Economic Dispatch and Cost Analysis on a Power System Network Interconnected With Solar Farm

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Abstract- Frequent escalation of fuel prices, concerns on environment and diminution of fossil fuel reserves have forced the incorporation of Renewable Energy resources with the existing generation. This paper presents an Economic Dispatch model developed for a system consisting of thermal units and Photo Voltaic (PV) plants. Since solar power is intermittent in nature, Beta distribution function is utilized for estimating the power output of PV panels. The seasonal changes of desired location are also included for effective analysis of the output. Case studies are carried out for various generation levels and seasonal changes. The possible choices of installing solar plants in the test system are analysed. The proposed methodology is tested and validated on a standard IEEE 30 bus test system..

Keywords Economic dispatch, solar irradiance, Beta distribution function, thermal generator, PV array.

1. Introduction

To meet the prerequisites of increasing population, reducing the utilization of fossil fuels and green house gases, convincing research has been conducted through the world for improvement of sustainable and renewable energy systems [1-2]. In general the power systems of many countries are planned as an interconnected systems and intensely depends on conventional sources of generation. This framework needs alterations and upgrades so as to meet the future necessitates. Integrated energy planning has become a necessity for the sustainable growth of energy sector for any country [3]. Many developing countries are executing the public policies required for the far reaching advancement of renewable energy technologies and markets. A minimum of 20% contribution from the renewables has been set as a target by many countries [4]. For example, in order to encourage improvement and generation of alternate or renewable energy, Indian government established Jawaharlal Nehru National Solar Mission in 2010. The main goal of this mission is to install 20000 MW capacity of Solar plants by year 2022 [5]. Globally many countries are setting up their own policies for the integration of renewable energy in to the grid and thereby reducing the emission from fossil fuels.

India is enriched with an exceptionally limitless solar energy potential. Most parts of the nation have around 300 sunny days. Normal solar radiation occurrence over the area is in the scope of 4-7 kWh every day. The solar energy can be used through solar photovoltaic technology which empowers direct change of sunlight into electrical energy [5]. At present solar energy generation contributes a very small proportion of total generation. But with the decreasing system costs and availability of resources, future expansion and integration of solar energy with the grid is necessary.

The balance between the power generation and load demand is a critical task while considering the renewables into account. This is due to the variability and uncertainty of the power output from the renewables with time [6-7]. The generation schedule of a solar panel depends on the solar irradiance available in a site. Solar irradiance varies from time to time over a day and also with seasons[8]. Therefore the solar irradiance must be properly modelled for exact value of output. There are many methods available for irradiance modelling out of which beta distribution PDF has been used by many researchers for its accuracy [9-10]. This requires historic data of the solar irradiation over a particular period. Past one year data is considered and processed in to three seasons namely summer, spring and winter. Now for the three seasons, variations in power output for the same installed capacity is observed and is further utilised in current problem.

Economic Dispatch (ED) is an imperative and a continual step in operational planning of a power system. The general economic dispatch problem is stated as the procedure of distributing generating levels to the thermal units, so that the system load may be supplied altogether economically [11]. Constraints like generation limits, power balance etc. are important considerations in this problem. Many researchers concentrated on the improvement in general economic dispatch problem where as the research on dispatch considering renewables is limited [12].

Economic dispatch using equal incremental cost was used initially and transmission loss and penalty factor were incorporated in that later. A review on ED methods from 1977 to 1988 are given in [19]. To evaluate the economic dispatch problem thermal generators were used extensively. Intelligent methods like Particle swarm optimization (PSO), Differential Evolution (DE), Genetic Algorithm (GA), Evolutionary Programming (EP) are used for complex dispatch problem considering prohibited operating zones, valve point and quadratic cost functions. ED with cost and emission is considered as a multi objective problem which requires optimization techniques to solve this.. In [20] PSO based ED with valve point effect is presented, which depicts the effects of valve point loading of thermal generation in generation cost. In [21] multi objective combined economic emission dispatch is converted to single objective economic dispatch using penalty factor and ABC algorithm is used to solve the problem. In [22] economic dispatch considering single solar and a wind farm is carried out on standard IEEE 30 bus system and SPEA algorithm is used for solving the problem. In [23] DED is carried out with the incorporation of two solar and two wind farms in addition to three thermal units using a PSO algorithm and shows that the emission is minimised with inclusion of these renewable energy sources.

