Integration of Demand Response and Distributed Generation for Economic Load Dispatch Problem

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Abstract— **In the recent years, while energy supply could not keep pace with the rapid growth of energy consumption the focus has been now shifted on to the consumer side which has led to more significant smart grid initiatives associated with energy management through demand response program. Demand response helps with paying incentives to the consumers to reduce their energy consumption during peak hours or when energy production is down. Also in order to meet the energy demand, Independent power producers (IPP's) are introduced into the electric power market where electricity is purchased by the Electric power utilities through competitive bidding. In this paper, economic load dispatch problem is solved by Lagrange multiplier method for a network of 8 bus system with 4 thermal units under competitive environment with inclusion of Demand Response programs with different strategy process for peak load reduction with the application of fuzzy logic principles and independent power producers (IPPs).**

***Index Terms*—**Energy management, Smart grid, Demand Response, Peak Load Curtailment, Fuzzy system, Independent power producer, Lagrange multiplier method, Economic Dispatch Problem.

I. INTRODUCTION

Energy management is a significant step for the global need of energy saving in order to reduce our reliance on the fossil fuels that are not only becoming limited in supply and also causing negative health and environmental effects.

The smart grid is associated to be an electric grid that delivers power in a controlled, smart way from generation end to the consumers. Demand response (DR) encourages interaction and approachability of the customers which will offer a wide range of potential benefits on system operation and expansion in the long term. Lowering peak demand, it reduces overall plant and capital cost investments and stalls the need for further upgrades and construction of power plants.

Methods for engaging customers in demand response programs include proposing time-basedrates such as time of pricing, critical peak pricing, variable peak pricing, real time pricing and critical peak rebates. It also includes direct load control programs[2] which provide the ability for the utilities to cycle on and off electrical appliances during periods of peak demand in exchange of a financial incentive.

Sensors identify the peak load problems and operate automatic switching to turn away or reduce power. Advanced metering infrastructure increases the range of time based rate programs and smart consumer systems such as in-home displays or home area networks which makes easier for consumers to reduce peak period consumption based on the information of the power consumption. Fuzzy system approach has been considered for peak load curtailment problem. Various Steps involved in its design are the fuzzification of inputs, fuzzy rules and inference engine, and defuzzification[2].

Furthermore, in order to make an efficient electric energy supply system, deregulation in the electric power industry is carried in various countries by adding the Independent power producers (IPP's) into the system. Electric power is purchased from IPP's through competitive bidding, where the evaluation is done on the basis of the operating cost of the corresponding generator's utility for the power purchased. It has also been observed that inclusion of IPP's have improved the flexibility in functioning of the power system in terms of system blackouts and the loading of various equipment in the power system.

Optimization techniques are involved in Economic load dispatch problem for minimization of fuel cost while satisfying certain constraints. Optimization is done by scheduling the thermal units in the network according to the demand with minimum operating cost. In this paper, comparative analysis of finding the minimum operating cost is performed using Lagrange multiplier method considering the inclusion of Demand response and power purchases from IPP.

II. ECONOMIC LOAD DISPATCH FORMULATION

Economic load dispatch is conducted in order to determine the minimum generation cost of thermal units, along with certain operating constraints. The total cost of this system is the sum of costs of each of the individual units. The generation cost function $F_i(P_i^t)$ is usually expressed as quadratic polynomial (1).

$$F_i(P_i^t) = a_i + b_i P_i^t + c_i (P_i^t)^2 \qquad (1)$$

Where a_i, b_i, c_i are cost coefficients of generating unit i, (P_i^t) is the real power output of generating unit during period t.

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The objective function of the economic load dispatch problem is to minimize the fuel cost function (2) of all generating units in the power system. The essential constraint on the operation of the system is that sum of output powers must be equal to the load (3).

