; 5: C^1_R; 6: C^1_N

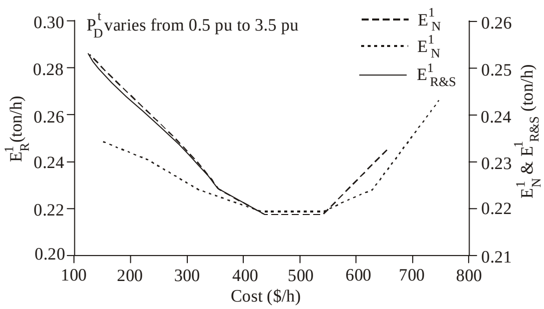

Fig. 4: Variation of emission with cost during T_u

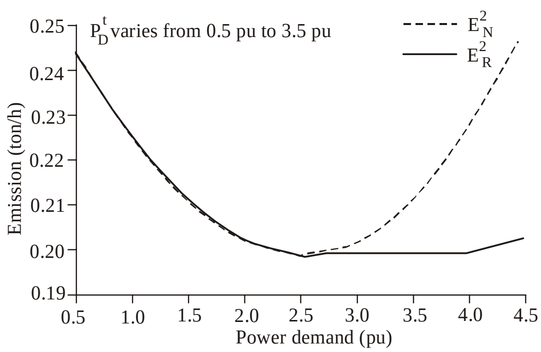

Fig. 5: Variation of emission with power demand during T_a

is seen that, the fuel cost per hour is such that $C^1_{R\&S} < C^1_R < C^1_N$ for a given amount of demand. Moreover, the emission per hour is $E^1_{R\&S} < E^1_R < E^1_N$ for higher values of demand. From Fig. 3 and 5, the demands which can be met with a cost of about 450 $/h in the case of non renewables, with renewable only and with both renewable and storage are 2, 3 and 3.5 pu, respectively while the amount of emission/hour in these cases remain the same and is equal to 0.22 ton/h.

EFD results: The variation of emissions/hour with demand during period T_a is shown in Fig. 5 and during period T_u is shown in Fig. 6. From Fig. 5, the value of E^2_R during T_a is almost equal to E^2_N for low demand.

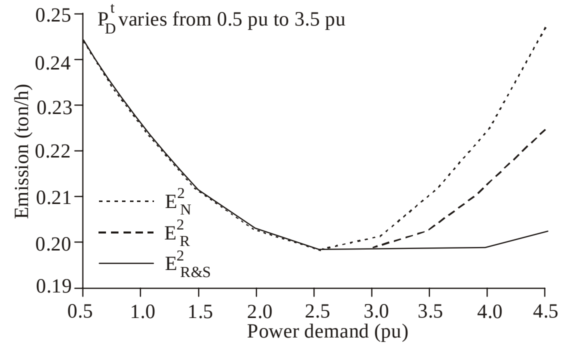

Fig. 6: Variation of emission with power demand during T_u

However, for higher demand, E^2_R is less than E^2_N. Also, the value of E^2_R, $E^2_{R\&S}$ and E^2_N is almost the same at low levels of demand during period T_u but for higher demands $E^2_{R\&S} < E^2_R < E^2_N$ is as shown in Fig. 6. The optimum values of emission/hour for low demands are obtained without the use of renewable sources and their 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 decreases the net emission. Therefore, it is advisable to store maximum renewable power during low demand periods and use this stored energy during peak load periods.

EED or EFD: Due to the carbon footprint, high cost and dwindling supplies of fuel, most of the countries have the objective 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 pollution emissions only, EFD is the best option.

Figure 7 shows the variation of %ΔE with time for meeting a specified load demand. % ΔE_R and % $\Delta E_{R\&S}$ are defined as:

$$\left(\%\Delta E_R = \left(1 - \frac{E^1_R}{E^1_N}\right)100\right) \text{ and } \left(\%\Delta E_{R\&S} = \left(1 - \frac{E^1_{R\&S}}{E^1_N}\right)100\right).$$

About 25% of emission can be reduced while supplying a demand of 4 pu during the Tu period if EED is adopted with the addition of renewable sources while this amount is about 40% when both renewable and storage are used. Similarly, the variation of %ΔC with time for a specified load demand is shown in Fig. 8, where, % ΔC_R and % $\Delta C_{R\&S}$ are:

$$\left(1 - \frac{C^1_R}{C^1_N}\right).100 \text{ and } \left(1 - \frac{C^1_{R\&S}}{C^1_N}\right).100\text{, respectively}$$