1.1. Proposed Work:

Considering the literature survey on ED and renewable energy sources, the solar plants are considered lossless and the climatic effects of their power outputs are not considered. Since, the same transmission line is utilized for the transmission of solar power also; considerable losses will occur because of the resistance and reactance of the transmission lines. The solar power depends upon the irradiation which in turn depends on the climatic conditions. Considering all these factors, in this work, a fixed percentage of loss is considered while transmitting solar power through the existing transmission lines. Since the output of solar power depends in climate, the case studies are considered for different climatic conditions. In this model solar power plants are assumed to be installed by the public utility and the cost for installation is not considered.

IEEE 30 bus test system consists of 6 thermal generators, 41 transmission lines interconnected to the 30 buses. The thermal generator cost coefficients, Power generation limits and Schematic diagram are given in appendix A and B. The following case studies are conducted on the above said test system.

- Cost comparison considering solar farm output as negative load
- Cost comparison including losses from Solar farm
- Cost comparison by incorporating Solar farm at desired location
- Cost comparison by replacing some thermal units with Solar farm

The rest of the paper is organised as follows: Section 2 describes the general economic dispatch problem and also the changes to be adopted with the integration of renewable energy in economic dispatch problem. Section 3 gives the information on solar irradiance modelling and estimation of power output from a PV array. In section 4 integration of solar energy in economic dispatch and the cost optimisation for various scenarios is described.

2. Economic Dispatch problem

The main objective of economic load dispatch problem is to minimise the fuel cost of the thermal generators [13]. The objective function can be formulated as

$$F_i(P_i) = \sum_{i=1}^{n} (a_i P_i^2 + b_i P_i + c_i) \tag{1}$$

where $F_i(P_i)$: Fuel cost of all the generators ($/hr)

a_i, b_i, c_i : Cost coefficients of i^{th} generator.

P_i : Power generated by i^{th} generator.

n : No of generators

subjected to:

Equality constraints:

The power balance of the system is given by

$$\sum_{i=1}^{m} P_i - P_D - P_L = 0 \tag{2}$$

where P_D : Load demand (MW)

P_L : Transmission losses (MW)

Transmission losses can be represented as

$$P_L = \sum_{i=1}^{n} \sum_{j=1}^{n} P_i B_{ij} P_j \tag{3}$$

where B_{ij} : Transmission loss coefficient

Inequality constraints:

The power generation of all the generators has maximum and minimum limits

$$P_i^{\min} \le Pi \le P_i^{\max} \tag{4}$$

where $P_i^{\min}, P_i^{\max}$ are the minimum and maximum generation limits

2.1. Coordinated Economic dispatch model considering solar energy:

The output power from a solar panel depends mainly on the irradiance. So, the power output for various irradiance values is the be estimated which requires proper functional model. The the best adopted model is beta distribution function. The historical data of solar irradiance is processed according to seasons and then it is utilised for modelling the beta distribution function. Using this function the output of a solar panel is estimated and then the total output obtained for the entire solar farm is calculated. This power generated by the solar farm is considered as negative demand and is incorporated at the specific point. Then economic dispatch is carried out using this model and the results are compared.

For incorporating the solar energy into the exiting generation, the power generated by PV arrays is considered as a negative load and equation (2) is updated as follows

$$P_D^{'} = P_D - \sum_{iS=1}^{n} P_{iS} \qquad (5)$$

where $P_D^{'}$ is new power demand and $\sum_{iS=1}^{n} P_{iS}$ is the sum of solar power generators.

