Multi-Agent System for Demand Side Management in Smart Grid

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Abstract—**This paper presents a Multi-Agent System (MAS) for Demand Side Management (DSM) in smart grid which uses an energy market for resource allocation. The multi-agent system contains Load Agents, Generator Agents and DSM Agent, which provides an electronic auction platform. The automation of the demand side management through the multi-agent system is equipped with an intelligent strategy which allows controllable devices to dynamically react to market changes and adapt their bidding behaviours accordingly. The agents are able to shift energy demand within certain boundaries from peak hours to off-peak hours to minimize the operational cost of the system. Simulation studies were carried out on the developed multi-agent system and the results show that the proposed approach provides a smoothed load curve for the whole system while operational cost and peak demand are reduced.**

Keywords-Demand side management; Smart grid; Microgrid; Multi-agent system; Energy market

I. INTRODUCTION

Demand Side Management (DSM) [1] is an effective solution, which contributes to distribution networks in various aspects such as transformation towards smart grid [2], liberalization of electricity market, enhancing effects of control management, reducing cost in infrastructure construction and increasing the feasibility of decentralized energy resources and electric vehicles. Controlling and influencing energy demand can reduce the peak demand and reshape the domestic load profile, which increases the grid sustainability by reducing the overall cost and carbon emission levels. This will lead to the avoidance of the construction of an under-utilized electrical infrastructure in terms of generation capacity, transmission lines and distribution networks.

Smart pricing is a unique characteristic in smart grids made possible by the usage of smart metering devices in an automatic metering infrastructure. It could lead to cost-reflective pricing based on the entire supply chain of delivering high quantity electricity at a certain location in a certain period. When used in tandem with the relevant demand side management technique, control of the customer's energy usage will be influenced by the real time penalty and incentive schemes at all levels of the supply chain. However, the rationale behind the implementation of demand side management within the context of the smart grid is to promote the overall system efficiency, security and sustainability by making full utilization of the existing network infrastructure while facilitating the integration of low carbon technology into the electrical network. Demand side management can also play a significant role in the liberalization of electricity markets [1,3,4]. If the demand side management system informs the cluster's central controller about the new load schedule and the available load reduction capabilities for each time step of the next day, the central controller can then place bids in the market offering load reduction capacity during periods of peak demand. Profits made can then be reimbursed to customers of that cluster.

There are several demand side management techniques and algorithms used in the literature [3-10]. Some of them are applicable only for the particular systems [5,7]. Most of them are based on dynamic programming [7], and linear programming [8] that has been used successfully to reduce the system peak, operating cost, or spinning reserve through load control for specific systems.

The transformation of today's grid towards the smart grid opens new perspectives to demand side management. Some of these perspectives are given here. First, significant part of the generation in smart grids is expected to come from renewable energy resources such as wind and solar [11]. The unpredictability of these renewable sources makes the dispatch of the smart grid challenging. Such a scenario necessitates the use of load control. Next, the operation of smart grids requires a two way communication between the central controller and the system elements. The designed demand side management system will benefit from this communication infrastructure allowing two-way real-time communication between the central controller and the controllable loads. At last but not least, the criteria for deciding the optimal load consumption can vary widely [12]. The criteria could be to maximize the use of renewable energy resources, to maximize the economic benefit by offering bids to reduce demand during peak periods, to minimize the amount of power imported from the main grid, and peak reduction.

In this paper, a multi-agent system [13-15] is proposed for demand side management in smart grid. The multi-agent system provides an autonomous electronic platform for demand side management in smart grid which are equipped with an intelligent devices. Intelligent strategies were developed into the agents allow controllable devices to dynamically react to market changes and adapt their bidding behaviours accordingly. The agents are able to shift energy demand within certain boundaries from peak hours to off-peak hours to minimize the operational cost.

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The remaining paper is organized as follows. Section II provides brief overview of possible demand side management techniques for future smart grid. Section III proposes a multi-agent system for demand side management. Section IV explains the demand side management techniques used in the proposed system. Section V provides simulation studies and results. Section VI concludes the paper.

II. DSM TECHNIQUES FOR SMART GRID

Demand side management alters customers electricity consumption patterns to produce the desired changes in the load shapes of power distribution systems. The changes in the final consumption profile will depend on the objectives of planning and operation of the utility companies. Demand side management focuses [16] on utilizing power saving technologies, electricity tariffs, monetary incentives, and government policies to mitigate the peak load demand instead of enlarging the generation capacity or reinforcing the network. To mitigate system instabilities brought about by increasing electricity demand, a suitable objective of demand side management activities could be to change the shape of the load demand curve by making a reduction in the total load demand of the distribution system during the peak periods and move these demand to more appropriate times in order to reduce the planning and operational cost of the network. Such a scheme requires a balance in the relationship between the network operators and customers.

