Multi-Agent Approach for Profit Based Unit Commitment

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***Abstract*—Deregulation in the electricity market offers freedom to the generator companies (GENCOs) to schedule their generators in order to maximize their profit without actually satisfying the load and the reserve requirements. Various techniques have been developed for solving the profit based unit commitment (PBUC) problem. Among them, the multi-agent approach is different where each generator unit is referred to as an intelligent agent. In this paper, we develop a new multi-agent approach for PBUC problem in which the rule based intelligence is provided to the independent system operator (ISO) agent. Intelligence of generator agents (GenAgents) is limited to maximize their profit for the given demand and reserve using real-parametric genetic algorithm (GA) and share the results with ISO agent. In this approach, ISO agent commits the maximum profit generating GenAgents for every hour while satisfying the up/down time constraints. ISO agent also asks other GenAgents to calculate their profit for the remaining demand and reserve. The simulation results of 10 units problem for two payment methods are shown and compared with other techniques.**

I. Introduction

Deregulation in the electricity power market brings the change in the operation, planning and controlling of the traditional power system. Earlier in vertically integrated power system, the generator companies (GENCOs) have an obligation to serve their customers by satisfying the demand and the reserve. Therefore, GENCOs have to optimally schedule their generator units in order to minimize their production cost. This problem is known as unit commitment (UC) problem.

From the last decade, the scenario of electricity power market has been changed. Deregulation in the power market increases the efficiency and reliability of system and allows customers to choose their supplier. Under decentralized environment, GENCOs are no longer obliged to exactly satisfy the demand and the reserve. However, GENCOs can decide the amount of deliverable power and reserve to be sold in market in order to maximize their profit. Now, the problem of UC is changed to profit based UC (PBUC) [1] for GENCOs. The hard constraints on demand and reserve satisfaction is changed to inequality constraints [2]. The objective function of minimum production cost has been changed to profit maximization. Profit of GENCOs now depends on revenue and production cost. Therefore, GENCOs can sell that amount of power and reserve in the market which can produce maximum revenue with minimum production cost to maximize their overall profit. This brings more competition among GENCOs.

Various techniques have been developed for finding the optimum solution to PBUC problem. The techniques like priority list [3], dynamic programming [4] etc. are not suitable for large unit system. However, the mathematical techniques like Lagrange relaxation (LR) [5], branch-and-bound method [6], muller method [7] etc. are sensitive to parameters and mostly converge to some sub-optimal solution. Stochastic algorithms like genetic algorithm (GA) [2], particle swarm optimization (PSO) [8], [9], evolutionary programming (EP) [10], simulated annealing (SA) [11] have been used for PBUC to over come the premature convergence. But, these algorithms are computationally extensive. Later, hybrid techniques such as LR with EP (LR-EP) [1], LR with evolutionary strategy (LR-ES) [12], LR with ant colony optimization [13], LR-GA [14], Tabu search with evolutionary PSO (TS-EPSO) [15] etc., are used that give better optimum results in reasonable time. Some other intelligent techniques such as selective enumerative method with dynamic programming [16], multi-agent system (MAS) approach [17] etc. also have been used to solve PBUC problem effectively.

Among the mentioned techniques, the multi-agent approach is different where the computing entity is referred to as an intelligent agent. These agent can communicate and share their information to solve the PBUC problem. Generally, each generating unit is considered as an intelligent agent (GenAgent). In this paper, we develop a new multi-agent approach in which rule based intelligence is provided to the independent system operator (ISO) agent. GenAgents maximize their profit for the given demand and reserve using genetic algorithm (GA). Thus, the intelligence of GenAgents is limited to optimization task. In the proposed approach, ISO agent commits the maximum profit generating GenAgents and also satisfies the up/down time constraint of GenAgents. ISO agent also asks the decommitted GenAgents to generate profit for the remaining demand and reserve.

The paper is structured as follows. PBUC formulation is given section II followed by two payment methods. Multi-agent approach for PBUC problem is discussed in section III. Simulation results for two payment methods are discussed in section IV and the results of proposed approach are compared with other techniques. The paper is concluded in section V with a note on future work.

