Economic Load Dispatch with ATC Improvement in Power System Network Including Solar Power Generation Systems

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***Abstract*— The present work deals with the active power rescheduling in an hour-ahead electricity market including solar energy based power generation. The schedules of various generators have been optimized according to active power demand bids by various load buses and availability of solar energy. In this work, various aspects such as congestion management, voltage deviation, and loss minimization have also been taken into consideration to achieve the goal. The interior point (IP) based optimal power flow (OPF) methodology has been used to obtain the economic system operation. The IP-based OPF methodology has been tested on a modified IEEE-30 bus system. The obtained test results show that not only the generation cost is reduced also the available transfer capabilities of transmission lines have also been improved.**

Keywords*— AC power flow; open access; optimal pricing; power market economics; optimal power flow; available transfer capability; solar energy.

I. Introduction

The Power market is one of the leading fields where various operational activities have been involved such as operational problems of a power system, security, reliability, and cost-effective load dispatch. A power system is a network of electrical components which are used for the generation, transmission and distribution of electrical power. One of the recent changes involved into the power system is its development as an open market. The demand of electricity market increases with the increasing rate of industrialization and the exponentially increasing rate of urbanization. This has been made the power market as a major attraction for the investors. The power market resulting in the fast evolution as the market has evolved more and more investors, public and private units' investments [1, 2]. Thus, power generation becomes a more attractive part of the market.

Most of the private investors have showing interest in this part. The main objective of the investors is to generate cost-effective power and optimize their respective revenues (profits). Also, utilities try to provide economical power to consumers. As a result, a number of municipal and private generation companies have involved in the market. The profit optimization becomes a challenging task in the power market.

At present, most of the power markets have been operated on the basis of bidding and auction-based mechanism. These bids or auctions have been based on day-ahead/hour-ahead or minute-ahead based mechanism. The system operators have fixed the bid on the basis of system constraints. Sometimes, this mechanism arises various operational problems in the scheduling of generators in the system such as congestion management and voltage deviation at different buses. The problem in the present time scenario is as the power system has emerged as a market, the investors want more profit by injecting and drawing more and more power through the transmission lines which results in the problem of congestion in the transmission system. All the generating companies try to get maximum profit for maximum power generation. However, the operational constraints of the system confine their objectives. Therefore, optimal power flow (OPF) based scheduling decision has been adopted by the system operators to get an efficient system operation with maximum profit. Many techniques have been developed by researchers to minimize the generation cost in the power system [3].

Though, OPF provides a good operational solution for power market. However, this becomes uneconomical during congestion management. The generation cost becomes high for managing the congestion in the network. Thus, it requires some additional arrangements in the system to flow economical power such as allocation of flexible AC transmission systems (FACTS), Distributed Generation (DG) etc [4-7]. Solar power plants are a good example of distributive generation based resources. These plants provide a clean and low-priced electrical power in the distribution system. Apart from economical power, the solar power plants have also provided a solution for congestion management, voltages deviation problems and enhanced the available transfer capability (ATC) in the transmission network [8-9].

The present paper investigates the opportunity to integrate solar power generation systems in a power system for economic load dispatch. Also, explore the possibility to improve the ATC of transmission lines which can also provide congestion free operation in the system. Most of the times, the problem of congestion in the transmission system arises due to less ATC [10]. Therefore, in the present work, the interior point

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lay total generation cost in a hour-ahead power market. has also improved the average ATC per day and also ases the loadability of the transmission network.

'he modified IEEE-30 bus system is used to study the osed work. In this work, the distribution companies COMs) at load buses have applied an hourly based ng to the system operator. Subsequently, the generations optimally rescheduled on the basis of applied bids and m constraints. The Interior Point (IP) optimization nique has been used to solve the problem objective [11- The result shows the effect of the proposed algorithm over ost of the generated system as well as the effects which r on the congestion management and voltage deviation in ystem. In the present work, the generation costs obtained se of conventional generations and integration of solar r generation have been compared. The purpose of the nt work is to get the better solution for the system which provide a less costly operation with more congestion free stable system.