3. Solar Power generation model

Solar power depends on meteorological conditions such as irradiance, ambient temperature which are directly related to geographical location [8,14]. For effective utilisation of PV arrays the characteristics should be desperately analysed. For the above case study, Vellore region which is located in Tamilnadu, India is considered.

3.1. Analysis of resources

Vellore region (79.15° E, 12.95° N) has noticeable seasonal changes. The study period of one year is divided into three seasons Summer (March to June), Spring (July to October) and Winter (November to February). Each day of the season is divided into 24 segments which refers to hours of a day. Mean and standard deviation of solar irradiance are calculated from the historical data [15]. For this study, mean and standard deviation at 12° clock of the day for the three seasons are calculated and furnished in Table 1.

Table 1. Mean and standard deviation for three seasons

Parameter	Summer	Spring	Winter
Mean (μ)	0.9402	0.7834	0.7152
Standard Deviation (σ)	0.1088	0.1772	0.2402

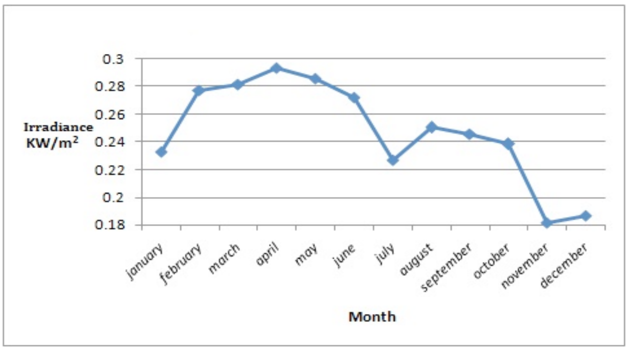

Fig. 1. Monthly variation of solar irradiation (kw/m^2)

The average value of variation in solar irradiance is shown in Fig. 1. It is observed that the irradiance is maximum in summer season (for the months March to June) and minimum for the months November to January.

3.2. Solar irradiance modelling

A stochastic model [16] of Solar panel is constructed based on Beta distribution function. Beta distribution is considered to be the most suitable model for statistical representation of the probability density function. The Solar irradiance distribution of the panel is given by

$$f_b(s) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} s^{(\alpha-1)} (1-s)^{(\beta-1)}, 0 \le s \le 1; \alpha, \beta \ge 0 \qquad (6)$$

$$\beta = (1-\mu)\left(\frac{\mu(1+\mu)}{\sigma^2} - 1\right), \ \alpha = \frac{\mu\beta}{1-\mu}$$

where $f_b(s)$ is Beta distribution function, Γ(°) is the gamma function and s is the random variable of solar irradiance (kw/m^2), α and β are the parameters of the Beta distribution function. μ and σ are the mean and standard deviation of s for the corresponding time segment.

3.3. Power generation from PV array

The expected output of PV is given by

$$P(s) = P_o(s) * f_b(s) \qquad (7)$$

The total output of the PV array corresponding to specific time segment is given by

$$TP = \int_0^1 P_o(s) * f_b(s) ds \qquad (8)$$

where power generation of panel at solar irradiance s is given by

$$P_o(s) = N * FF * V_y * I_y \qquad (9)$$

where N is the total number of PV modules.

The voltage - current characteristics of a PV module for a given radiation level and ambient temperature are determined using the following relations

$$FF = \frac{V_{MPPT} * I_{MPPT}}{V_{OC} * I_{SC}} \qquad (10)$$

$$V_y = V_{oc} - K_v * T_{cy} \qquad (11)$$

$$I_y = s[I_{sc} + K_i(T_{cy} - 25)] \qquad (12)$$

$$T_{cy} = T_A + s\left(\frac{N_{OT} - 20}{0.8}\right) \qquad (13)$$

where FF is the fill factor, V_{MPPT},I_{MPPT} are the voltage and current maximum power point, $V_{OC,}$ I_{oc} are the open circuit voltage and short circuit current of PV module, K_v and

K_i are the voltage temperature coefficient and current temperature coefficient, T_A, T_{CY},N_{OT} are the ambient temperature, PV cell temperature and Normal operating temperature respectively. The specifications of a 220 W PV module[17] are given in Table 2.