TABLE I
NOTATION

i	Index of generator (i = 1, ..., N)
t	Index of hour (t = 1, ..., T)
$X_{i,t}$	Commitment status (1 or 0) of generator i at hour t
$P_{i,t}$	Power generation of generator i at hour t (MW)
$R_{i,t}$	Reserve generation of generator i at hour t (MW)
$D_t^{'}$	Forecasted demand at hour t
$SR_t^{'}$	Forecasted reserve at hour t
SP_t	Forecasted spot price at hour t
RP_t	Forecasted reserve price at hour t
ST	Start up cost
P_i^{min}	Minimum generation limit of generator i
P_i^{max}	Maximum generation limit of generator i
$T_{i,up/down}$	Minimum up/down time of generator i
PF	Profit of GENCO
RV	Revenue of GENCO
TC	Total cost of GENCO
$F_i(P_i)$	Fuel cost = $a_i + b_iP_i + c_iP_i^2$, where a_i, b_i and c_i are constants
r	Probability that the reserve is called and generated

II. PROFIT BASED UNIT COMMITMENT FORMULATION

In the deregulated market, GENCOs sell their power and reserve to maximize their profit. In this scenario, it is not obligatory to meet the required demand and reserve. The standard formulation for PBUC [1] is given in equations (1) to (8). The notation are described in Table I.

$$\textit{Maximize PF: RV - TC} \tag{1}$$

Subjected to the following constraints:

1. Demand Satisfaction: $\sum_{i=1}^{N} P_{i,t}X_{i,t} \leq D_t^{'}$ (2)

$$\textit{2. Reserve Satisfaction: } \sum_{i=1}^{N} R_{i,t}X_{i,t} \leq SR_t^{'} \tag{3}$$

3. Power and Reserve Satisfaction:

$$\begin{aligned} &P_i^{min} \leq P_{i,t} \leq P_i^{max} \\ &0 \leq R_{i,t} \leq P_i^{min} - P_i^{max} \\ &P_{i,t} + R_{i,t} \leq P_i^{max} \end{aligned} \tag{4}$$

4. Minimum up and down time constraints:

$$\begin{aligned} &X_{i,t} = 0 \textit{ for } \sum_{h=t-T_{i,up}}^{t-1} X_{i,h} < T_{i,up} \\ &X_{i,t} = 1 \textit{ for } \sum_{h=t-T_{i,down}}^{t-1} (1 - X_{i,h}) < T_{i,down} \end{aligned} \tag{5}$$

Two payment methods [18] are adopted in this paper which are as follows:

A. Payment for Power Delivered

In this method, reserve is paid when it is actually used. Thus, the reserve price is more than the spot price. For this method, the revenue (RV) and total cost (TC) of equation (1) is given below:

$$\begin{aligned} RV = &\sum_{i=1}^{N} \sum_{t=1}^{T} (P_{i,t}.SP_t).X_{i,t} + \\ &\sum_{i=1}^{N} \sum_{t=1}^{T} (r.R_{i,t}.RP_t.X_{i,t}) \end{aligned} \tag{6}$$

$$\begin{aligned} TC = &(1-r) \sum_{i=1}^{N} \sum_{t=1}^{T} F(P_{i,t}).X_{i,t} + \\ &r. \sum_{i=1}^{N} \sum_{t=1}^{T} F(P_{i,t} + R_{i,t}).X_{i,t} + ST.X_{i,t} \end{aligned} \tag{7}$$

B. Payment for Reserve Allocated

In this method, GENCO receives the reserve price per generator of reserve for every time period that the reserve is allocated but not used. When reserve is used, GENCO receives the spot price for the reserve that is generated. Here, the reserve price is much less than the spot price. For this method, total cost is same as of equation (7) and revenue is given below:

$$\begin{aligned} RV = &\sum_{i=1}^{N} \sum_{t=1}^{T} (P_{i,t}.SP_t).X_{i,t} + \\ &\sum_{i=1}^{N} \sum_{t=1}^{T} ((1-r)RP_t + r.SP_t)R_{i,t}.X_{i,t} \end{aligned} \tag{8}$$

III. MULTI-AGENT APPROACH FOR PBUC

Multi-agent approach is a form of distributed artificial intelligence technique in which each computing entity is referred to as an intelligent agent. These agents act in an environment to achieve a common goal either cooperatively or competing together. This approach is beneficial to solve the high dimension combinatorial PBUC problem because the generators can intelligently be scheduled so that the profit can be maximized and the constraints on up/down time can be satisfied. However, the remaining generators can also commit and schedule if they can produce positive profit for the remaining demand and reserve. Moreover, the optimization task becomes relatively easier (discuss later in this section).