ECONOMIC LOAD DISPATCH INCLUDING SOLAR POWER GENERATION: PROBLEM FORMULATION

he main objective of the present work is to minimize the ration cost with congestion free system operation by poration solar power generation systems. Thus, this work ng two objectives; first, optimal placement of solar power in a system and the second is to optimally reschedule the rations for economic load dispatch. The problems of estion management and voltage deviation have also been ed out in the work. Mainly, the installation of solar power s in a power system is based on the availability of solar tion in the region. However, in the present work, it is ned that the solar radiation in the region is uniform and nergy per hour is same in the region. In the present work, ations of solar power plants have been based on the basis itical voltage bus. Therefore, firstly, identify the critical bus in the system on the basis of available load patterns day with load flow solutions. The lowest voltage buses be considered as a critical bus and on the priority basis, ified buses have been considered as critical buses. eafter, the solar power plants have been integrated with ified buses. The OPF based economic rescheduling has adopted in the present work. The cost of generation has varied with the change in solar power availability. efore, in the present work, the cost of solar power ration and its availability has also been incorporated in roblem formulation. The OPF based problem formulation nstituted by two terms; first related to generation cost of entional power plants and second is associated with able solar power generation in day time duration. The ctive function and related constraints can be represented

$$F(P_{gi}, P_{gs}, t) = \sum_{i=1}^{Ng} C_i(P_{gi}) + \sum_{s=1}^{Nc} C_s(P_{gs}^t) \quad (1)$$

ect to

$$P_{gi} + \sum_{s=1}^{Nc} P_{gs}^{max} = \sum_{j=1}^{Nl} P_{di} \quad (2)$$

$$P_{gi} \le P_{gi} \le P_{gi} \quad (4)$$

$$P_{gs} = P_{gi}^{max,t} \quad (5)$$

$$Q_{gi}^{min} \le Q_{gi} \le Q_{gi}^{max} \quad (6)$$

$$V_i^{min} \le V_i \le V_i^{max} \quad (7)$$

$$P_{ij} \le P_{ij}^{max} \quad (8)$$

In general, the average ATC per day can be calculate by following equation

$$Av.ATC_{ij}(per\ day) = \frac{\sum_{t=1}^{24} P_{ij}^{max} - P_{ij}(t)}{24} \quad (9)$$

where

t	Time at solar power is available (hr);
C_i	Operational conventional generation cost;
C_s	Operational solar power generation cost;
P_{gi}	Conventional generator output;
P_{gs}	Solar power generator output;
N_g	No. of generator buses;
N_c	No. of critical voltage buses;
N_l	No. of load buses;
P_{di}	Active power demand at load bus;
Q_{di}	Reactive power demand at load bus;
P_{gi}^{min}	Minimum active power limits of generators;
Q_{gi}^{min}	Minimum reactive power limits of generators;
P_{gi}^{max}	Maximum active power limits of generators;
Q_{gi}^{max}	Maximum reactive power limits of generators;
P_{ij}	Power flow in line between bus *i* and *j*;
P_{ij}^{max}	Maximum power flow of line between bus *i* and *j*;
$P_{ij}(t)$	Power flow in line between bus *i* and *j* at *t*;
V_i	Voltage at bus *i*.
V_i^{max}	Maximum and minimum bus voltages;
V_i^{min}	Minimum bus voltages;
ATC_{ij}	Available transfer capability of line between bus *i* and *j*

III. SOLUTION BY INTERIOR POINT METHOD

This method is an efficient conventional non-li optimization technique which is also known as Karma interior point method. In fact, conventional optimiza techniques needed the number of iterations to reach optimum solution can grow exponentially. Due this conventional optimization technique takes more time to r an optimal solution. In fact, there are extreme points vis before the optimum is reached in linear programming (LP interior point based optimization, a polynomial-time algori that cuts across the interior of the solution space. The algori is effective for extremely large LPs [11]. The main idea o interior point method is introduced here and then is prov the computational details of the algorithm.

