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Multi-Agent Based Responsive Residential DR for Managing and Trading Power in Smart Distribution Networks

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Abstract-In this paper, a MEMF consisting of a MAS and a grid-tied Microgrid is proposed for trading and managing power in automated DNs. In addition to management, the framework effectively utilizes DR potential by enabling customers to participate in multiple DR options. The game theoretic analysis based double auction energy trading mechanism is modified and is used in the trading and the energy management.The control over DR participation is provided to the customers rather than to the aggregator. A modification is proposed to the generally used incentive policy, which assures more benefit to the customers by proportionately reducing the profit margin of the aggregator. In the proposed framework, both the MAS and the grid-tied microgrid DN are simulated using MATLAB/SIMULINK. The simulation results on the test system are presented for illustrating the effectiveness of the trading mechanism and the improvements in the benefits with respect to the earlier results in this field.

Keywords: - Demand Side Management, Demand Response, Multi-Agent System, Microgrid and Double Action Protocol.

NOMENCLATURE

MEMF	Multi-Agent based Intelligent Energy Management Framework
MAS	Multi-Agent System
DR	Demand response
DN	Distribution network
DG	Distribution Generation
DERs	Distributed energy resources
DSM	Demand-Side Management
GTADA	Game-Theoretic Analysis based Double Auction
MGTADA	Modified Game-Theoretic Analysis based Double Auction
ICA	Intelligent Control Agent
GSP	Grid Selling Price
GBP	Grid Buying Price
MGSP	Microgrid Selling Price
MGBP	Microgrid Buying Price
MCMGSP	Market Cleared Microgrid Selling Price
ΔP	Supply-Demand Mismatch Factor
P_{MG}	Real Time Local Power Generation in Microgrid
TL_{MG}	Real Time Total Load Consumption of Microgrid
LAs	Load/customer Agents
MCGBP	Market Cleared Grid Buying Prices
MCGSP	Market Cleared Grid Selling Prices
UGA	Utility Grid Agent
DGA	Distribution Generator Agent
DLCF	Distribution Load Consumption Factor
C_{CLP}	Clearing Power of The Customers Form The Local Generation
L_{TAL}	Maximum Demand/Connected Load of the Distribution Network
LCP	Load Clearing Price
M_{PP}	Microgrid Profit Price in INR/kWh
MPP_{TB}	Microgrid Profit Price in INR/ Time Block
β	Number of Hours in One Time Block
C_{GP}	Customer Give-Up Power From Their Allotted C_{CLP}
C_{TL}	Customer Total Load Consumption
ToU	Time-of-Use
L_{AL}	Allotted load of the customer
L_{UL}	Uninterruptable load of the customer

1. Introduction

Electric power DNs have been a fundamental element and a large part of the traditional power grid infrastructure. Deployment of different kinds of DG units into the distribution system of the traditional grid for the economic, environmental, and security/reliability benefits constitutes a grid-tied microgrid [1]. The large penetrations of DERs and the implementation of smart distribution technologies such as smart metering/smart appliances have changed the DN from passive to active systems [2],[3].

The non-dispatchable DG units such as wind turbines and PV panels [4], and the varying loads in a microgrid create supply-demand mismatch. This gap between supply and demand can be effectively and economically reduced by incorporating DSM techniques [5],[6]. The goal of the DSM technique is to match supply and demand by incorporating peak clipping [7], load shifting [8], or by valley filling. DR is a popular mechanism to implement DSM techniques, where customers are encouraged to participate in the DR programs by providing price [9] and service incentives [10].

The present automated DNs are designed to balance the supply and demand locally, using the DGs and DSM techniques. When the power balance is not possible locally, the deficit power must be imported, and the surplus power is to be exported to the grid, using a suitable trading mechanism. For these purposes, the DN will have to accommodate bi-directional power flow using proper control and communication. All these smart features will make the distribution system active and more complex. An effective energy trading [11], scheduling [12],[13] and management systems [14] are therefore required for the economic and secured operation of such microgrids.

Implementation of smart features in the distribution system demands an intelligent and reliable mechanism such as the agent theory [15],[16]. Agents are individual entities that react to changes in an environment, schedule different tasks, and are able to interact with other coexisting agents [17]. A system developed with a group of such agents is called MAS [18],[19]. There are different co-ordination strategies in MAS based microgrids, such as centralized [20], decentralized [21] and a combination of both [22]. In the centralized control strategy, a single control agent takes care of all the control activities. Whereas in the decentralized control strategy, the individual agents can do their local tasks and exchange their information among the other agents. The microgrid DN and the MAS should be able to communicate in real time so that the relevant data is accessible to the agents within the acceptable delay for initiating the required tasks.