Multi-agent system has been used earlier [17] for profit based unit commitment. In this study, various intelligent agents were used in which central agent (CA) was considered as central operator. This agent commanded the mobile agent (MA) to achieve the maximum profit objective. Thereafter, MA visited generator agents (GAs) in the network using different traveling routes. For every route, MA accepted the supply plan including profit, power and reserve when GA satisfied the local constraints with some positive profit. Thereafter, MA migrated to another GA according to the traveling route to negotiate for the rest of the load and reserve.

In this paper, JADE (Java Agent DEvelopment) [19] framework is used that conforms to Foundation for Intelligent Physical Agents (FIPA) [20] standards for intelligent agents. JADE platform provides a set of functions and classes to implement agent functionality, such as agent management service, directory facilitator and message passing services. Agent management service (AMS) is responsible for managing the agent platform, which maintains a directory of Agent Identifiers (AIDs) and agent states. Directory facilitator (DF) provides the default yellow page services in the platform which allows the agents to discover the other agents in the network based on the services they wish to offer or to obtain. Finally, the message transport service (MTS) is responsible for delivering messages between agents, provides services for message transportation in the agent system.

Using JADE platform, an ISO agent and various GenAgents are created and registered with DF. ISO agent then fetches the forecasted demand, reserve and spot price from the database and sends "Call for Proposal" message to all GenAgents as shown in step 1 of algorithm 1. Those GenAgents which are willing to supply the power and reserve, reply with "Agree" message. Thereafter, ISO agent shares the forecasted data with the agreed GenAgents.

Step 1: ISO agent sends "Call for Proposal" message to all GenAgents
Step 2: Willing GenAgents reply with "Agree" message to ISO agent
Step 3: ISO shares the forecasted demand, reserve and spot price with agreed GenAgents
Step 4: GenAgents calculate their profit and deliverable amount of power and reserve for the given data on demand, reserve and spot price
Step 5: GenAgents share the profit and the amount of power and reserve with ISO agent
Step 6: ISO agent receives the data from GenAgents
Step 7: ISO agent commits the maximum profit generating GenAgent for every hour
Step 8: ISO agent evaluates the remaining forecasted demand and reserve for every hour
Step 9: ISO agent satisfies the up/down time constraint for each committed GenAgent according to algorithm 2
Step 10: Repairing by ISO agent
Step 11: ISO calculates the total profit of committed GenAgents for the given period and subtracts the startup cost, if any
Step 12: If the total profit of any GenAgent is **not** positive, then ISO agent shuts down that GenAgent for the whole period. ISO agent updates the remaining demand and reserve.
Step 13: **if** *Summation of profit of GenAgents is same as last time grand profit,;*
then
  Report the results and terminate
else
  Update the last time grand profit to the present grand profit of committed GenAgents and Go to step 3 with the remaining demand and reserve for every hour
end

Algorithm 1: *Multi-agent approach*

$$TC = (1-r)F(P_{i,t}) + r.F(P_{i,t} + R_{i,t})$$
$$\text{Method A: } RV = P_{i,t}.SP_t + r.R_{i,t}.RP_t$$
$$\text{Method B: } RV = P_{i,t}.SP_t + ((1-r)RP_t + r.SP_t)R_{i,t}$$
Subjected to constraints given in equation (4) (9)