A. Basic idea of the Interior-point Algorithm

For the solution by this technique, the problen formulated as

Min	*f(x)*
Subject to	*g (x) = 0*
	hl ≤ h(x) ≤ hu (10)

where *f(x)* is the objective function and *g(x)* is a set of nonlinear equality constraints (Power balance). The $hl \leq h(x) \leq hu$ *shows* a set of nonlinear inequality constraints where x is a vector consists of state variables and control variables. For OPF solution by interior point method, construct a Lagrange function for (1) and it can be rewritten as

$$L_h = f(x) - y^T g(x) - z^T[h(x) - l - hl] - w^T[h(x) + u - hu] - \mu \sum_{i=1}^{r} \ln l_i - \mu \sum_{i=1}^{r} \ln u_i \qquad (11)$$

where y, z and w are Lagrange multipliers for equality and inequality constraints respectively; l_i and u_i are slack variables; μ is the barrier parameter. Now, verifying the KKT condition for (11) and obtain Jacobian matrices J_f, J_g and J_h and Hessian matrices H_f , H_g and H_h of *f(x), g(x)* and *h(x)* respectively. Now, using reduced Newton method obtain a decomposed linear equations for (11). The following are the main steps for interior point OPF based solution

Step 1) Initialization: give initial values to the formulated objective function.

Step 2) Formulate Jacobian and Hessian matrix of objective function, equality and inequality constraints: J_f, J_g, J_h, H_f, H_g and H_h.

Step 3) Formulate linear system equation for (11), using predictor-corrector strategy to solve this linear system. If convergence criteria are satisfied, then stop; otherwise, go to step 2.

IV. Test Results and Discussion

In the present work, the IP-based OPF method has been used to obtain the economic load dispatch by generation rescheduling including solar power generation. In order to demonstrate the effectiveness and performance of solar power plant in a power system, the cost of solar power generation has also been included in the problem objective. The proposed algorithm has been tested on modified IEEE-30 bus system. This system consists of 6 generator buses and 21 load buses. In the present system, the solar energy based power plants have been included in the system at bus 20 and 27 as shown in Fig. 1. Where bus 20 is a load bus and bus 27 is a freewheeling bus.

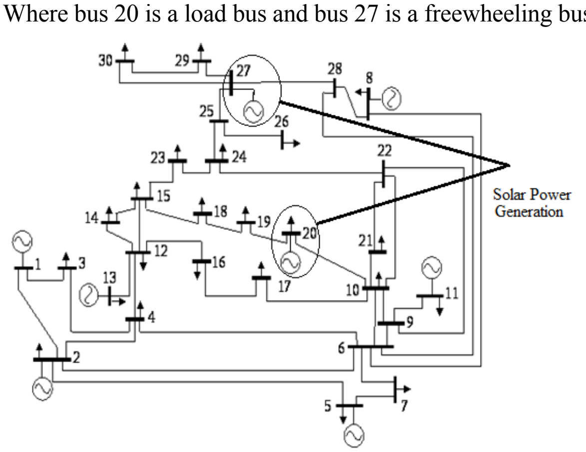

Fig. 1 Modified IEEE-30 bus System Model including solar power generations

The marginal generation cost of various generators and solar power generation have been listed in Table I and II respectively. The per day active power demand curve on various load buses have been shown in Fig. 2. The values of active power demands on various load buses have been generated to observe the generation schedule. In order to observe the congestion management in the system, the transfer limits of branches have also been considered in the problem formulations. In the present case studies, suggested IP technique has been used to obtain an optimal solution for OPF in the test system. The parameters selection for IP has been also been plays an important role in optimization techniques. Thus, the parameter selection criterion has been discussed in subsequent section.

A. Case Studies

The following cases have been considered and test carried out to observe the effectiveness of solar power plants in the modified IEEE-30 bus system. The two cases have been studied to justify the proposed work.

Case 1: Economic rescheduling of generators without Solar Power Generation

In this case, all the constraints of system components and the transfer limits of the lines have been considered in the problem objective for studying problem objective and congestion management. The generations scheduled have been rescheduled using OPF based optimal rescheduling and the corresponding costs of generations have also been varying. The generation costs on various generator buses have been given in Table III. Also, the results obtained by OPF provide that the voltages on various buses have been in its minimum and maximum limits (0.95pu – 1.02pu). Thus, the OPF based rescheduling has been fulfilled all the technical limitations of the system and provide economic benefits.