Table 2. Specifications of 220W solar panel

Parameter	Value
Maximum Power point Voltage, V_{MPPT}	28.36 V
Maximum Power point Current, I_{MPPT}	7.76 A
Open circuit Voltage, V_{OC}	36.96 V
Short Circuit current, I_{SC}	8.38 A
Nominal Operating Temperature, N_{OT}	43 °C
Ambient Temperature, T_A	30.76 °C
Voltage Temperature Coefficient, K_v	0.1278 V/°C
Current Temperature Coefficient, K_i	0.00545 A/°C

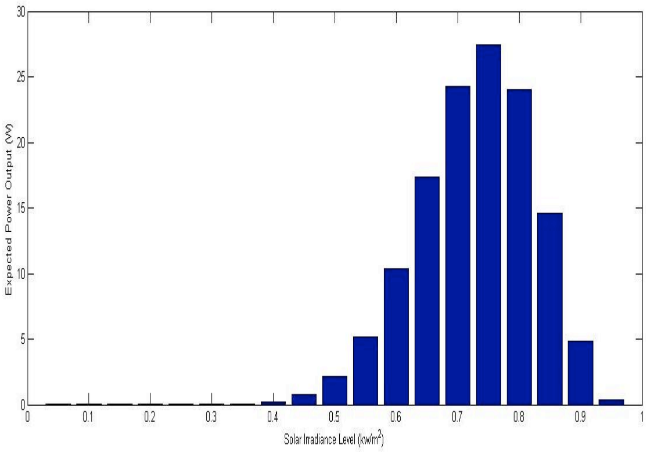

Fig. 2. Discrete Power distribution (W) of a PV module in Winter season

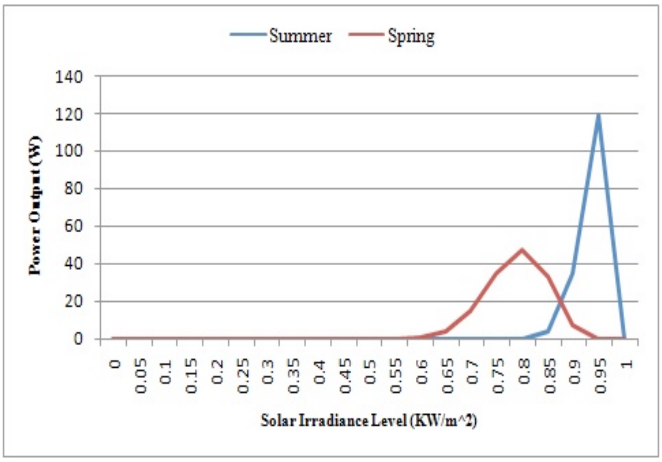

Fig. 3. Power variation (W) of PV module during Summer and Spring seasons

The discrete solar distribution of the solar panel during 12^o clock of a day in winter is shown in Fig. 2 and the power variation during summer and spring is shown in Fig. 3.

4. Results and Discussion

Proposed methodology has been simulated on standard IEEE 30 bus system. The details of the test system are given in [18]. Newton- Raphson power flow is used to evaluate the test system. A constant load model is assumed throughout the year**.** It is also assumed that the geographical conditions analysed for considered location are similar for the test system. Based on the solar power generation model shown in Section 2 various cases are considered for the study.