The term energy trading is used to refer to the buying and selling of energy in the electricity market. The electricity market consists of the main grid, the DG units and the customers in the microgrid. The integration of large number of local generation(potential sellers) and consumers(potential buyers) into the DN necessitates techniques such as the Game–Theoretic approaches [23] to design the trading model for conducting the market auctions. This trading model is responsible for energy transactions among the stakeholders (potential sellers and buyers) in the local market and the global market. When the local generation is not sufficient to meet the load, the energy is to be traded from the grid. In [24], Yajuan Wang et.al., presented a double auction mechanism based on auction mechanism design theory, for allocating resource providers (sellers) to resource consumers (buyers) in the grid. In [25], Mohsen Khorasany et.al., presented a auction based P2P energy trading in DN, where prosumers and consumers actively participate in the energy market as seller or buyer to trade energy. In [26], Srikanth Kotra et.al., presented an energy management system for a grid integrated PV based hybrid microgrid. In [27], Bodhisattwa P. Majumder et.al., presented an iterative double auction mechanism for energy trade between buyer and seller agents. In [28], Jian Wang et.al., proposed a direct electricity transaction mode between DG (seller) and consumer (buyer) in a microgrid, based on the combination of blockchain and continuous double auction mechanisms. In [29], M. Nazi ffaqiryet.al., have presented a distributed double auction algorithm considering the social welfare of the stakeholders, as well as the aggregator's revenue for an islanded microgrid. In [30], Hongseok Kim et.al., have proposed a two-stage market model as a Stackelberg game, wherein microgrids can sell their surplus power to the grid via aggregators.

In this work, a new two-phase market model is proposed for trading energy. The concepts of the double action mechanism [29] and the two-stage market model [30] are combined, and this combination is modified to form a new trading mechanism called as 'Modified GTADA (MGTADA).In GTADA trading mechanism, market clearing prices depend on ask and bid prices of the stake holders. Whereas in the proposed MGTADA trading mechanism, in addition to ask and bid prices, market clearing prices will also depend on supply-demand mismatch factor of the microgrid. The GTADA and MGTADA trading mechanisms are explained in Section 2.

This article presents a MEMF to enable the grid-tied microgrid to conduct two-phase market auction using the proposed MGTADA trading mechanism. In the first phase, the trading of locally available DG unit power within the microgrid is conducted by the local market. In the second phase, the grid will sell/buy deficit/surplus power to/from the microgrid. In addition, the proposed MEMF can harvest DR potential in the automated/smart DN.

In the trading mechanism, a novel load distribution management mechanism for proportional allocation of locally available resources is introduced in the DN by using two factors: DLCF and C_{CLP}. A new 'give-up' policy is introduced for the customers and the generally used incentive policy is also modified to yield more benefits to the customers when they are participating in the DR program. The effects of DR programs on the market cleared energy prices from the two-phase market auction using the GTADA and the proposed MGTADA protocols are presented and compared.

The proposed MEMF consists of a MAS and a smart DN. A total of 7 agents consisting of one ICA, one UGA, one DGA and four LAs constitute the MAS. The smart DN is a miniature microgrid consisting of a DG unit, four smart homes (customers). This prototype DN is connected to the grid. In this work, both the MAS and the grid-tied microgrid are simulated using MATLAB/SIMULINK. The MEMF provides a platform for the customers to voluntarily relinquish a part of their allotted power from local resources to receive the available incentives. This relinquished power act as a virtual generator and effects the peak clipping of the load. Each customer in the DN can participate in three different DR options. They can select the option based on their willingness. After the DR options, the deficit of power in the microgrid is purchased from the grid, while the surplus power in the microgrid is sold to the grid. The price at which the power is traded in the market is determined by the proposed MGTADA energy trade mechanism. This trading and energy management mechanism is tested by conducting simulation studies, and the corresponding results are encouraging.

In the remaining part of the paper, Section 2 presents the proposed energy trade mechanism. The architecture of the MAS, the working of each agent in energy trade mechanism and the incorporated DR options are described in Section 3. A representative grid-tied microgrid DN system is modeled for the testing purpose. The simulation results on this test system using the proposed energy trade mechanism and DR options are presented in Section 4. Finally, the conclusions are drawn in Section 5.