Case 2: Economic rescheduling of generators including Solar Power Generation

In the present case, the system used has been modified and solar power generators are installed in the system. All the constraints of the system components and the transfer limits of the lines are taken as the same as that in the previous case to study the problem objectively. In the present case, all the components of the system are chosen to participate in the problem objective taken into consideration that the system becomes more relaxed and the generation cost is reduced. Suggested IP-based OPF technique has been used to obtain the results as required for the problem objective. The total generation costs in a day for both the cases have been given in Table III. The results show that the generation cost has been decreasing in OPF based generation scheduling and this has been further decreases by including solar energy based power generation. Initially, the generation cost in a day is 18826.9 \$/day and it has been decreasing using OPF based scheduling is 16475.1 \$/day as given in Table III. Thus, the result reveals that the total generation cost obtained by OPF method provides a considerable amount of saving is 2351.8 \$/day. The results also show that the generation cost has been decreased by including solar plants in the system. The total generation cost in a day including solar energy based power generation is 15072.4 \$/day and the substantial saving of 1402.7 \$/day.

TABLE I. COST FUNCTION OF GENERATION IN USING MODIFIED IEEE-30 BUS SYSTEM MODEL

Generator Number	Bus Number	Marginal Generation Cost Function $/hr.
1	1	2P+0.02P2
2	2	1.75P+0.0175P2
3	5	1P+0.0625P2
4	8	3.25P+0.00834P2
5	11	3P+0.025P2
6	13	3P+0.025P2

TABLE II. COST FUNCTION OF SOLAR POWER GENERATION

Generator Number	Bus Number	Marginal generation cost function $/hr
7	20	1.85P
8	27	1.85P