After receiving the forecasted data, GenAgents perform the optimization task to maximize their profit according to equation (9). Note that revenue and total cost described in equations (6), (7) and, (8) are summed up for every generator unit and for the given time period. However, when multi-agent approach is used, ISO agent performs the summation for the generators over the given time period. In this case, GenAgents have to just maximize their profit within their power capacity for every hour and for the given demand and reserve. Thus, the optimization task for GenAgents becomes relatively easier as compared to solve equations (6), (7) and, (8). In this paper, GenAgents use real-parametric genetic algorithm (GA) to solve the optimization problem of equation (9) in which a standard SBX crossover is used, followed by a polynomial mutation [21]. The elitist strategy of choosing good individ-

if *GenAgent is committed for the given hour;*
then
  Go to Step 1:
else
  Go to Step 2:
end
Step 1:
if *GenAgent was not committed in the last hour;*
then
  Check for how long the GenAgent was **not committed**. If GenAgent satisfies equation 5, then startup cost will be subtract from the total profit of this agent. Otherwise, ISO agent shuts down the GenAgent and updates the remaining demand and reserve for the given hour
else
  Constraints are already satisfied
end
Step 2:
if *GenAgent was committed in the last hour;*
then
  Check for how long the GenAgent was **committed**. If GenAgent satisfies equation 5, then shutdown cost will be subtract from the total profit of this agent. Otherwise, go to step 3
else
  Constraints are already satisfied
end
Step 3:
if *The remaining demand* $< P_i^{min}$ *or remaining reserve* ≤ 0*;*
then
  Shut down the GenAgent for the present time as well as for the previous hours till the down time constraint of equation 5 is not satisfied
else
  ISO agent asks the GenAgent to recalculate the profit and amount of power and reserve. ISO agent then updates the recalculated profit of GenAgent and also the remaining demand and reserve
end

Algorithm 2: *Up/Down constraint satisfaction* uals from parent and child populations is adopted based on ranking. Binary tournament selection is used for making the mating pool for crossover. After performing the optimization, GenAgents share their profit and deliverable amount of power and reserve with the ISO agent (step 5 of algorithm 1).

In the present approach, ISO agent is most intelligent agent which commits the maximum profit generating GenAgents. Intelligence of GenAgenst is limited to maximize their profit within the range of its power capacity. After committing the maximum profit generating GenAgents, ISO agent calculates the remaining demand and reserve (step 8) for every hour and satisfies the up/down time constraint (step 9) according to algorithm 2.

In algorithm 2, ISO agent checks the present and the last time status of every GenAgent. If any GenAgent starts or shuts down according to the last time status, then ISO agent examines the GenAgent. In case of down time constraint, if the GenAgent satisfies equation (5), then the startup cost will be subtracted from the total profit of that GenAgent. Otherwise, ISO agent de-commits the GenAgent and updates the remaining demand and reserve. Similarly, ISO agent investigates the up time constraint. However if the up time constraint is not satisfied, then ISO agent does not commit the GenAgent immediately. ISO agent first checks whether the minimum power capacity of GenAgent is greater than the remaining demand or reserve. If yes, then ISO agent asks GenAgent to recalculate its profit and deliverable power and reserve for the remaining demand and reserve for that hour. If minimum power capacity condition is not satisfied, then the GenAgent will shut down for the present hour as well as for the previous hours till the total shut down time becomes equal to $T_{i,down}$.

At this stage, ISO agent performs repairing operation (step 10) for two cases as shown in Fig. 1. In case 1, suppose the GenAgent is de-committed currently, that is, at time t but it was committed last time, that is, at time $t-1$. When ISO agent will check the down time constraint for time $t+1$, it will not satisfy. Hence, ISO agent will keep de-committing the GenAgent for next few hours till the down time constraint is not satisfied. In that case, the profit of GenAgent can reduce significantly. However in this paper, ISO agent allows the GenAgent to commit at t so that it will remain commit till $t+1$ hour. Accordingly, ISO agent will update the profit of GenAgent and remaining demand and reserve for time t. Similarly for case 2, ISO agent will de-commit the GenAgent for time t.

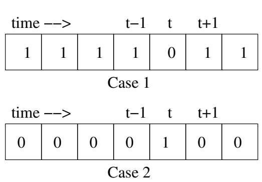

Fig. 1. Cases for repairing.

Now, ISO agent has the profit of all committed GenAgents for every hour. The total profit for each GenAgent is calculated for the given time period and the startup cost is subtracted, if any. ISO agent then checks whether the profit of any GenAgent becomes negative. If yes, then that GenAgent is shut down and the remaining demand and reserve are updated for every hour in which the GenAgent was committed.

