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Demand Response Unit Commitment using Modified Hybrid Method in Power System

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Abstract: **This paper presents a new modified hybrid method in predicting the optimal value of the demand response unit commitment optimization problem. Overloading the operation of generators during peak loads is cumbersome. Demand-side management is employed to smoothen the peak loads incorporated with unit commitment followed by dispatching of committed units for minimization of cost and emission. The modified hybrid method makes use of a modified non-dominant sorting genetic algorithm (MNSGA-II) and modified population variant differential evolution (MPVDE) techniques. In price-based demand response, customers are awarded incentives based on their contribution to the demand response program. The proposed modified hybrid method is effectively applied to two test systems.**

Index Terms: **Demand response, unit commitment, economic dispatch, incentives, and peak load.**

I. INTRODUCTION

In the present scenario, load demand varies continuously day-to-day and attains the different peak values. Due to variation in load demand, pertinent information is required for turning on/off the committed generating units. The course of action, planning, and selecting generating units over some time in equating load demand is termed unit commitment. Thermal units cannot be turned on/off instantly whenever it is essential to meet the load demand. In a power system, unit commitment is the problem of predicting the on/off states of the thermal units for the minimization of fuel cost value [1]. Unit commitment (UC) is the mixed integer programming, nonlinear and related to the combinatorial optimization problem which is tedious and complex in evaluating the optimal solution [2]. In the unit commitment optimization problem (UCOP) the total cost is the combination of running cost, startup cost, and shutdown cost.

Industrial power generation imposed a great challenge in the environmental regulation, due to pollution caused by the combustion of fossil fuel in thermal units during the power generation. The emission has become another important objective in power dispatch. Multi-Objective unit commitment (MOUC) is associated with two conflicting objectives as cost and emission are subjected to inequality and equality constraints [3]. Many techniques were proposed to achieve an optimal solution of a MOUC. Conventional methods require the exact mathematical modeling and chances of getting stuck in local optima rather than achieving global optimal value [4].

Some of the conventional methods are priority list method [5], branch and cut [6], Benders decomposition [7], Lagrangian relaxation [8], Quadratic programming, Linear Programming, Newton Rhapson implemented to solve economic dispatch (ED) with a piecewise linear cost function. Heuristic methods genetic algorithm [9], simulated annealing [11], particle swarm optimization [10] are used to predict optimal values in a feasible search space. To enhance performance and efficiency, a combination of methods is proposed. Some of the hybrid techniques are Lagrangian relaxation with Particle Swarm Optimization [12], Lagrangian relaxation with Genetic Algorithm [13], and Fuzzy Adaptive Particle Swarm Optimization [14].

Demand Response (DR) point-outs reshaping the demand curve by shifting load to off-peak periods or by reducing the load at peak periods [15]. Demand Response Programs (DRPs) offer customers to change their energy consumption in their demand response. Customers are encouraged by electricity pricing signals with associated network operators [16]. In general, DRPs are of two types, time-based rate programs, and incentive-based programs, these two categories are divided into further subgroups. In the incentive-based program (IBP), fascinated by the emergency demand response program (EDRP) in which incentives are offered to the customers by independent system operators (ISO) based on their contribution to DRPs. Voluntary customer participation is involved in DRPs and supported by ISO for enhancement of the participation of customers [17]. DRPs incorporated with UC are modeled to study environmental and economic dispatch [18] and include the cost of DR in total cost. Based on the robust optimization technique, day-ahead unit commitment with economic power dispatch is presented [19]. Implementation of demand response not only leads to diminishing loads in peak times but also reduces the need for new installation of generating units [27]. With the association of demand-side management in power systems, the effective utilization of energy takes place with efficient power system operation [26].

In this paper, Demand response is incorporated with unit commitment, with the percentage participation of customers in DRPs leads to a reduction in peak loads. Incentives are awarded to customers based on their participation followed by the unit commitment for dispatch of power over a period for the minimization of cost and emission. The modified hybrid method is applied for the optimization problem of DRUC in achieving the optimal value. The proposed method was applied on two test cases, IEEE 39 bus system with 10 generators and a 17 unit system. Section II discusses the problem formulation of MOUC and DR in section III, the methodology applied for solving the optimization problem is

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presented, and section IV presents the results and discussion applied on test systems.