4.1. Scenario 1: Combined Economic dispatch with Thermal and Solar generation

The solar farm is designed with 20000 PV modules which comprises an installed capacity of 44 MW (20000*220W). The power output for each season is estimated using Beta distribution function. The contribution in each season for meeting the demand is plotted in Figure 4. Here four possible combinations of utilising the solar power are discussed.

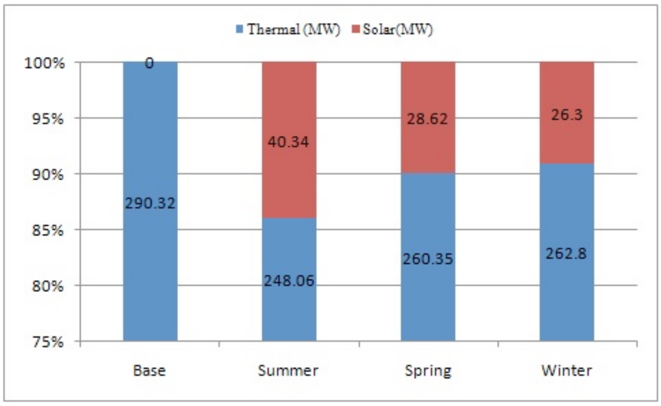

Fig. 4. Contribution of solar energy during various seasons

4.1.1 Case 1:

In this case, output of solar farm is considered as negative load such that the updated demand is the difference between the actual load and the solar power output. Economic dispatch is carried out for the updated demand and the objective function is optimised for three seasons and is analysed. The power generated and fuel cost of all the thermal units are given in Table 2.

From Table 2, it is clear that, the generation cost is less in summer season, since the contribution from the solar farm is considerable compared to the remaining cases. In this case, a random location is considered for installing solar farm in the test system. Even though the solar power generation in winter and spring is less compared to summer season, the profit obtained with the incorporation of solar farm is significant compared to the base case.

Table 2. Generating capacities and Fuel costs of the combined solar thermal systems

Gen No	Base case		Winter		Spring		Summer	
	Gen (MW)	Cost ($/hr)	Gen (MW)	Cost ($/hr)	Gen (MW)	Cost ($/hr)	Gen (MW)	Cost ($/hr)
Pg 1	178.5827	476.7596	162.5436	424.1639	160.7432	418.3804	151.7077	389.7226
Pg 2	53.6740	144.3451	49.6172	129.9128	49.1022	128.1217	46.5319	119.3220
Pg 3	19.5279	43.3617	18.6417	40.3611	18.5061	39.9108	17.8287	37.6951
Pg 4	15.0412	50.7618	10.0000	33.3300	10.0000	33.3300	10.0000	33.3300
Pg 5	11.5033	37.8180	10.0000	32.5000	10.0000	32.5000	10.0000	32.5000
Pg 6	12.0000	39.6000	12.0000	39.6000	12.0000	39.6000	12.0000	39.6000
Pg S	0	-	26.30	-	28.62	-	40.34	-
Pg Total	290.3291	**792.6462**	262.8025	**699.8678**	260.3515	**691.8429**	248.0683	**652.1697**

4.1.2 Case 2:

Here, the case study is carried out similar to Case 1 by considering the losses incurred with the incorporation solar farm into the system. It is observed from the base case that the real power losses is 2.4% of the total demand. As the solar power is transmitted through the same transmission lines, similar proportion of real power loss is considered for solar power also. Here also a random location is considered for installing solar farm in the test system. The generation cost obtained without and with solar along with the profit for various seasons is given in Table 3. It is observed from Table 3 that, the generation cost is increased by a small percentage when losses are considered.