The load shapes which indicate the daily or seasonal electricity demands of industrial, commercial or residential consumers between peak and off peak times can be altered by means of six broad methods [16,17,18]: peak clipping, valley filling, load shifting, strategic conservation, strategic load growth, and flexible load shape. Generally, these are the possible demand side management techniques that can be employed for future smart grid. These six demand side management techniques are illustrated in Fig.1.

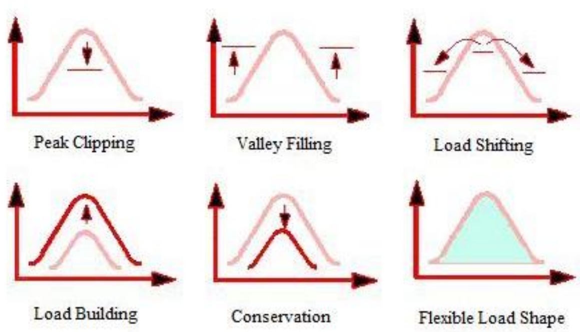

Fig.1. Demand side management techniques

Peak clipping and valley filling focus on reducing the difference between the peak load level and the valley load level in order to mitigate the burden of peak demand and increase the security of the smart grid. Peak clipping [16,18] is a direct load control technique to make reduction of the peak loads, and valley filling constructs the off-peak demand by applying direct load control.

Load shifting [18] is widely applied as a most effective load management strategy in current distribution networks and it takes advantage of time independence of loads. Load shifting shifts loads from peak time to off-peak time. Strategic conservation [16] indicates the load shape optimization through applying demand reduction methods directly at customer premises. The distribution management system would have to consider this for longer term implications of demand reduction on network planning and operation.

Strategic load growth [16,17,18] optimizes the daily response in case of large demand introduction beyond the valley filling technique. It is based on increasing the market share of loads supported by energy conversion and storage systems or distributed energy resources. It is a planning and operations issue to balance the increasing demand with processes for constructing necessary infrastructure that accompanies applying strategic load growth. The future smart grid will provide the necessary infrastructure for strategic load growth. Flexible load shape [16,17,18] is mainly related to reliability of smart grid. Smart grid management systems identify customers with the flexible loads which are willing to be controlled in critical periods in exchange for various incentives. Studies have to be conducted to identify the anticipated load shape which includes demand side activities forecasted over the planning horizon.

III. PROPOSED MULTI-AGENT ARCHITECTURE

The proposed decentralized multi-agent system architecture contains Load forecasting agent, Load agents, Market agent, Distribution Management System agent, DSM (Demand Side Management) agent, and bidding strategy module.

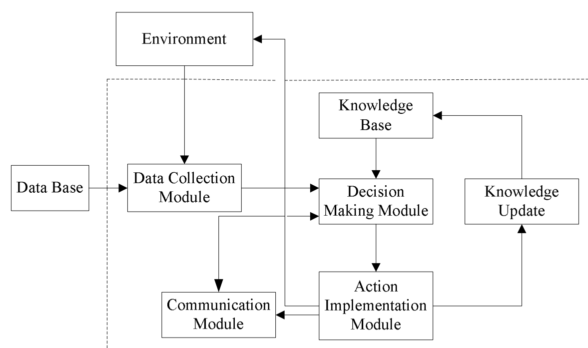

Fig.2. Generic architecture of an intelligent agent

Generic architecture of an intelligent agent in the proposed multi-agent system is shown in Fig.2. Knowledge base modules are implemented with rules base systems and there is no learning of agents (i.e. Knowledge update) implemented at this moment. It will be implemented in the future if there is a need of learning for better performance of any agent. Details implementation of decision making module is explained in next section, and agent communication is implemented according to FIPA standards.

Some of the important agents in the system and other important modules are briefly explained in below.

Load Forecasting Agent: It estimates the future energy demands of customers based on various information sources such as historic market prices. Throughout the day, the forecast generated based on the information must be steadily adjusted to a changing environment in which forecasted loads for specific time slots are subject to change. Overall, all information are aggregated into a continuously adjusted load forecast, which is made available to other agents.