In the final decision step 12 of algorithm 1, ISO agent adds the profit of all committed GenAgents and checks with the last time value of grand profit of GenAgents. In case of first iteration, last time grand profit is zero. If the present and last time values of grand profit is same, the ISO agent terminates the simulation and reports the optimal scheduling. Otherwise, the last time grand profit is updated with the present grand profit of all GenAgents and go back to step 3 of algorithm 1 with the remaining demand and reserve for every hour. In this case, ISO agent will share the remaining demand and reserve instead of actual values of appendix Table V.

Additional intelligence has been provided to ISO agent where it can remove GenAgents from the list which are agreed to supply the power and reserve in step 2 of algorithm 1 based on their profit. If GenAgent is committed for full time period, then this agent will be removed from the list of agreed GenAgents (discussed in section IV-A). Rest of agreed GenAgents will be asked to calculate their profit for the remaining demand and reserve. Those agreed GenAgents will also be removed from the list, if they can not generate positive profit for any hour (discussed in section IV-A).

IV. Simulation Results

In this paper, simulations are done for 24-hours time period of 10 generating units [1]. The forecasted data and generator unit data are given in appendix Tables V and VI, respectively. GenAgents use GA parameters as given below:

Population	100
Number of generations	100
Crossover probability of individual	0.9
Crossover probability of variable	0.5
Mutation probability of individual	1.0
Mutation probability of variable	1/(nb of variables)
Distribution crossover index	15
Distribution mutation index	20

The simulation results for payments methods A and B (described in sections II-A and II-B) are presented and further compared with results of other techniques.

A. 10 Generator Unit Test System for Payment Method A

In this section, scheduling of 10 generators is done for payment method A. For this method, $r = 0.05$ and reserve price is five times of spot price. As Table II shows, generator units U1 and U2 are scheduled to commit for 24-hours in which U1 contributes the maximum profit followed by U2. As discussed in the last paragraph of section III, during the simulation, U1 and U2 are removed from the list of agreed GenAgents when they are committed for full 24-hours. Similarly, U8, U9 and U10 are also removed from list because they generate negative profit in every hour. Although, U7 is

TABLE II
OPTIMAL SCHEDULE FOR PAYMENT METHOD A (SECTION II-A)

	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
1	455.0	245.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	70.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	455.0	295.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	75.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	455.0	395.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	60.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	455.0	455.0	0.0	0.0	40.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	95.0	0.0	0.0	0.0	0.0	0.0
5	455.0	455.0	0.0	0.0	62.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	99.6	0.0	0.0	0.0	0.0	0.0
6	455.0	455.0	0.0	130.0	52.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	110.0	0.0	0.0	0.0	0.0	0.0
7	455.0	455.0	0.0	130.0	47.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	114.9	0.0	0.0	0.0	0.0	0.0
8	455.0	382.7	0.0	130.0	114.4	0.0	0.0	0.0	0.0	0.0	0.0	72.3	0.0	0.0	47.6	0.0	0.0	0.0	0.0	0.0
9	455.0	455.0	130.0	130.0	32.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	130.0	0.0	0.0	0.0	0.0	0.0
10	455.0	455.0	130.0	130.0	162.0	67.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.8	0.0	0.0	0.0	0.0
11	455.0	455.0	130.0	130.0	162.0	80.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	455.0	455.0	130.0	130.0	162.0	80.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13	455.0	455.0	130.0	130.0	25.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	137.0	0.0	0.0	0.0	0.0	0.0
14	455.0	455.0	130.0	130.0	32.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	129.3	0.0	0.0	0.0	0.0	0.0
15	455.0	455.0	0.0	130.0	42.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	120.0	0.0	0.0	0.0	0.0	0.0
16	455.0	444.7	0.0	0.0	67.3	0.0	0.0	0.0	0.0	0.0	0.0	10.3	0.0	0.0	94.7	0.0	0.0	0.0	0.0	0.0
17	455.0	430.7	0.0	0.0	86.3	0.0	0.0	0.0	0.0	0.0	0.0	24.3	0.0	0.0	75.7	0.0	0.0	0.0	0.0	0.0
18	455.0	357.4	0.0	0.0	149.6	0.0	0.0	0.0	0.0	0.0	0.0	97.6	0.0	0.0	12.4	0.0	0.0	0.0	0.0	0.0
19	455.0	415.5	0.0	0.0	81.5	0.0	0.0	0.0	0.0	0.0	0.0	39.5	0.0	0.0	80.5	0.0	0.0	0.0	0.0	0.0
20	455.0	455.0	0.0	0.0	25.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	137.0	0.0	0.0	0.0	0.0	0.0
21	455.0	455.0	0.0	0.0	32.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	130.0	0.0	0.0	0.0	0.0	0.0
22	455.0	455.0	0.0	0.0	52.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	110.0	0.0	0.0	0.0	0.0	0.0
23	455.0	444.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
24	455.0	345.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	80.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Profit	55760.6	44404.2	3295.7	3742.5	5518.8	534.5	0.0	0.0	0.0	0.0	Total Profit ($)					113256.3				