Objective function:

$$\text{Min } F_T = \sum_{t=1}^{T} \sum_{i=1}^{n} F_i\,(P_i^t) \qquad (2)$$

Loading Constraints:

$$\Phi = P_{load} - \sum_{i=1}^{n} P_i^t = 0 \qquad \text{for } t = 1\ldots T \qquad (3)$$

Unit Limits:

$$P_{i,min}^{\ t} \le P_i^t \le P_{i,max}^{\ t} \qquad (4)$$

III. LAGRANGE MULTIPLIER METHOD

In Lagrange multiplier method, the extreme value of the objective function is obtained by multiplying the constraint function by an undetermined multiplier and is added to the objective function. This is known as Lagrangian function [1] and is represented as:

$$£ = F_T + \lambda * \Phi \qquad (5)$$

In order to obtain the extreme values of the objective function, first derivative of Lagrange function (6) is taken w.r.t to the each of the independent variables and set the derivative equal to zero.

$$D£ = \partial F_i(P_i) / \partial(P_i) - \lambda = 0 \qquad (6)$$

$$\partial F_i(P_i) / \partial(P_i) = \lambda \qquad (7)$$

Equation (7) forms the necessary condition for the minimum operating cost for the power system which says that the incremental cost rates of all units be equal to some undetermined value (λ)

Considerable insight can be gained into characteristics of optimal solutions through use of the Kuhn Tucker conditions. One important insight comes from our standard economic dispatch problems i.e., when we recognize the inequality constraints, the necessary conditions may be expanded slightly as the shown in the set of equations (8).

$$\partial F_i/\partial P_i = \lambda \quad \text{for} \quad P_{i,min} < P_i < P_{i,max}$$

$$\partial F_i/\partial P_i < \lambda \quad \text{for} \quad P_i = P_{i,max} \qquad (8)$$

$$\partial F_i/\partial P_i > \lambda \quad \text{for} \quad P_i = P_{i,min}$$

The algorithm for the implementation of economic dispatch problem is depicted below:

Step1: Read all the generator data and 24 hour load.

Step2: Considering there are n generators, all the possible combinations (2^n states) along with ON and OFF conditions, the maximum and minimum power for all the states are displayed.

Step3: Based on the load for that particular hour, all the feasible states meeting the load are considered and the corresponding power generated of the individual generators are calculated based on the Lagrange function.

Step4: The operating cost of all feasible states is calculated individually using the quadratic cost function.

Step5: Among all the feasible states, the state with minimum operating cost is displayed which is considered to be the economic dispatch of the load for that particular hour.

Step6: Similarly the operating costs are calculated for 24 hours and are added to get the total operating cost.

IV. DEMAND RESPONSE PROGRAM

Demand response helps with two issues. As an alternative for adding generation capacity, incentives are paid to customer to use less energy during a given time period. By acting as "virtual power plants," demand response participants also help in stabilizing the grid. All categories of customers (industrial, commercial, and residential) can be made involved in the Demand response program by introducing different technologies or strategies for achieving reduction in load or shifts in demand. Common strategies include 1.reduction or temporary interruption in consumption with no change in consumption in other periods. 2. Adjustment in power consumption to less peak periods 3. Temporary utilization of onsite generation in place of energy from the grid.

A. Types of DR Programs

DR programs are broadly classified by the manner the customer is motivated. (i.e., direct control or market price). Specific DR Programs can be discussed in terms of these two response programs as discussed below

When the customers are offered incentives by the utilities for reduction of load during specified periods, the program is called load response. When customers voluntarily reduce their load in response to market prices, the program is called price response. Each of these categories divided in several subgroups. Here, we have focused on Direct Load Control which comes under load response

In this paper, load curtailment is done by using a fuzzy system approach with the application of fuzzy logic principles [2]. Utilities peak load data consisting of many load demand scenarios are the inputs to the system, and the corresponding power reductions during peak load periods are the outputs. In this paper, the system considers peak load profiles of different types of customers (industrial, commercial, and residential) obtained from its load data. For further explanation on implementation of fuzzy system and its different stages the membership function for the domestic load is shown in Fig 1. Similar procedure can be applied for load reduction for industrial and commercial customers.

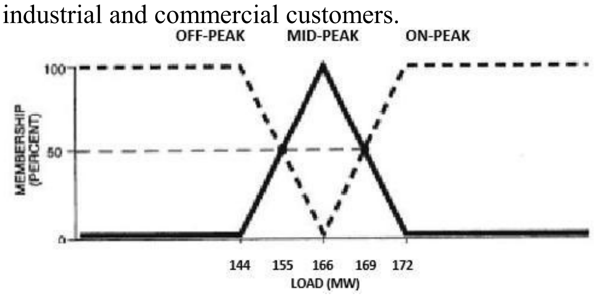

Fig 1. Membership function for Domestic load

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B. Fuzzy System

As mentioned above for the fuzzy system, the membership function has been developed and is used for the fuzzification of the input parameters and also during the defuzzification of output variables of control.