2. Energy Trade Mechanism

In the two-phase energy trading mechanism, energy trading takes place in two steps between the microgrid and the grid. First, the microgrid will purchase the available energy from the local DG units and sell it to the customers connected to it. If there exists any deficit/surplus power, the microgrid will employ the second step trading with the grid. In this work, two-phase market auction (local/global) is used between the microgrid and the main grid. When there is surplus/deficit power in the microgrid than the present load, the corresponding trade is initiated between the microgrid and the grid. The popular GTADA [31],[29] protocol is modified and is called MGTADA protocol and this is used for the trading. Several DR options are created for the customers, based primarily on the power balance and the market economics. For testing and validation of the proposed scheme, a prototype market consisting of a DG unit, the grid and four smart loads are used. The DG unit may be consisting of a pool of the Windmills and PV panel units.

2.1 Local Market

The present load demand and the local generation are monitored by the ICA. The ICA is also called as an aggregator. The energy balance is established in the local market using the DR options if necessary, by the aggregator.

For the local market auction, the aggregator uses MGTADA protocol to clear the local market. GTADA is a popular market trade mechanism, and it can be considered as a game for buying and selling single type of goods like power or energy [31].Potential buyers submit their 'bids' to purchase a unit of the commodity and potential sellers simultaneously submit their 'ask' prices to sell one unit of that commodity to an auctioneer. The lowest ask price is the outstanding ask (oa) price and the highest bid is the outstanding bid (ob) price in the market. Then the auctioneer declares the clearance price of the market in the following way:

- If $oa>ob$ then no trade occurs (the seller wants more than what the buyer pays)
- If $oa \leq ob$ then Clearing Price = $(oa+ob)/2$ (where the clearing price is the weighted average of the lowest ask and the highest bid).

This GTADA mechanism has been modified (MGTADA) to suit to one buyer and one seller pattern. Hence the following assumptions are made.

- Only trade between Microgrid and utility grid is considered.
- Both microgrid and utility grid act as seller/buyer depending on supply demand mismatch.

The grid proposes a GSP and a GBP. Where GSP is the ask price of the grid and GBP is the bid price of the grid for market auction. Similarly, the microgrid will also propose MGSP, where MGSP is the contractual selling price of DG unit to microgrid. MGSP is both ask and bid price of the microgrid for market auction. Further, it is assumed that GBP is equal to MGSP.

The aggregator uses MGTADA protocol in local market to determine the MCMGSP based on: (i) the ΔP, and (ii) weighted average of GSP and MGSP. The ICA computes the following:

i. The supply-demand mismatch factor

$$\Delta P = \frac{P_{MG}}{TL_{MG}} \tag{1}$$

ii. The MCMGSP

- In GTADA protocol

$$MCMGSP = \frac{(GSP + MGSP)}{2} \tag{2}$$

- In MGTADA protocol
  - When $\Delta P < 1$

$$MCMGSP = \{[1 + (1 - \Delta P)^2]MGSP\} \tag{3}$$

  - When $\Delta P > 1$

$$MCMGSP = MGSP \tag{4}$$

iii. Communicate these values to LAs

2.2 Global Market

In the global market, the aggregator initiates trading between the grid and the microgrid when there exists a surplus/deficit power in the microgrid even after the DR options are applied. It clears this surplus/deficit power from/to microgrid at MCGBP/MCGSP. The computing of MCGSP and MCGBP in global market are as follows:

- In GTADA protocol

$$MCGSP = GSP \tag{5}$$

$$MCGBP = GBP \tag{6}$$

- In MGTADA protocol

$$MCGSP = \left\{[1 + (1 - \Delta P)^2]\left\{\frac{(GSP + MGSP)}{2}\right\}\right\} \tag{7}$$

$$MCGBP = MGSP \tag{8}$$

In this two-phase market auction: (i) MCMGSP is limited between MGSP and weighted average of MGSP and GSP, (ii) MCGSP is limited between GSP and weighted average of MGSP and GSP, and (iii)when the microgrid local generation is greater than or equal to demand, then MCMGSP and MCGBP will be equal to MGSP.

3. Multi-agent architecture and DR options

3.1. The Multi-Agent System Architecture

The proposed MAS architecture for managing the energy trading, and to embed DR into a residential DN is shown in Fig.1.The MAS is modeled as two layers of agents: (i) Action layer, and (ii) Control layer. The auction layer is designed to: (i) monitor real-time DG unit power, GSP, GBP, MGSP, MGBP and the real-time total load demand of DN, (ii) calculate the market clearing price of local and global markets, and (iii) generate action signal for agents in control layers to achieve power balance in the DN. The control layer is responsible to control the loads in residential DN, based on action signal generated by the action layer and customer's requirements. M-function in MATLAB is used to develop the proposed MAS architecture.