II. PROBLEM FORMULATION

A. Objective function

The two conflicting objectives, cost, and emission are considered and the corresponding objective function is represented. The total cost is the sum of running cost, startup cost, and repayment cost associated with customers implemented and its objective function is as follows

$$\min \sum_{x=1}^{M} \sum_{y=1}^{T} \left[F_x\left(Pg_x(y)\right) + SUC_x\left(1 - U_x(y - 1)\right)\right] U_x(y) + R_c(y) \tag{1}$$

where T equates to 24 hours' time period and M initiates to the number of generators and on/off status generating units is indicated as Ux. The quadratic form of the cost function is represented a

$$F_x\left(Pg_x(y)\right) = a_x + b_x Pg_x(y) + c_x Pg_x^2(y) \tag{2}$$

where $Pg_x(y)$ is the real power generation of unit 'x' at time instant of 'y' and a_x, b_x, c_x indicates the cost coefficients. The start-up cost is expressed as

$$SUC(x) = \begin{cases} HC(x), & if\ MD(x,y) \le TC(x) \le MD_{yo} \\ CSC(x), & if\ \ TC(x) > MD_{yo} \end{cases} \tag{3}$$

where $MD_{yo} = MD(x,y) + CST(x)$

CSC and HC are the cold startup cost and hot startup of unit 'x', minimum downtime of unit 'x' is represented as MDx, off duration of unit 'x' is TC(x). Incentives awarded for customers in DRPs is expressed as

$$R_c(y) = \sum_{y=1}^{24} MI * \left(T_{c,y}^{in} - T_{cc,y}\right)^2 \tag{4}$$

Multilevel incentives awarded in cents/kw.min are indicated as MI. The repayment fee awarded to the customer 'c' at hour y is represented as $R_c(y)$. $T_{c,y}^{in}$ represents the indoor temperature of customer 'c' at hour y and $T_{cc,y}$ indicates a comfortable temperature of customer 'c' at hour y. The secondary objective function, emission can be expressed in terms of a quadratic form

$$E_x\left(Pg_x(y)\right) = d_x + e_x Pg_x(y) + f_x Pg_x^2(y) \tag{5}$$

emission coefficients of unit 'x' are represented as d_x, e_x, f_x and the corresponding constraints of unit commitment are

1. Power balance constraint

Real power generation from the thermal plants has to meet the demand which equals the power balance constraint.

$$\sum_{x=1}^{M} Pg_x(y) \cdot U_x(y) = d_o(y) \tag{6}$$

2. Generation Range

The real power generated from thermal units has to be maintained within limits of maximum and minimum generation.

$$Pg_{x,min} \le Pg_x \le Pg_{x,max} \tag{7}$$

where $Pg_{x,min} Pg_{x,max}$ are the minimum and maximum power generation limits of thermal units.

3. Spinning reserve

Maintaining the spinning reserve capacity of a system can be expressed as

$$\sum_{x=1}^{M} Pg_x(y) \cdot U_x(y) \ge d_o(y) + SR(y) \tag{8}$$

Spinning reserve at y hour is indicated as $SR(y)$

4. Minimum up and downtime

ON/OFF time of each thermal unit can be expressed as

$$X_{x,on} \ge MUT_x \tag{9}$$

$$X_{x,off} \ge MDT_x \tag{10}$$

where $X_{x,off}$ and $X_{x,on}$ is the off/on duration of unit 'x' and MDT_x and MUT_x are the minimum downtime and uptime of unit 'x'.