C. Fuzzy System Rules and Inference

Let Pdom be the domestic load of the system and is the fuzzified input variable. Let m represent the fuzzified values defined based on the membership function defined from fig 1 and the corresponding fuzzified output values are based on the algorithm in Fig 2.

D. Defuzzificiation

In defuzzification, the fuzzified output values (P_red) are related with the domestic load corresponding to the degree of membership for the power reduction and the output vales are obtained. The output values obtained are based on the algorithm shown below.

Step1: Read the load(Pdom) for the particular interval of time

Step2: If (Pdom>=144&&Pdom<=155) then display off-peak period and go to step 7 for membership function for fuzzified outputs else go to step3.

Step3: If (Pdom>=155.1&&Pdom<=166) then display “off-peak period-mid-peak period” and go to step8 for membership function of fuzzified outputs else go to step4.

Step4: If (Pdom>=166.1&&Pdom<=169) then display “mid-peak period” and go to step9 for membership function of fuzzified outputs else go to step5.

Step5: If (Pdom>=169.1&&Pdom<=172) then display “mid-peak period-on-peak period” and go to step10 for membership functions of fuzzified outputs else go to step6.

Step6: If (Pdom>=172.1) then display “on-peak period” and go to step11 for membership function of fuzzified outputs else go to step 12

Step7: m=1-(0.0454*Pdom-6.5454), corresponding defuzzified output is Pdom_red=0 and go to step12.

Step8: m=(0.045*Pdom-6.5454), corresponding defuzzified output is Pdom_red=Pdom*0.06 and go to step 12.

Step9: m=(28.66-0.1667*Pdom), corresponding defuzzified output is Pdom_red=Pdom*0.06 and go to step 12.

Step10: m=1-(28.66-0.1667*Pdom), corresponding defuzzified o/p is Pdom_red=Pdom*0.06 and go to step 12.

Step11: m=1 and corresponding defuzzified output is Pdom_red=Pdom*0.12 and go to step12.

Step12: Stop.

V. INDEPENDENT POWER PRODUCER

When the electricity is purchased from an IPP, the incremental generator capacity of the utility is reduced by the capacity of the IPP. In this paper the Distribution generation (DG) units of independent producers are considered to be of wind farms [3]. The maximum price paid for procuring the power is considered as an assessment for total generation cost of electric power system. Upon the purchase of power the reduced generation cost per unit is termed as breakeven cost.

It is also witnessed that if the inclusion of independent power producers is done with appropriate choices there is a significant reduction in production cost and fuel heat consumption associated with generating units owned by the utility.

VI. NUMERICAL STUDIES

The network considered is of 8-bus system in Fig.2 consisting of four thermal units[3].The parameters of thermal units are given in Table I .The 24 hour system load is specified in Table II. The fuel price is 1$/MBtu. Among the generation units, G1 is assumed to be committed with maximum output. Here 4 scenarios are considered where economic dispatch is done with the present load, with the implementation of demand response (DR), power purchased from IPP, both DR and IPP included in which where the total operating cost of the system is compared in each case. The dispatch of units of scenario 1 is given in Table III.

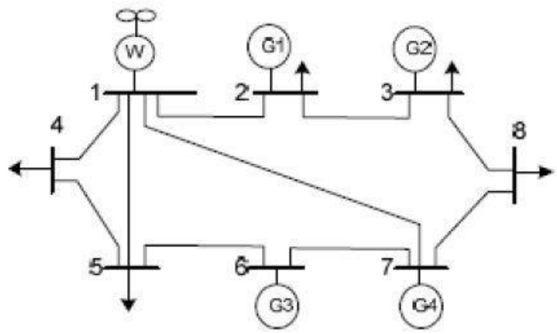

Fig.2 8 Bus system

Table I. Thermal units Parameters

Bus/Gen	2(G1)	3(G2)	6(G3)	7(G4)
A($/MW^2h)	0.012	0.0014	0.0085	0.0046
B($/MWh)	8.66	9.66	19	12.69
C($/hr)	190	230	270	250
Pmin(MW)	50	50	10	20
Pmax(MW)	200	150	50	100
ST($)	1600	1500	500	500
Min Up	8	8	1	1
Min down	8	8	1	1