TABLE III
OPTIMAL SCHEDULE FOR PAYMENT METHOD B (SECTION II-B)

	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
1	455.0	245.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	70.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	455.0	295.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	75.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	455.0	395.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	60.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	455.0	455.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	455.0	455.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	455.0	455.0	0.0	130.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	455.0	455.0	0.0	130.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	455.0	455.0	0.0	130.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	455.0	455.0	130.0	130.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	455.0	455.0	130.0	130.0	162.0	68.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.0	0.0	0.0	0.0	0.0
11	455.0	455.0	130.0	130.0	162.0	80.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	455.0	455.0	130.0	130.0	162.0	80.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13	455.0	455.0	130.0	130.0	162.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	455.0	455.0	98.0	130.0	162.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	32.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	455.0	455.0	0.0	128.0	162.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0
16	455.0	455.0	0.0	130.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
17	455.0	455.0	0.0	90.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	40.0	0.0	0.0	0.0	0.0	0.0	0.0
18	455.0	455.0	0.0	130.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
19	455.0	455.0	0.0	130.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20	455.0	455.0	0.0	130.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21	455.0	455.0	0.0	130.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	455.0	455.0	0.0	130.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	455.0	445.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
24	455.0	345.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	80.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Profit	55760.6	43070.4	3066.5	3980.7	2990.1	464.3	0.0	0.0	0.0	0.0	Total Profit ($)					109332.6				

de-committed for 24-hours but it is not removed from the list of agreed GenAgents. It is because U7 generates some positive profit. However, the total profit of U7 for 24-hours becomes negative when the startup cost is subtracted. Hence, it is shut down according to step 12 of algorithm 1. Units U3, U4, U5 and U6 are also committed for a few hours as shown in Table II and contribute in the grand profit of PBUC problem.

B. 10 Generator Unit Test System for Payment Method B

For the present example, $r = 0.005$ and the reserve price is 1% of spot price. The optimal schedule of 10 generator units is shown in Table III. In this example also, units U1 and U2 are committed for 24-hours whereas, the units U3, U4, U5 and U6 are committed for a few hours. U8, U9 and U10 are again removed from the list as they generate negative profit for every hour.

C. Comparison

The results of proposed multi-agent approach are compared with the results of other techniques including the state-of-art algorithms in Table IV. For payment method A, the proposed method shows the best profit found so far. However for payment method B, the profit of present approach is quite close to the best profit found by another multi-agent system approach [17].

The techniques mentioned in Table IV are mostly hybrid optimization techniques in which two optimization methods or algorithms are coupled together. For them, PBUC problem given in equations (1) to (8) is still difficult to solve. On the other hand, equations of revenue and total cost are reduced using multi-agent approach and optimization problem is subjected to less number of constraint (equation 9) for GenAgents. The rest of the constraints, commitment or de-commitment of GenAgenst and summation their total profits are taken care by ISO agent with rule based intelligence as described in algorithm 1. This could be the reason behind getting better profit using the proposed multi-agent approach.

Multi-agent approach presented in [17] however showed better profit than the proposed approach. The reason could be the repairing technique used in this paper. It is because when ISO agent repairs the binary string of GenAgent against up/down time constraints, ISO agent allows this GenAgent to commit first over the maximum profit generating GenAgent.