B. Economic Demand Model

The price elasticity model can be expressed

$$E = \frac{\partial d}{\partial \rho} = \frac{\rho_o}{d_o} \cdot \frac{dd}{d\rho} \tag{11}$$

where ρ₀ is the electricity price ($) initially, d₀ is the initial demand (MW)

1. Modelling of Multi period

Cross elasticity among y^{th} and j^{th} hour

$$E(y,j) \le 0\ if\ y = j$$
$$E(y,j) \ge 0\ if\ y \ne j$$

The function of linearity that indicates demand variation to price variation as

$$d(y) = d_o(y) + \sum_{y=1}^{24} E(y.j) \frac{d_o(y)}{\rho_o(y)} \left[\rho(y) - \rho_o(y)\right] \tag{12}$$

At hour y the demand function with incentives are expressed as

$$d(y) = d_o(y) + \sum_{y=1}^{24} E(y.j) \frac{d_o(y)}{\rho_o(y)} \left[\rho(y) - \rho_o(y) + I(y)\right] \tag{13}$$

2. HVAC appliance modeling

Load aggregators are crucial in making end-users participate in DRPs with their HVAC appliances. Based on the measure of comfort, the end user's HVAC is controlled. A close relationship between temperature and time of an HVAC unit is expressed as

$$T_{in}^{y+1} = T_{out}^{y+1} - \left(T_{out}^{y+1} - T_{in}^{y}\right)\varepsilon; \qquad s = 1 \tag{14}$$

$$T_{in}^{y+1} = T_{out}^{y+1} - \eta P_y / A - (T_{out}^{y+1} - \eta P_y / A - T_{in}^{y})\varepsilon; s = 0 \tag{15}$$

where T_{in}^{y+1} T_{in}^{y} are the room temperatures at y+1 and y hours, T_{out}^{y+1} , T_{out}^{y} are the ambient temperatures at y+1, y hours. ‘s’ indicates the on/off status of the HVAC unit which is a controllable variable. ‘ε’ is the coefficient of heat dissipation and ‘A’ is the thermal conductivity coefficient. ‘ η’ is the HVAC efficiency ratio and P_y rated real power at hour ‘y’. The range of temperature over which the customers have to maintain their indoor temperature within the maximum and minimum temperature is indicated as T_{max} and T_{min}. Based on the supporting participation of customers in DRPs the incentives are awarded to the end-users. Over the range of temperature, the contribution of customers are awarded multilevel incentives and load balancing services are incorporated with baseline

$$M = \begin{cases} I_1 & if\ T_{min} \le T_{in} \le T_{max} \\ I_2\ if\ T_{in} \ge T_{max}\ and\ T_{in} \le T_{min} : Com = 1 \\ I_3\ if\ T_{in} \ge T_{max}\ and\ T_{in} \le T_{min} : Com = 0 \end{cases} \tag{16}$$

Based on the requirement of load reduction at peak periods utilities enforces the load aggregators to allow the customers to participate in DRPs with HVAC appliances. Load aggregators collect the customer’s participation, in blocking off their HVAC unit or not based on their consolation. End-users maintaining the indoor temperature within the range of set point will be awarded I_1 and I_2 awarded for the customers who are violating the range of set point and compromise in blocking off their HVAC unit. Only under emergencies, I_3 will be awarded to the customers who don’t compromise to turn off their HVAC unit, so to participate in DRPs this is a very rare case. Customers awarded with I_3 have to give up the opportunities of I_2 and I_1 in any situation. Customers violating the agreement and unfair for the participation of customers will not be penalized or punishable.

III. METHODOLOGY

A. Modified hybrid method

In this Modified hybrid method (MHM), both NSGA-II and PVDE are modified to achieve a better optimal solution than compared with a hybrid method (HM). MHM is employed for DRUC optimization problem to achieve optimal value with better diversity and the procedure is as follows

a) Initial parameters: population size, number of objectives, number of iterations, emission and cost coefficients, and decision variables are initialized.

b) Random generation of the parent population is generated which has maintained both equality and inequality constraints represented in equation (6) and (7).

c) Evaluate the cost and emission function values which indicate strength using equation (2) and (5)

d) With the application of MNSGA-II for fifty percent of the parent population, the non-dominant sorting, crowding distance, and ranking-based techniques are applied.

e) Binary crossover, and polynomial mutation takes place for the production of half the child population with the bisection of the parent population.