Table II. 24 Hour Load Demand

Hour	Load (MW)	Hour	Load (MW)	Hour	Load (MW)
1	377.800	9	428.950	17	406.200
2	365.920	10	435.170	18	431.550
3	362.860	11	432.060	19	468.170
4	363.110	12	424.820	20	477.400
5	370.560	13	416.860	21	480.000
6	386.830	14	408.600	22	465.260
7	411.610	15	402.840	23	439.860
8	421.200	16	401.670	24	409.720

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Table III. Dispatch Result for Scenario1

Hour	P1 (MW)	P2 (MW)	P3 (MW)	P4 (MW)	Hour	P1 (MW)	P2 (MW)	P3 (MW)	P4 (MW)
1	200	150	0	27.8	13	200	150	0	66.86
2	200	145.92	0	20	14	200	150	0	58.6
3	200	142.86	0	20	15	200	150	0	52.4
4	200	143.11	0	20	16	200	150	0	51.67
5	200	150	0	20.56	17	200	150	0	56.2
6	200	150	0	36.83	18	200	150	0	81.55
7	200	150	0	61.61	19	200	150	18.17	100
8	200	150	0	71.2	20	200	150	27.4	100
9	200	150	0	78.95	21	200	150	30	100
10	200	150	0	85.17	22	200	150	15.26	100
11	200	150	0	82.06	23	200	150	0	89.6
12	200	150	0	74.82	24	200	150	0	59.72

A. Implementation of demand response program

The present load is divided into three different ranges: On peak (430 – 480 MW), mid peak (390-430 MW), off peak (360-390 MW). All categories of customers are considered here where domestic consumers constitute 40% of load, while industrial (25%) and commercial (35%).The incentives for all customers is assumed to be 10$/MW for 12% of reduction during peak period while 5$/MW for 6% reduction during mid-peak period and there is no reduction in load during off peak period [5].

As discussed earlier the peak load reduction is done using fuzzy system and the process is explained in Fig 2 and the new load after the implementation of demand response program is shown in Table IV.

Table IV. 24 Hour Load Demand after implementation of Demand Response

Hour	Load (MW)	Hour	Load (MW)	Hour	Load (MW)
1	377.800	9	403.213	17	381.828
2	365.920	10	382.949	18	379.764
3	362.860	11	380.212	19	411.989
4	363.110	12	399.330	20	420.112
5	370.560	13	391.848	21	422.400
6	386.830	14	384.084	22	409.428
7	386.913	15	378.669	23	387.077
8	395.928	16	377.569	24	385.136

The economic dispatch problem is conducted for the new load and the dispatch results are shown in Table V and the operating cost is calculated also along with this the incentives which are to be paid to the customers based on the rates given above and is added to the operating cost of the system which sums to the total cost and is compared with other scenarios.

Table V. Dispatch Result for Scenario2

Hour	P1 (MW)	P2 (MW)	P13 (MW)	P4 (MW)	Hour	P1 (MW)	P2 (MW)	P3 (MW)	P4 (MW)
1	200	150	0	27.8	13	200	150	0	41.848
2	200	145.92	0	20	14	200	150	0	34.084
3	200	142.86	0	20	15	200	150	0	28.67
4	200	143.11	0	20	16	200	150	0	27.57
5	200	150	0	20.56	17	200	150	0	31.828
6	200	150	0	36.83	18	200	150	0	29.764
7	200	150	0	36.913	19	200	150	0	61.91
8	200	150	0	45.928	20	200	150	0	70.112
9	200	150	0	53.213	21	200	150	0	72.4
10	200	150	0	32.95	22	200	150	0	59.429
11	200	150	0	30.213	23	200	150	0	37.077
12	200	150	0	49.331	24	200	150	0	35.137

B. Power purchase from IPP

The 24 hour generation data of wind power is taken from [3] and the remaining load to be met by the thermal units is shown in Table VI and the bidding prices of an generation company are taken from [4] where 5.3055$/MW is the price for purchase of power.

Table VI. 24 Hour Load Demand after purchase of power from IPP

Hour	Load (MW)	Hour	Load (MW)	Hour	Load (MW)
1	319.530	9	355.550	17	391.200
2	283.800	10	386.060	18	420.670
3	273.640	11	401.350	19	453.670
4	278.380	12	411.730	20	464.860
5	293.310	13	406.060	21	464.000
6	321.700	14	396.100	22	436.850
7	335.700	15	387.840	23	409.520
8	349.650	16	380.050	24	372.620

The economic dispatch problem is conducted for the above load and the dispatch result for the same is shown in Table VII. The operating cost is calculated also along with this the amount to be paid on purchase of power is added to the operating cost of the system which sums to the total cost.