Table 3. Profit analysis of Thermal and Combined solar thermal systems

Season	Thermal ($/hr)	Thermal + Solar ($/hr)	Profit ($/hr)
Summer	792.64	655.41	137.24
Spring	792.64	694.20	98.44
Winter	792.64	702.04	90.60

4.1.3. Case 3:

For the above two cases, random location is assumed for solar installation. In this case , it is assumed that the solar farm is located near generators 5 and 6. The generation in these two locations are completely replaced by solar power. The cost obtained in this case in given in Table 4. This cost is more compared to the winter season in Case 1 since, the cost coefficients are different for all generators. In the same case, three generators namely Pg 3, Pg4, Pg5 are replaced by solar power and the analysis is carried out . This cost is also slightly more than the cost for summer season compared to Case 1. From this it is clear that, installing solar farm in proper location can reduce the generation cost. If the solar plants are distributed randomly, the generation cost may increase depending on the generation.

4.1.4. Case 4:

In this case it is assumed that the solar power farm is situated at a near a generator bus and the burden on that particular generator is reduced. Results when the solar power generator is situated at bus 1 and bus 2 are shown in Table 5.
From the case studies above in scenario 1, it is clear that the total generation cost with the incorporation of solar energy depends on climatic conditions. This cost varies with the irradiation available at various seasons. During summer season the solar contribution is more and the thermal generation can be reduced depending on the load demand. But in winter season, the contribution of solar is less and the thermal plants are forced to increase their generation compared to summer season. The solar power cannot be considered as a fixed share for all climatic conditions. This analysis is done with fixed load demands throughout. It is evident from Table 4 that the location solar place plays a vital role in generation cost.

Table 4. Generating capacities and fuel costs after replacing some thermal generators by solar

Gen No	Base case		Winter		Spring		Summer	
	Gen (MW)	Cost ($/hr)	Gen (MW)	Cost ($/hr)	Gen (MW)	Cost ($/hr)	Gen (MW)	Cost ($/hr)
Pg 1	178.5827	476.7596	178.5827	476.7596	178.5827	476.7596	178.5827	476.7596
Pg 2	53.6740	144.3451	53.6740	144.3451	53.6740	144.3451	53.6740	144.3451
Pg 3	19.5279	43.3617	19.5279	43.3617	19.5279	43.3617	17.7279	37.3703
Pg 4	15.0412	50.7618	12.2445	41.0390	10	33.33	-	0
Pg 5 (S)	11.5033	37.8180	-	0	-	0	-	0
Pg 6 (S)	12.0000	39.6000	-	0	-	0	-	0
Pg Total	290.3291	**792.6462**		**705.5054**		**697.7964**		**658.475**

Table 5. Cost comparison by incorporating Solar farm at desired location

Gen No	Winter ($/h)	Spring($/h)	Summer($/h)
Pg 1 - Pg S	707.41	700.10	664.00
Pg 2 - Pg S	709.32	703.09	674.72

4.2 Scenario 2: Combined Economic Dispatch considering start up constraints

The solar farm is designed with 10000 PV modules which comprises an installed capacity of 22 MW (10000*220W). Here two case studies are done for various seasons considering the start up constraints for the thermal generators.

4.2.1. Case 1:

This case follows the equation (5) given in section 2 and the economic dispatch is obtained. Here the cost comparison for various seasons is presented in Table 6.

4.2.2. Case 2:

The studies carried out in Case 3 and 4 of Scenario 1 is applicable when the generators can be shut down only for a specific period such that there is negligible start up cost. But practically all the generators have finite start up time. Hence, in this case analysis is made considering the start up constraint. Here output from solar generator is sufficient to turn off the units 4,5 and 6 for the particular time interval. But it is not feasible to turn off the units as it imposes additional penalty costs for the upcoming intervals if the thermal units are to be immediately started. So for this situation we will run the thermal units 4,5 and 6 at minimum MW limit and the available solar power is utilised by reducing the generation of unit 2. The cost analysis is presented in Table 7.

From the case studies above in Scenario 2, it is evident that the scheduling of generation is an essential part. The power generation from thermal units cannot be turned off as required depending on the solar power available. In this condition, these generators are allowed to run in its minimum generation value and the dispatch is carried out, which aviods the additional penalty costs. However, this may result in increased generation cost if the costly generators are put into service.