f) Remaining fifty percent of parent population is applied with MPVDE, in which interquartile [20] is replaced with a coefficient of quartile deviation associated with semi quartile range and mid quartile range for the refreshment of the population at the initial stage.

$$\text{Var} = \frac{P_1 - P_2}{P_1 + P_2} \tag{17}$$

Where P_1 and P_2 are the semi interquartile range and mid quartile range

P_1 = (high quartile - low quartile)/2;
P_2 = (high quartile + low quartile)/2;

g) The same sequence is applied in MPVDE as that of MNSGA-II in the initial stage followed by genetic operations for the production of the other fifty percent child population.

h) The two-child populations are combined to form a child population of original population size and combined with parent population of original population size.

i) From the twice original population best population of original size is selected based on Euclidean distance

$$D_{a,b}^{i} = \left(\sqrt{\textstyle\sum_{m=1}^{n}(d_m^a - d_m^b)^2}\right)/(n-1) \quad ; i=1, 2, 3…. \tag{18}$$

If Ni > N then the best fitness population members are selected. If Ni < N then a new random population is generated which should lie in the range of Euclidean distance. Where N is the original size of the population, Ni is the total number of population combinations of parent and child population.

j) The process repeats until the maximum iteration is reached.

k) The best optimal value is selected based on the concept of fuzzy set theory.

IV. RESULS AND DISCUSSION

The MHM is applied to two test cases. Case 1 is applied to IEEE 39 bus with 10 generating units and case 2 is related to the 17 units system. In these test cases, the DRUC optimization problem is implemented for achieving an optimal value with inequality and equality constraints. A MATLAB program was developed using the operating system Windows 10.

Case1: In this case study, the DRUC problem was solved using a modified hybrid method which is the combination of MNSGA-II and MPVDE. The cost and emission coefficients, maximum and minimum generation limits [21], demand and price values [22] are considered. Participation of percentage customer compromise is considered in DRPs i.e. 50, 80, and 100 percent is implemented in DRUC. Percentage of customer compromise represents maintaining room temperature within the prescribed limits of T_{max} and T_{min}. Without DRPs the scheduling of thermal units over 24 hours with a time horizon of one hour is shown in table 1.

The associated total cost and emission values are 565347.8 ($) and 44370.28(lb). Over the peak load, all the units are committed to power dispatch of load demand. The total cost and emission values are high in comparison with other load hours. The demand curve is shown in figure 1. With the incorporation of 50 percent customer compromise in DRPs, the total cost at peak load was diminished from 33950.162($) to 33902.89($) with miniature variation in emission values which can be observed in table 2. With the incorporation of DR with UC, change in load demand, cost, and emission values are encountered. The reduction in demand over the peak loads with the participation of customers in DRPs with fifty percent compromise is shown in figure 2.

Enhancement percentage of customer compromise in DRPs leads to an increase in the reduction of demand. The corresponding values of 50 percent customer compromise running cost, startup cost, repayment, total cost, and emission values are shown in table 2. The reduction in total cost and emission is 0.0087, 0.028 percent in comparison without DRPs. Figure 3 shows incentives awarded to the customers over the peak hours. Multilevel incentives are awarded to the end-users based on their contribution to DRPs. Incentives I_1, I_2, and I_3 are awarded a based range of room temperature.