Table VII. Dispatch Result for Scenario3

Hour	P1 (MW)	P2 (MW)	P13 (MW)	P4 (MW)	Hour	P1 (MW)	P2 (MW)	P3 (MW)	P4 (MW)
1	200	119.53	0	0	13	200	150	0	56.06
2	200	83.8	0	0	14	200	150	0	46.1
3	200	73.64	0	0	15	200	150	0	37.84
4	200	78.38	0	0	16	200	150	0	30.05
5	200	93.31	0	0	17	200	150	0	41.2
6	200	121.7	0	0	18	200	150	0	70.67
7	200	135.7	0	0	19	200	150	10	93.67
8	200	149.65	0	0	20	200	150	14.86	100
9	200	135.55	0	20	21	200	150	14	100
10	200	150	0	36.06	22	200	150	0	86.85
11	200	150	0	51.35	23	200	150	0	59.52
12	200	150	0	61.73	24	200	150	0	22.62

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C. Inclusion of both Demand Response and IPP. In this scenario the economic dispatch is done for the load after the implementation of Demand response and IPP and the operating cost is calculated along with the amount to be paid to costumers and power producer. The new load after the inclusion of demand response and IPP is shown below in Table VIII.

Table VIII. 24 Hour Load Demand after inclusion of Demand Response & IPP

Hour	Load (MW)	Hour	Load (MW)	Hour	Load (MW)
1	319.530	9	329.813	17	366.828
2	283.080	10	333.840	18	368.884
3	273.640	11	349.503	19	397.490
4	285.860	12	386.241	20	407.572
5	293.310	13	381.048	21	406.400
6	321.700	14	371.584	22	381.019
7	311.003	15	363.670	23	356.737
8	324.378	16	355.950	24	348.037

The economic dispatch problem is conducted for the above load and the dispatch result for the same is shown in Table IX. The operating cost is calculated also along with this the amount to be paid on purchase of power and incentives to be paid to consumers are added to the operating cost of the system which sums to the total cost.

Table IX. Dispatch Result for Scenario4

Hour	P1 (MW)	P2 (MW)	P13 (MW	P4 (MW)	Hour	P1 (MW)	P2 (MW)	P3 (MW)	P4 (MW)
1	200	119.53	0	0	13	200	150	0	31.05
2	200	83.8	0	0	14	200	150	0	21.58
3	200	73.64	0	0	15	200	143.67	0	20
4	200	78.38	0	0	16	200	135.95	0	20
5	200	93.31	0	0	17	200	146.83	0	20
6	200	121.7	0	0	18	200	148.88	0	20
7	200	111	0	0	19	200	150	0	47.49
8	200	124.38	0	0	20	200	150	0	57.57
9	200	129.81	0	0	21	200	150	0	56.4
10	200	133.84	0	0	22	200	150	0	31.02
11	200	149.5	0	0	23	200	136.74	0	20
12	200	150	0	36.24	24	200	148.04	0	0

Table X. Comparison of Total Cost for various scenarios

S.NO	SCENARIO	OPERATING COST OF THERMAL UNITS	DR REDUCTION -INCENTIVE PAY	POWER PURCHASE FROM IPP	TOTAL COST
1	ECONOMIC DISPATCH FOR PRESENT LOAD	$131,205.01	-	-	$131,205.01
2	ECONOMIC DISPATCH INCLUDING DR PROGRAM	$120,027.37	$5,595.105	-	$125,622.48
3	ECONOMIC DISPATCH INCLUDING IPP-DG (WIND POWER)	$116,649.66	-	$5,279.927	$121,929.59
4	ECONOMIC DISPATCH INCLUDING BOTH DR PROGRAM & IPP-DG (WIND POWER)	$105,491.19	$5,595.105	$5,279.927	$116,366.23

VII. CONCLUSION

The solution for economic dispatch problem of the system considering different scenarios of load profile is calculated and the operating cost of the system is compared as shown in Table X. It can be observed that there is a reduction in operating cost. In this manner with the application of these kinds of program, flexibility of the power system can be improved in terms of managing system outages and operation of various equipment in the power system.

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