DSM Agent: It does load shifting and is responsible for identifying those parts of the energy demand that can be consumed in different time slots. Based on the demand forecast for a time slot and the agent's performance on the market, the module decides whether to reallocate shiftable energy loads to other time slots or not. Basically there are two reasons why an agent might want to shift load: (i) to ensure that the demand is entirely satisfied even if supply is scarce and (ii) to save money. Still the agent has to take load shifting restrictions into consideration: in this case only a certain percentage of the forecasted energy demand can be shifted to an adjustable time window before or after the respective time slot.

Bidding Strategy Module of agents: These determine behaviours of the agents. It analyzes and calculates the amount of energy and the price limit for all orders submitted to the different auctions for the different time slots.

Before participating in the auction, a buyer agent needs to determine its reservation values, the quantities to be acquired and the already existing stocks for each time slot. Once a new round has started, the agent decides for each market (time slot) whether to bid or not to bid. For each market, it has an individual bidding strategy module as indicated in the flow chat. The agent only bid on a market if (i) the market for this time slot is not closed and (ii) the amount of energy has not been entirely acquired yet. Additionally the decision whether to bid on a market or not depends on the potential utility. i.e. the difference between the actual market price and the agent's valuation for acquiring energy in that time slot.

After a trading cycle ends, the bids and asks are matched by the auctioneer. Subsequently the trading agents update their stock levels and update their forecasting based on the new market prices observed. The load shifting module then assesses the potential for reallocating energy demand between markets in order potentially reduce costs by buying energy in cheaper time slots. After all the processes are finished, the agent possesses the update demand quantities for each time slot and thus can start the next trading cycle.

The DMS Agent is responsible for monitoring the operation of the power distribution system and coordinating the Local Controllers. Therefore, it gathers information from the Intelligent Load Controllers (ILC) and the inverters who control the PVs output and the batteries, regarding the amount of energy consumed and the amount of energy produced respectively. The DMS Agent is also informed about which controllable loads are in operation every moment. If the production units of the power distribution system (i.e. PVs and batteries) are able to supply the requested power, then the DMS Agent takes no action. If the PVs are capable of producing more power than the loads request, then the DMS Agent sends a message to the batteries informing the relevant agents that there is a surplus of power. The agents controlling the batteries are able to decide if there is need for the batteries to be charged, according to their state of charge.

On the other hand, the loads on operation demand more power than the production units can offer, the DMS Agent informs the Intelligent Load Controllers that there is need for load shedding. The ILCs, equipped with intelligent agents, and, hence, with communication skills, are required to interact with each other and most probably negotiate in order to decide which load is going to be disconnected from the grid. Finally, the possibility the produced power not to be sufficient while all the non-important loads have already been disconnected should also be anticipated. In this case, the diesel generator is started to supply the additional power.

IV. Proposed Algorithms

The main tasks of the proposed demand side management can be solved by following two different load control algorithms.

1. Shifting algorithm
2. Curtailment algorithm

Shifting algorithm is based on the existence of the system that calculates suitable control actions in a day ahead and sends them to the loads. It receives the objective load curves as an input and calculates the required load control actions in order to fulfil the desired load consumption. The system is flexible in the sense that it is completely independent from the criteria used to generate the objective load curve. The shifting algorithm runs a quadratic program and finds the best possible load scheduling. It is run usually on a daily basis. It is mathematically formulated as,

The proposed demand side management strategy schedules the connection moments of each shiftable device within the system in a way that brings the total load consumption curve as close as possible to the objective load consumption curve. The problem is mathematically formulated as follows.

Minimize,

$$\sum_{t=1}^{N}\left(PLoad(t)-Objective(t)\right)^2 \qquad (1)$$

where, $Objective(t)$ is the value of the objective curve at time t, and $PLoad(t)$ is the actual consumption at time t, which is given by,

$$PLoad(t)=Forecast(t)+Connect(t)-Disconnect(t) \qquad (2)$$

where, $Forecast(t)$ is the forecasted consumption at time t, and $Connect(t)$ and $Disconnect(t)$ are the amount of loads connected and disconnected at time t respectively during the load shifting.

The term $Connect(t)$ is made up of two parts: the increment in the load at time t due to the connection times of devices shifted to time t, and the increment in the load at time t due to the device connections scheduled for times that precede t. $Connect(t)$ is given by the following equation,

$$Connect(t)=\sum_{t=1}^{t-1}\sum_{k=1}^{D}X_{kit}.P_{1k}+\sum_{l=1}^{j-1}\sum_{i=1}^{t-1}\sum_{k=1}^{D}X_{ki(t-1)}.P_{(1+l)k} \qquad (3)$$

where, X_{kit} is the number of devices of type k that are shifted from time step i to t, D is the number of device types,

P_{1k} and $P_{(1+l)k}$ are the power consumed at time steps *1* and *1+l* respectively for device type *k*, and *j* is the total duration of consumption for device of type *k*.