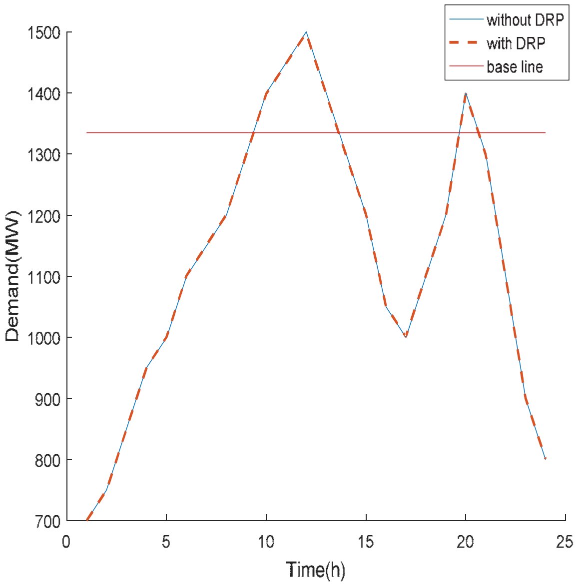

Figure 1. Load curve of IEEE 39 bus system

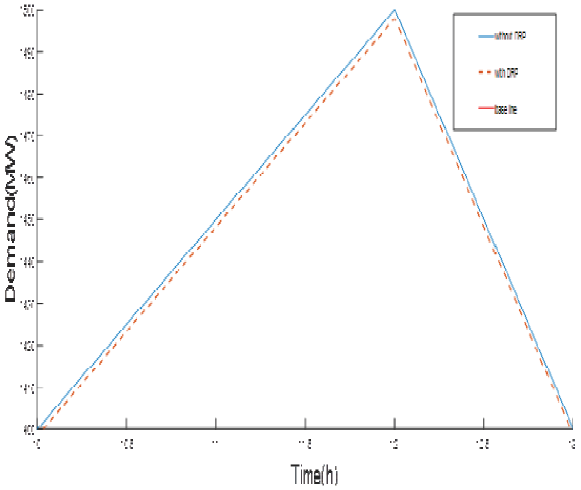

Figure 2. Peak load curve with and without DRPs

Case 2: In this case study of 17 unit system, the emission values are considered based on the strategy followed in [23], and the corresponding fuel cost coefficients and startup cost values are considered [24]. Parameters are initialized initially, population size 80, a maximum number of iteration was 100, and crossover and mutation values are 0.90 and 0.01. The load curve is shown in figure 4 with two peak load values. Figure 5 illustrates the repayment award for the end-users for the 100 percent customer's compromise participation in DRPs. The respective running cost, startup cost, repayments, emission, the total cost of the 17 unit system with 100 percent customer compromise is shown in table 3.

Comparison of 50 percent, 80 percent, and 100 percent end-user compromise of IEEE 39 bus system with 10 units using a hybrid method and modified hybrid method is shown in table 4. With the modification in NSGA-II and PVDE as a consequence, there is a reduction in emission followed by enhancement in percentage compromise reduction in running cost and total cost and fixed startup cost. The reduction in emission value with the modified hybrid method is 0.363 percent in comparison with the hybrid method. The running fuel cost and emission values are reduced in comparison with the hybrid method shown in table 5. Over 50, 80, and 100 percent compromise of end-users there is a corresponding reduction in all the parameters except startup cost illustrated in table 5. The startup cost is low in a hybrid method in comparison with a modified hybrid method.

V. CONCLUSIONS

The modifications in both NSGA-II and PVDE applied on IEEE 39 bus system and 17 unit system emphasize a reduction in emission value. The reduction in running cost, total cost, and emission is the enhancement percentage of customer participation in DRPs. The associated startup cost value is lower in a hybrid method in comparison with the proposed one. Participation of end-users in DRPs is beneficial to customers with the repayment,