Table 6. Generating capacities and Fuel costs of combined solar thermal systems

Gen No	Base case		Winter		Spring		Summer	
	Gen (MW)	Cost ($/hr)	Gen (MW)	Cost ($/hr)	Gen (MW)	Cost ($/hr)	Gen (MW)	Cost ($/hr)
Pg 1	178.5827	476.7596	171.2218	452.3821	170.5699	450.2425	169.7285	447.4863
Pg 2	53.6740	144.3451	51.6330	137.0122	51.4529	136.3720	51.2206	135.5480
Pg 3	19.5279	43.3617	19.0209	41.6332	18.9761	41.4819	18.9183	41.2872
Pg 4	15.0412	50.7618	12.3899	41.5412	12.1540	40.7266	11.8494	39.6759
Pg 5	11.5033	37.8180	10.3166	33.6105	10.2115	33.2414	10.0760	32.7660
Pg 6	12.0000	39.6000	12.0000	39.6000	12.0000	39.6000	12.0000	39.6000
Pg S	0	-	13.15	-	14.31	-	20.17	-
Pg Total	290.3291	**792.65**	276.5822	**745.78**	275.3644	**741.66**	273.7928	**736.36**

Table 7. Cost comparison by incorporating solar farm considering start up constraints

Gen No	Base case		Winter		Spring		Summer	
	Gen (MW)	Cost ($/hr)	Gen (MW)	Cost ($/hr)	Gen (MW)	Cost ($/hr)	Gen (MW)	Cost ($/hr)
Pg 1	182.8443	491.0587	182.8443	491.0587	182.8443	491.0587	182.8443	491.0587
Pg2-PgS	55.4914	150.9977	42.3413	105.4710	41.1743	101.7232	35.3159	83.6289
Pg 3	20.1840	45.6462	20.1840	45.6462	20.1840	45.6462	20.1840	45.6462
Pg 4	10.0	33.3303	10.0	33.3303	10.0	33.3303	10.0	33.3303
Pg 5	10.0	32.5004	10.0	32.5004	10.0	32.5004	10.0	32.5004
Pg 6	12.0	39.6000	12.0	39.6000	12.0	39.6000	12.0	39.6000
Pg Total	290.5199	**793.1333**	277.3698	**747.6066**	276.2028	**743.8588**	270.3444	**725.7645**

5. Conclusion

In this paper a simple method to solve Economic dispatch problem for a system containing conservative thermal generators and solar farms is presented. Four case studies with six thermal generators and a solar farm have been examined. Economic dispatch problem has been solved for three different seasons with two installed capacities of solar farm. In addition, the uncertainty of solar irradiance is solved using beta distribution function. The maximum solar shares of 40.34 MW (13.8 % of 290 MW), 28.62 MW(9.8% of 290 MW) and 26.30MW (9.06% of 290 MW) have been recorded at 12:00 hr of a day during summer, spring and winter respectively. It shows that higher solar irradiation provides maximum solar share in all the seasons. Cost analysis by incorporating solar farm at various locations in the chosen test system is analysed. Maximal solar share for a given load demand results in reduced fuel cost of the convectional generators. The future work is aimed at investigating the real time economic dispatch considering multiple fuels, cost recovery of newly established plants in a scheduled period

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Appendix A: Cost coefficients and generation limits for an IEEE 30 bus system

Generator Bus No	*Cost Coefficients ($/hr)*			*Generation Limits(MW)*	
	a_i	b_i	c_i	Pg_{min}	Pg_{max}
1	0.00375	2	0	50	200
2	0.0175	1.75	0	20	80
5	0.0625	1	0	15	50
8	0.0083	3.25	0	10	55
11	0.025	3	0	10	30
13	0.025	3	0	12	40

Appendix B: Schematic diagram of an IEEE 30 bus system