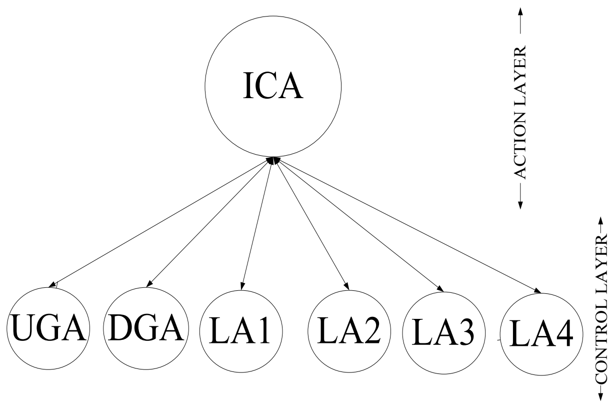

Figure 1. Agent architecture of MEMF.

The action layer consists of an ICA which is also called as an aggregator. The control layer consists of UGA, DGA, and LAs. The functions of these agents are as follows:

a) **Utility Grid Agent (UGA):** UGA is in the control layer and it holds GSP and GBP of the grid power. This information is communicated to the ICA.

b) **Load Agents (LA):** The load agents are in control layer and are represented in general by LAx. The subscript "x" indicates an agent's location. These load agents are holding the real-time load data of their owners and communicate the same to ICA. Apart from this, the load agents effect the control operation of the individual appliances as per requirements.

c) **Distribution Generation Agent (DGA):** The DGA is in the control layer and it holds the generation information and contractual DG selling price to microgrid. This information is communicated to the ICA.

d) **Intelligent Control Agent (ICA):** The MEMF has a dedicated ICA. This agent is in the action layer. ICA continuously monitors in real-time: (i) the available supply from DG and actual load demand of DN; and use them to calculate DLCF and C_{CLP}; (ii) GSP, GBP and MGSP and use them to calculate MCMGSP,MCGSP and MCGBP. These values are then communicated to LAs, which will in turn initiate load clearing based on DR option opted by the customer.

The ICA will:

- Compute the real-time DLCF for all the customers. DLCF is introduced in this work to allocate the available power to the customers. DLCF is based on P_{MG} and L_{TAL}. The DLCF is given by:

$$\left\{\begin{array}{c} If\ P_{MG} < L_{TAL} \\ DLCF = \dfrac{P_{MG}}{L_{TAL}} \\ If\ P_{MG} \geq L_{TAL} \\ DLCF = 1 \end{array}\right\} \tag{9}$$

- Computes the C_{CLP}.

$$C_{CLP} = (\text{Allotted Power of customer} * DLCF) \tag{10}$$

- Conduct the two-phase market trade auction depending on real-time ΔP and quoted prices of the microgrid and the grid. It uses GSP, GBP and MGSP to calculate MCMGSP, MCGSP, MCGBP, and LCP of the customers.
- Work as DR agent, to receive and serve the DR options placed by LAs in the DN.
- Compute M_{PP}, where M_{PP} is the microgrid/aggregator surcharge/commission per kWh in the two-phase market trade auction.

i. When $P_{MG} \geq TL_{MG}$

$$M_{PP} = \frac{\begin{Bmatrix} (TL_{MG} * MCMGSP) + \\ [(P_{MG} - TL_{MG}) * MCGBP] \end{Bmatrix}}{P_{MG}} - \left\{\frac{(P_{MG} * MGSP)}{P_{MG}}\right\} \quad (11)$$

ii. When $P_{MG} < TL_{MG}$

$$M_{PP} = MCMGSP - MGSP \quad (12)$$

- Compute MPP_{TB}. Where MPP_{TB} is the microgrid/ aggregator profit price/time block in the two-phase market trade auction.

$$MPP_{TB} = \{P_{MG} * M_{PP} * \beta\} \quad (13)$$

3.2 The DR options

In this work, three DR options are provided for the customers. These options are designed to benefit the customers participating in DR while satisfying their comfort requirements. In these DR options, customer may give-up some part of power from their C_{CLP} to get incentives. These DR options are:

i.Demand Response-option 1(DR-O1):DR-O1 is a capacity market DR program[32],[33],[34]. This will restrict the total power consumption level to the available supply within the given time frame. Individual customers are supplied with this reduced supply and they have to limit their consumption to C_{CLP}, by setting the priority to their load, according to the constraint. Obviously, this restriction on the power usage will bring some amount of discomfort, but this may partially neutralized by the incentive policy.