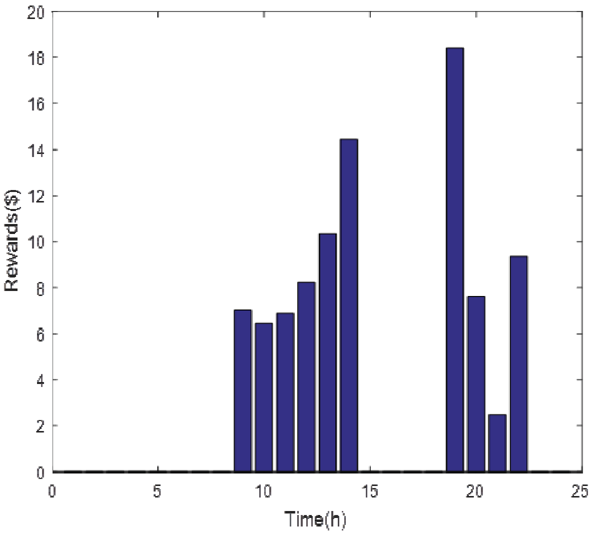

Figure 3. Reward Vs time for 50 percent customer compromise

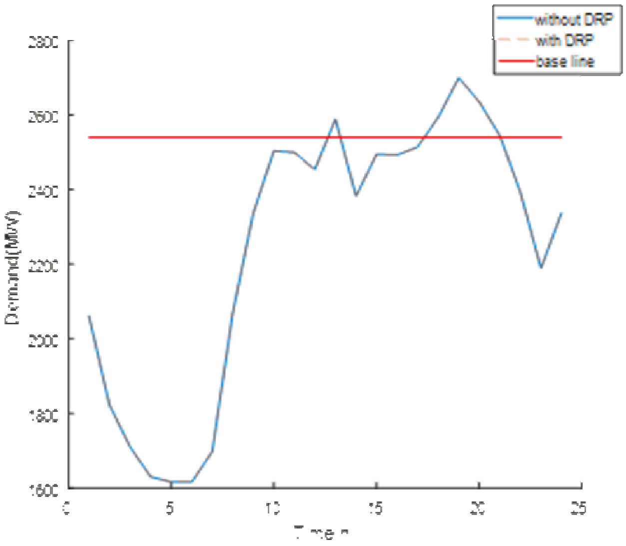

Figure 4. Load curve of the 17 unit system

as well as utilities for the demand reduction, total cost, and emission. With incorporation of DRPs with UC additional establishment of new generating unit is not required.

An ample of opportunities are available for the participation of customers DRPs in various categories. The proposed method has inferred that variation in NSGA-II and PVDE leads better optimal value compared with a hybrid method

TABLE I.
SCHEDULING OF COMMITTED THERMAL UNITS FOR 24 HOURS

S.No	PG1 (MW)	PG2 (MW)	PG3 (MW)	PG4 (MW)	PG5 (MW)	PG6(MW)	PG7 (MW)	PG8 (MW)	PG9 (MW)	PG10 (MW)	Total cost ($)	Emission (lb)
1	455	245	0	0	0	0	0	0	0	0	13683.129	956.39
2	455	295	0	0	0	0	0	0	0	0	14554.499	1055.03
3	455	370	0	0	25	0	0	0	0	0	17709.448	1270.793
4	455	455	0	0	40	0	0	0	0	0	18597.667	1558.926
5	455	390	130	0	25	0	0	0	0	0	20601.160	1556.594
6	455	360	130	130	25	0	0	0	0	0	23507.044	1552.705
7	455	410	130	130	25	0	0	0	0	0	23261.979	1704.245
8	455	455	130	130	30	0	0	0	0	0	24150.340	1863.089
9	455	455	130	130	85	20	25	0	0	0	28111.056	2191.277
10	455	455	130	130	162	33	25	0	10	0	30135.859	2618.669
11	455	455	130	130	162	73	25	10	10	0	31976.061	2945.212
12	455	455	130	130	162	80	25	43	10	10	33950.162	3229.393
13	455	455	130	130	162	33	25	10	0	0	30057.550	2599.17
14	455	455	130	130	85	20	25	0	0	0	27251.056	2191.277
15	455	455	130	130	30	0	0	0	0	0	24150.340	1863.089
16	455	310	130	130	25	0	0	0	0	0	21513.659	1424.165
17	455	260	130	130	25	0	0	0	0	0	20641.824	1318.625
18	455	340	130	130	25	20	0	0	0	0	23025.552	1520.623
19	455	415	130	130	25	20	25	0	0	0	25601.600	2004.263
20	455	455	130	130	162	33	25	10	0	0	30117.550	2599.17
21	455	455	130	130	85	20	25	0	0	0	27251.056	2191.277
22	455	360	130	130	25	0	0	0	0	0	22387.044	1552.705
23	455	420	0	0	25	0	0	0	0	0	17684.693	1426.932
24	455	345	0	0	0	0	0	0	0	0	15427.419	1176.67
											565347.8	44370.28