TABLE IV
COMPARISON

Techniques	Profit ($)	
	Method A	Method B
LR-EP [1]	1,12,818.93	1,07,838.5
MAS [17]	-	**1,09,485.19**
Improved PSO [9]	1,13,018.7	-
Improved SA [11]	1,13,134	-
Muller method [7]	-	1,03,296
TS-EPSO [15]	-	1,05,873.8
New LR-PSO [22]	-	1,07,838.57
Proposed Multi-agent approach	**1,13,256.3**	1,09,332.6

D. Salient Features of Proposed Multi-Agent Approach

1) In the present approach, all GenAgents respond to the ISO agent simultaneously to exploit the multi-threading platform of JADE. However, earlier MAS approach [17] used the mobile agent to visit and negotiate with the GenAgents according to the traveling route that can only be followed sequentially.
2) Iteration by iteration, GenAgents are committed according to their generated maximum profit. This allows to commit those GenAgents first who contribute maximum in the grand profit of PBUC problem. However in earlier MAS approach approach [17], when the mobile agent finished its journey of visiting every GenAgent, it again visited the GenAgents by following another traveling route.
3) Using multi-agent approach, the optimization task becomes relatively easier (equation 9) as compared to equations (1) to (8). Also, equation 9 is subjected to less number constraints.
4) Providing rule based intelligence to ISO agent can effectively solve such type of non-linear, high-dimensional combinatorial problem where it can take decisions as it is done in the real-world.
5) Multi-agent approach provides a flexible platform which is not limited to solve specific problems. However, the optimization techniques in the literature are dedicated to solve UC or PBUC problem. Moreover by changing the rules of ISO agent, GenAgents can work cooperatively as for PBUC problem or also can compete.

V. Conclusions

In this paper, a multi-agent approach has been applied to solve PBUC problem. The PBUC optimization formulation was divided among GenAgents and ISO agent that reduced its complexity. GenAgents optimized their profit using genetic algorithm (GA) whereas ISO committed GenAgents and satisfied various constraints based on some intelligent rules. The multi-agent approach using GA generated the best profit for payment method A. However for payment method B, the profit was quite close to the best found in the literature. Multi-agent JADE platform allowed the ISO agent to interact with GenAgents and asked them to generate the profit for satisfying the actual and the remaining demand and reserve.

In future work, the same multi-agent approach can be used to solve for larger system. Ramp up/down constraints can also be included into the formulations. Accordingly, the rules of ISO agent can be changed for a more robust platform. The procedure of repairing technique can further modify for better profit. Simulation time is also an interesting factor that can also be included in the future work to observe the overall performance of proposed multi-agent approach.

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APPENDIX

TABLE V
FORECAST DEMAND, RESERVE AND SPOT PRICE FOR 24 HOURS

Hours	Forecast demand (MW)	Forecast Reserve (MW)	Forecast spot price ($/MW-h)
1	700	70	22.15
2	750	75	22.00
3	850	85	23.10
4	950	95	22.65
5	1000	100	23.25
6	1100	110	22.95
7	1150	115	22.50
8	1200	120	22.15
9	1300	130	22.80
10	1400	140	29.35
11	1450	145	30.15
12	1500	150	31.65
13	1400	140	24.60
14	1300	130	24.50
15	1200	120	22.50
16	1050	105	22.30
17	1000	100	22.25
18	1100	110	22.05
19	1200	120	22.20
20	1400	140	22.65
21	1300	130	23.10
22	1100	110	22.95
23	900	90	22.75
24	800	80	22.55

TABLE VI
UNIT DATA

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
P^{max}	455	455	130	130	162
P^{min}	150	150	20	20	25
a	1000	970	700	680	450
b	16.19	17.26	16.60	16.50	19.70
c	0.00048	0.00031	0.00200	0.00211	0.00398
$T_{i,up}$	8	8	5	5	6
$T_{i,down}$	8	8	5	5	6
ST	4500	5000	550	560	900
Initial status	8	8	-5	-5	-6

	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
P^{max}	80	85	55	55	55
P^{min}	20	25	10	10	10
a	370	480	660	665	670
b	22.26	27.74	25.92	27.27	27.79
c	0.00712	0.00079	0.00413	0.00222	0.00173
$T_{i,up}$	3	3	1	1	1
$T_{i,down}$	3	3	1	1	1
ST	170	260	30	30	30
Initial status	-3	-3	-1	-1	-1