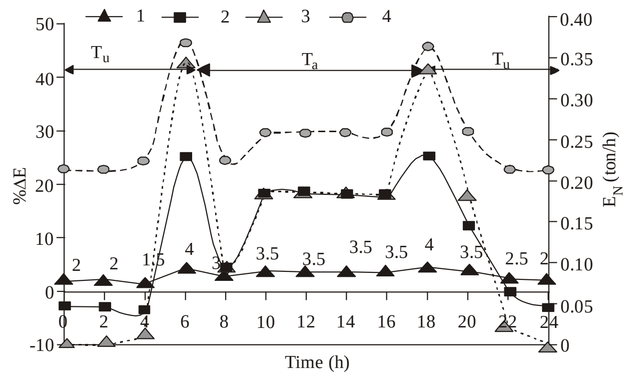

Fig. 7: Percentage change in emission and E_N with load curve (in EED) 1: Load (pu); 2: % ΔE_R; 3: % $\Delta E_{R\&S}$; 4: E_R^1

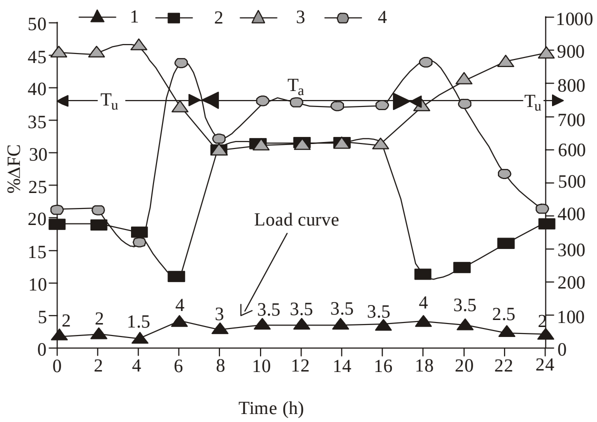

Fig. 8: Percentage change in cost and C_N with load curve (in EED),1: Load (pu); 2: % ΔC_R; 3: % $\Delta C_{R\&S}$; 4: C_N^2

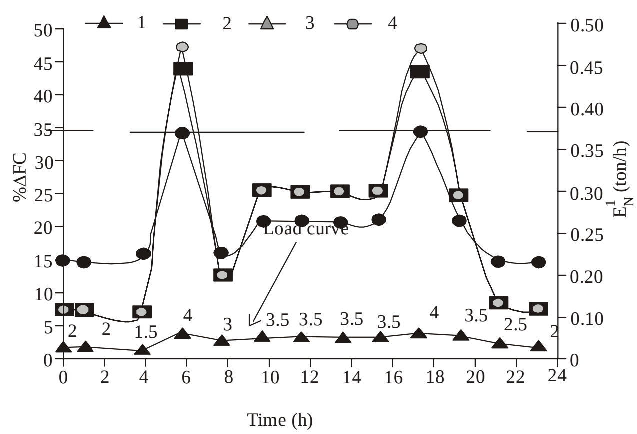

Fig. 9: Percentage change in emission and E_N with load curve (in EFD) 1: Load (pu); 2: %$\Delta E'_R$; 3: %$\Delta E'_{R\&S}$; 4: E_R^1

The percentage saving of cost with renewable sources at a demand of 3.5 pu during T_a is about 30% and it is about 12% during T_u but the percentage saving is approximately 45% with the use of both renewable sources and the storage.

The variation of percentage reduction of emission in the EFD formulation with a specified load curve while comparing with E_N^1, for renewable only:

$$\%\Delta E'_R = \left(1 - \frac{E_R^2}{E_N^1}\right).100$$

and for both renewable and storage:

$$\%\Delta E'_{R\&S} = \left(1 - \frac{E^2_{R\&S}}{E^1_N}\right).100$$

is shown in Fig. 9 and these values corresponding to 4 pu power demand during T_u are about 43% and 48%, respectively. Comparing Fig. 7 and 9, it is clear that the reduction in the amount of emission in the case of EFD is always higher than that of the amount in the case of EED for all the considered operating strategies.

CONCLUSION

EED and EFD problems are formulated for a hybrid system which includes thermal generating units, solar and wind renewable and energy 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 solar radiation 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, it consumes less amount of extracted renewable power while for EFD formulation renewable power for optimal dispatch is not used at low values of power demands and thus 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 formulation than in the EED formulation. A strategy based on storage and reuse of renewable power can help in optimizing both the cost and pollutants emission. Thus, power utilities should examine the storage option seriously.

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