TABLE II.
50 PERCENT CUSTOMER COMPROMISE OF IEEE 39 BUS WITH 10 UNITS

Fuel cost	SUC	Reward ($)	Total cost ($)	Emission (lb)
13690.73	0	0	13690.73	957.1515
14562.79	0	0	14562.79	1056.078
16817.78	900	0	17717.78	1272.171
18608.89	0	0	18608.89	1559.299
20060.79	550	0	20610.79	1558.288
22398.01	1120	0	23518.01	1554.463
23274.07	0	0	23274.07	1706.497
24165.26	0	0	24165.26	1863.525
27231.5	860	7.006	28098.51	2190.281
30021.34	60	6.468	30087.81	2598.217
31874.84	60	6.906	31941.74	2943.56
33834.67	60	8.226	33902.89	3229.396
30023.19	0	10.345	30033.53	2598.265
27215.41	0	14.436	27229.85	2189.467
24173.76	0	0	24173.76	1863.775
21531.83	0	0	21531.83	1426.607
20659.16	0	0	20659.16	1320.501
22874.93	170	0	23044.93	1523.531
25307.52	260	18.392	25585.92	1997.847
30027.86	60	7.611	30095.47	2598.387
27234.59	0	2.477	27237.07	2190.437
22366.47	0	9.357	22375.83	1549.416
17705.62	0	0	17705.62	1430.944
15446.16	0	0	15446.16	1179.531
561107.176	4100	91.228	565298.40	44357.632

TABLE III.
100 PERCENT CUSTOMER COMPROMISE OF 17 UNIT SYSTEM

Fuel cost	SUC	Reward ($)	Total cost ($)	Emission (lb)
37036.25	0	0	37036.25	37036.25
30736.1	0	0	30736.1	30736.1
28587	0	0	28587	28587
26741.44	0	0	26741.44	26741.44
26422.78	0	0	26422.78	26422.78
26401.13	0	0	26401.13	26401.13
28954.44	2650	0	31604.44	28954.44
36890.48	1489	0	38379.48	36890.48
43569.26	1201	0	44770.26	43569.26
48147.86	6659	0	54806.86	48147.86
48043.52	0	0	48043.52	48043.52
46827.4	0	7.006	46834.4	46827.4
50058.65	3334	4.088	53396.73	50058.65
44451.23	0	2.245	44453.47	44451.23
47646.03	2870	1.519	50517.55	47646.03
47594.13	0	1.950	47596.08	47594.13
48074.97	0	18.392	48093.36	48074.97
50158.08	3789	11.824	53958.9	50158.08
53035.07	632	6.233	53673.31	53035.07
51339.68	0	2.637	51342.32	51339.68
49224.4	0	3.652	49228.05	49224.4
45268.44	0	0	45268.44	45268.44
40219.68	0	0	40219.68	40219.68
43565.66	500	0	44065.66	43565.66
998993.67	23124	59.549	1022177.22	998993.67

TABLE IV.
COMPARISON OF COST AND EMISSION VALUES OF IEEE39 BUS SYSTEM WITH 10 THERMAL UNITS

customer	Modified hybrid method				Hybrid method [25]			
	Running cost	SUC	Total cost	Emission	Running cost	SUC	Total cost	Emission
50%	561107.1765	4100	565298.4052	44357.63262	559756.100	4090	563937.329	44519.50893
80%	561105.818	4100	565283.366	44354.99385	559755.6	4090	563923.1	44516.37
100%	561103.1788	4100	565263.8923	44352.2432	559754.624	4090	563905.338	44512.810

TABLE V.
COMPARISON OF COST AND EMISSION VALUES OF 17 UNIT SYSTEM

customer	Modified hybrid method				Hybrid method [25]			
	Running cost	SUC	Total cost	Emission	Running cost	SUC	Total cost	Emission
50%	999015.555	23124	1022256.853	999015.555	999996.792	17798	1017912.09	999996.792
80%	999005.389	23124	1022220.823	999005.389	999986.080	17798	1017875.514	999986.080
100%	998993.679	23124	1022177.229	998993.6798	999955.194	17798	1017796.472	999955.194

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