Similarly, the term $Disconnect(t)$ also consists of two parts: the decrement in the load due to delay in connection times of devices that were originally supposed to begin their consumption at time step *t*, and the decrement in the load due to delay in connection times of devices that were expected to start their consumption at time steps that precede *t*. $Disconnect(t)$ is given by the following equation,

$$Disconnect(t) = \sum_{q=t+1}^{t+m} \sum_{k=1}^{D} X_{ktq} . P_{1k} + \sum_{l=1}^{j-1} \sum_{q=t+1}^{t+m} \sum_{k=1}^{D} X_{k(t-1)q} . P_{(1+l)k} \tag{4}$$

where, X_{ktq} is the number of devices of type *k* that are delayed from time step *t* to *q*, *m* is the maximum allowable delay.

This minimization problem is subject to the following constraints,

The number of devices shifted cannot be a negative value.

$$X_{kit} > 0 \qquad \forall i, j, k \tag{5}$$

The number of devices shifted away from a time step cannot be more than the number of devices available for control at the time step.

$$\sum_{t=1}^{N} X_{kit} \le Ctrlable(i) \tag{6}$$

where, $Ctrlable(i)$ is the number of devices of type *k* available for control at time step *i*.

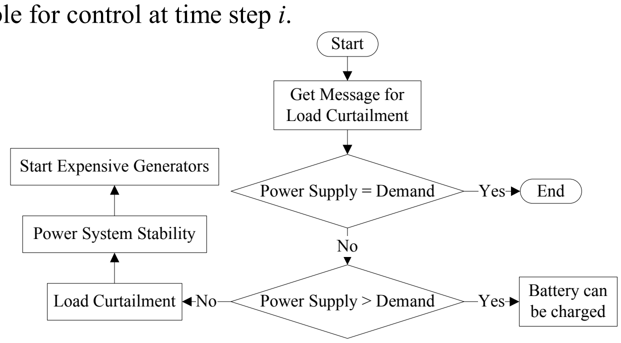

Fig.3. Load curtailment algorithm

Curtailment algorithm is run in real-time. The main objective of the algorithm is to minimize the use of expensive generators like diesel generators. In order this goal to be accomplished; the agents are required to cooperate so that they make efficient use of the power supplied from other sources. Load curtailment is something that should only be executed under exceptional circumstances for system security, which is shown in Fig.3.

V. SIMULATION STUDIES AND RESULTS

The developed multi-agent system for demand side management is tested in three smart grids which are a 1.5MW residential smart grid, a 2MW commercial smart grid, and a 3MW industrial smart grid. The main objective of the demand side management technique is to reduce the utility bill of these smart grids. Therefore, the objective curve is chosen as inversely propositional to the electricity market prices. Details of the smart grids are given in below.