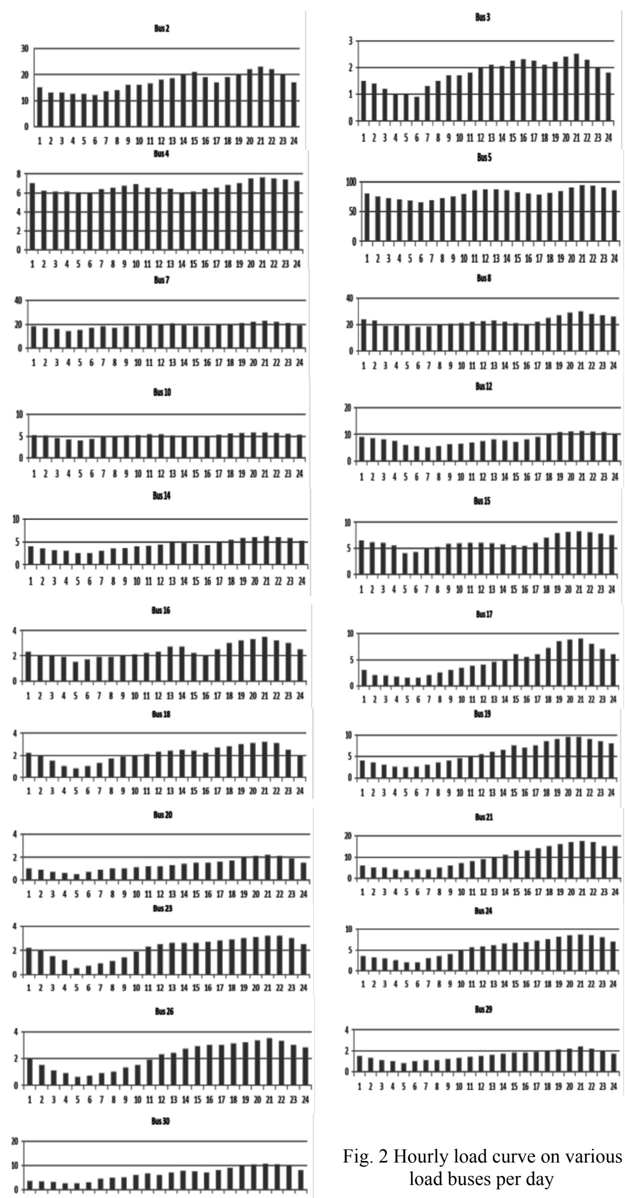

Fig. 2 Hourly load curve on various load buses per day

TABLE III. GENERATION COST USING LF, OPF AND SOLAR

No. of Hours	Generation Cost using Load Flow	Generation Cost using OPF	Generation Cost using Solar Energy
1	697.372	620.13	620.13
2	641.445	558.23	558.23
3	599.168	509.65	509.65
4	562.515	472.01	472.01
5	541.404	444.59	444.59
6	539.382	441.31	441.31
7	590.494	491.27	464.34
8	618.602	527.83	491.04
9	654.857	573.65	500.26
10	699.268	616.93	477.2
11	769.748	670.75	495.69
12	813.561	705.83	525.4
13	838.607	730.23	545.5
14	827.254	728.77	542.32
15	829.708	723.81	585.95
16	808.758	702.23	601.08
17	831.01	789.3	664.45
18	905.447	801.01	765.73
19	984.029	864.2	864.2
20	1075.79	938.83	938.83
21	1108.94	977.14	977.14
22	1045.42	934.57	934.57
23	970.79	869.8	869.8
24	873.292	783	783
Total Generation Cost in a day ($/day)	**18826.9**	**16475.1**	**15072.4**

In the present work, the power flow limits of transmission lines have also considered in the problem formulation. The flow in the lines depends on the scheduling of generators in the system. The percentage average ATC per day of individual lines has also been varied accordingly. The obtained results have been given in Table IV. This table shows that the variation of % average ATC per day using load flow, OPF, and OPF with solar power plants are different and it is observed that the % average ATC per day of maximum lines (25 highlighted lines) have been improved by the inclusion of solar power plants in the problem objective. These test results reveal that apart from the economic generation of power, the use of solar power plants in the power system also fulfills many other technical aspects of the system resulting in the better functioning of the system.

V. CONCLUSION

The present work deals with the economical rescheduling of the generation cost along with making the system more efficient and relaxed. In the present work, OPF based generation rescheduling has been carried out on a modified IEEE-30 bus system with the inclusion of solar energy based power generations. It has been observed that the inclusion of solar power plant reduces the total generation cost in the system. This has also been providing a better solution for ATC improvement of lines and congestion management. Hence, it is clear from the study that use of the solar power plants in the system reduces the generation cost significantly and cures many other technical problems such as congestion, ATC etc.

TABLE IV. PERCENTAGE AVERAGE ATC PER DAY WITH VARIOUS CASES (% AV. ATC/DAY)

Line No.	LF	OPF	SOLAR
1	8.44	25.62	30.77
2	31.31	24.58	34.91
3	24.29	37.52	48.42
4	32.65	29.53	40.05
5	14.57	17.83	18.94
6	18.97	39.82	49.87
7	-6.94	39.31	41.18
8	43.16	19.77	9.28
9	29.31	24.13	19.52
10	38.48	37.13	42.85
11	2.4	59.46	37.63
12	49.62	47.93	49.86
13	32	31.35	40.73
14	45.26	36.84	46.26
15	71.1	53.43	61.84
16	8.3	39.24	46.65
17	26.87	35.54	42.15
18	17.08	32.83	42.06
19	16.26	49.43	56.99
20	86.59	88.08	86
21	28.37	67.07	71.15
22	19.38	43.52	27.8
23	35.24	64.66	13.27
24	57.97	39.07	19.74
25	51.1	36.56	10.41
26	36.31	55.43	32.3
27	45.35	42.76	46.48
28	50.82	47.55	51.71
29	82.88	89.46	76.28
30	36.31	55.51	60.29
31	54.59	49.35	52.4
32	62.33	80.27	79.05
33	72.87	87.25	35.33
34	57.3	58.06	57.86
35	65.69	60.9	4.55
36	40.94	39.7	31.49
37	54.42	54.84	54.86
38	56.65	55.98	56
39	73.76	73.89	73.9
40	53.89	45.94	48.59
41	23.33	43.4	16.68

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