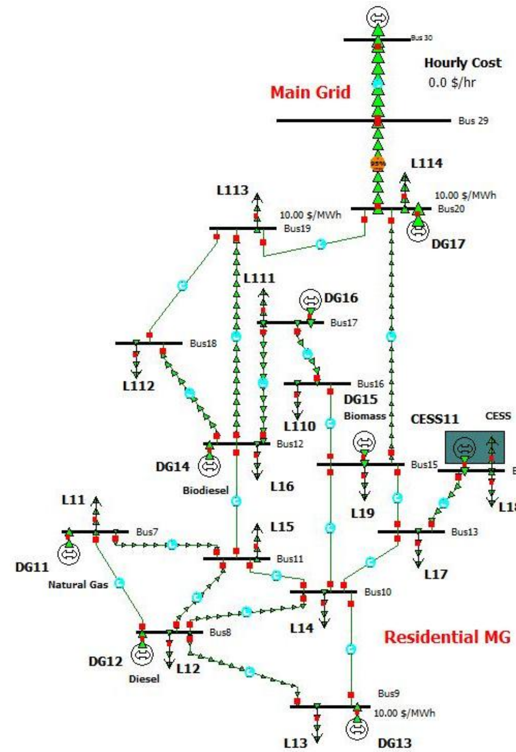

Fig.4. Network diagram of the residential smart grid

TABLE 1. CONTROLLABLE DEVICES IN THE RESIDENTIAL SMART GRID

Device Type	Consumption Pattern of Device (kW)			Number of Controllable Devices
	1st Hour	*2nd Hour*	*3rd Hour*	
Dryer	1.2	-	-	189
Dish Washer	0.7	-	-	288
Washing Machine	0.5	0.4	-	268
Oven	1.3	-	-	279
Iron	1.0	-	-	340
Vacuum Cleaner	0.4	-	-	158
Fan	0.20	0.20	0.20	288
Kettle	2.0	-	-	406
Toaster	0.9	-	-	48
Rice-Cooker	0.85	-	-	59
Hair Dryer	1.5	-	-	58
Blender	0.3	-	-	66
Frying Pan	1.1	-	-	101
Coffee Maker	0.8	-	-	56
Total Number of Devices	-	-	-	2604

Fig.4 shows the network diagram of the residential smart grid. The entire network operates at low voltage (410V). Each interconnection link including the link between the smart grid and the main grid has a resistance of 0.003pu, a reactance of 0.01pu, and maximum power transfer limit of 500kVA. Length of interconnection links is 2km. The network information helps for scheduling of distributed energy resources without any congestion. The devices subjected to control in this smart grid have the small power consumption ratings and the short durations of operation. Those details are given in Table 1.

Fig.5 shows the network diagram of the commercial smart grid. The devices subjected to control in the commercial smart grid have consumption ratings slightly higher than those in the residential smart grid. The consumption patterns of the loads under the control are given in Table 2.

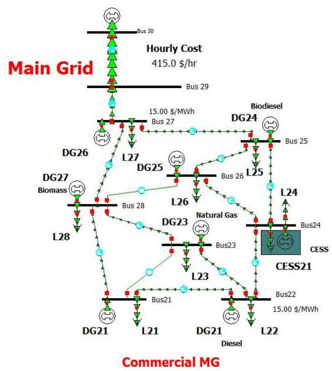

Fig.5. Network diagram of the commercial smart grid

TABLE 2. CONTROLLABLE DEVICES IN THE COMMERCIAL SMART GRID

Device Type	Consumption Pattern of Device (kW)			Number of Controllable Devices
	1st Hour	2nd Hour	3rd Hour	
Device 1	2.5	-	-	156
Device 2	3.5	-	-	117
Device 3	3.0	2.5	-	123
Device 4	5.0	-	-	77
Device 5	2.0	2.0	-	99
Device 6	3.5	3.0	-	93
Device 7	4.0	3.5	3.0	56
Device 8	2.0	1.75	1.5	87
Total	-	-	-	808

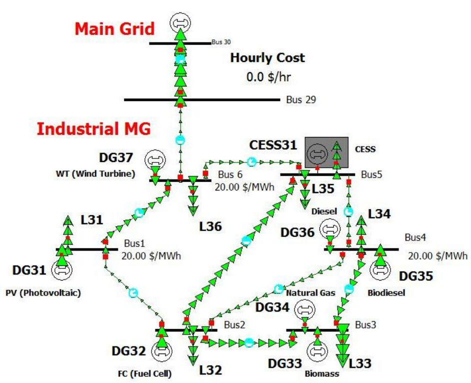

Fig.6. Network diagram of the industrial smart grid

Fig.6 shows the network diagram of the industrial smart grid. The number of devices available for control in the industrial smart grid is the smallest among the all three smart grids; however the devices have largest consumption ratings and longest consumption periods. The reason for a small number of devices available for control can be attributed to the fact that most of the industrial loads are critical and cannot be subjected to load control. The control periods of the devices are similar to those in previous cases. The consumption patterns of the devices in this area are given in Table 3.

TABLE 3. CONTROLLABLE DEVICES IN THE INDUSTRIAL SMART GRID

Device Type	Consumption Pattern of Device (kW)						Number of Controllable Devices
	1st Hr	2nd Hr	3rd Hr	4th Hr	5th Hr	6th Hr	
Device 1	12.5	12.5	12.5	12.5	-	-	39
Device 2	25.0	25.0	25.0	25.0	25.0	-	35
Device 3	30.0	30.0	30.0	30.0	30.0	-	16
Device 4	50.0	50.0	50.0	50.0	50.0	50.0	8
Device 5	100	100	100	100	100	100	5
Device 6	150	150	150	-	-	-	6
Total	-	-	-	-	-	-	109

The results obtained from the proposed demand side management strategy for the residential, commercial and industrial smart grids are given in Fig.7, Fig.8 and Fig.9 respectively.

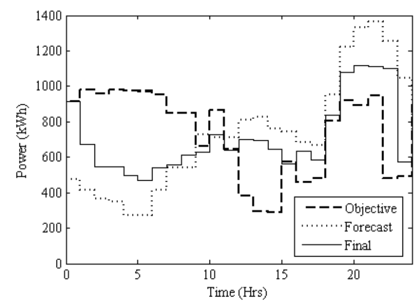

Fig.7. Results for the residential smart grid

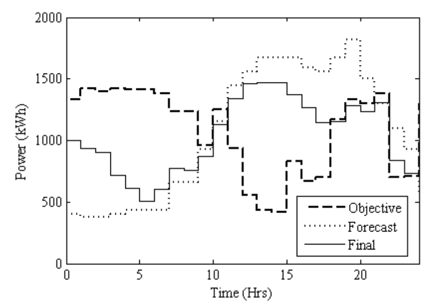

Fig.8. Results of the commercial smart grid

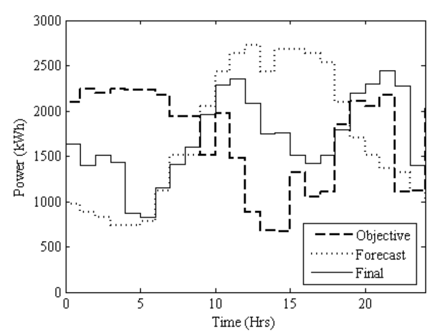

Fig.9. Results of the industrial smart grid

It is observed that load shifting has managed to bring the final consumptions closer to the objective load curves in all test smart grids. The utility bills are decreased by the proposed demand side management strategy. Not only load shifting provides benefit to the end users but also it provides advantages to the utilities. This comes in the form of reduced system peaks during the peak periods. Table 4 summarizes the results obtained from demand side management for the three different smart grids of customers.

TABLE 4. SUMMARY OF RESULTS

Type of Area	Cost without DSM ($)	Cost with DSM ($)	
		Multi-Agent System	Evolutionary Algorithm
Residential	2302.90	2161.21	2188.30
Commercial	3636.60	3401.11	3424.30
Industrial	5712.00	5111.92	5141.60

It can be observed that load shifting has managed to bring the final consumptions closer to the objective load curves. This is evident in the fact that the utility bills after load shifting have decreased in all three cases. Furthermore, the outcome from the multi-agent system approach does not have much difference from the outcome from the evolutionary approach [19]. Not only does load shifting provide benefit to the end users it also provides advantages to the utilities. This comes in the form of reduced system peaks during the peak periods. Table 5 shows the peak demands of each smart grid with and without DSM.

TABLE 5. SUMMARY OF PEAK REDUCTION

Type of Area	Peak Load Without DSM (kW)	Peak Load With DSM (kW)	
		Multi-Agent System	Evolutionary Algorithm
Residential	1363.6	1121.2	1114.4
Commercial	1818.2	1499.1	1485.2
Industrial	2727.3	2356.0	2343.6

The reduction in peak demand would mean huge savings in terms of generation scheduling for the utility. Normally, costly generators will be turned on to provide power during peak demand. As the system peak load reduces, the system operating cost is reduced enormously. This would also result in an increase in the reserve generation capacity. It can be noted that outcome from the multi-agent system approach does not have much difference from the outcome from the evolutionary approach [19] for the peak load reduction.

The centralized demand side management strategy [19] that considers all system and unit constraints at the time of simulation. Even though the central strategy is able to find an optimal solution, this solution is strictly dependent on exact data about the behaviour of units and system. In reality, exact data is not available at the time of simulation. Decentralized multi-agent system shows its potential of solving the problem dynamically. This strategy considers load shedding/curtailment in addition to perform the load shifting. Furthermore, it is infeasible approach for real smart grid where incomplete information is available. The main advantage of the proposed MAS approach is scalability.

VI. CONCLUSION

This paper presents a demanded side management strategy with multi-agent system that can be employed for future smart grid. The proposed strategy is based on load shifting and load curtailment techniques. The main objective of the proposed demand side management strategy is to achieve low operational cost by maximizing of the use of renewable energy sources and environmental friendly technologies in smart grid. This is achieved through the coordination of actions from the distribution management system and the negotiation skills of the local controllers. Simulations were carried out, and the simulation outcomes show that proposed technique achieves sustainable saving, while it reduces the peak load demands of the systems. This research will progress to apply and adapt other demand side management techniques, which will lead to a more realistic demand side management for future smart grid.

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