In DR-O1, the load agents control the energizing of prioritized appliances of the customer, so that the total load is within their C_{CLP}. Suppose some part of power remains unused after energizing prioritized appliances, but which is not sufficient to energize the next preferred appliance. This amount of power will automatically make available to the local center and is called 'give-up' power. A suitable incentive is offered to the customer for this power. The load clearing price (LCP) for the participating customer is calculated by using,

$$LCP = \left\{\frac{[(C_{TL} - C_{GP}) * MCMGSP] + (C_{GP} * MGSP)}{C_{TL}}\right\} \quad (14)$$

It is observed from (14) that, out of the total power consumption of a customer, the power equivalent to give-up power of the customer is cleared at MGSP, and the remaining power is cleared at MCMGSP.

Suppose, C_{CLP} is lower than the uninterruptable load of the customer. Then LA will meet the customer uninterruptable load requirement by initiating purchase of the deficit power from the global market. For this case, the LCP of the customer is calculated by using,

$$LCP = \left\{\frac{[(C_{TL} - C_{CLP}) * MCGSP] + (C_{CLP} * MCMGSP)}{C_{TL}}\right\} \quad (15)$$

ii. Demand Response – option2 (DR-O2):DR-O2 is a ToU Pricing DR program. ToU pricing is a method of charging different unit prices for energy usage during different blocks of time. This will effectively reflect the time-varying costs of supplying energy during those time periods and load response analysis [35],[36].

The LA of the customer switches the loads as per the customer requirement, irrespective of variation in their C_{CLP} from local market. In this case, a neural network is employed to energize the loads of customer based on their histories of load consumption. Although customer is charged as per ToU principle, the pattern of load curve is known apriori, and hence the load switching is performed automatically. This apriori load information will help in proper management of the energy market. The ToU unit price or LCP of the customer depends on C_{CLP} and C_{TL}. If $C_{CLP} \geq C_{TL}$, then LCP of customer is determined by using (14), else by using (15).

iii. Demand Response – option3 (DR-O3): DR-O3 is also based on ToU DR program. This option is similar to DR-O2 except that the customer can switch to their maximum demand instead of the known load pattern. This will ensure the comfort of the customer on special occasions. This sudden, unprecedented load changes may require quick energy transactions between the markets and therefore results in a slightly higher price for the customer. For the additional power to fulfill the demand of the customer, LCP is determined by using (15).

4. Market simulation and result analysis

This section illustrates the working of the proposed MEMF with the help of different case scenarios on the test DN. The smart residential DN is a grid-tied microgrid system as shown in Fig.2. A very small smart DN is used to avoid large amount of data in the result tables. The DN can be expanded to represent a real system if necessary. The integrated system is simulated using MATLAB/SIMULINK.

The grid-tied smart microgrid consists of: an intelligent

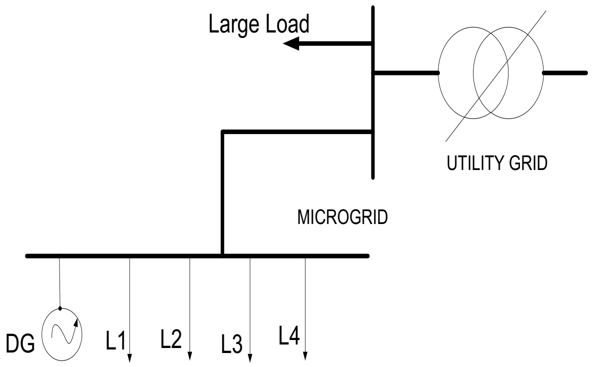

Figure 2. Test DN- A grid-tied smart microgrid.

controller (ICA) for managing and trading power in the microgrid. A representative DG with a total installed capacity of 80kW (wind turbine 60kW and solar panel 20kW), and four representative loads/customers (Lx) with controllable loads. The total connected load is 50 kW, and a specified total power is allocated to each of the customer.

In the present study, for each of the customer, 20% of the load is regarded as uninterruptible load to account for some essential services. The agents LAx are representing the customers in the DN.

In this study, four hour interval is considered as one time block for taking market clearing auction, and hence, one day is divided in to six time blocks. The duration of the time blocks can be varied if necessary. The GSP is taken as 14 INR/kWh and MGSP is taken as 10 INR/kWh. The market clearing prices; MCMGSP, MCMGBP, MCGSP and MCGBP during any auction are decided by MGTADA market trade mechanism.

Table 1 tabulates the data pertaining to DG power availability in the microgrid, DLCF, C_{CLP}, individual load demands, total load demand and power mismatch for time blocks 1 to 6 of the DN. Figure 3 shows the supply-demand profile of the system.

Four cases based on the different DR options are considered for simulation. These are:

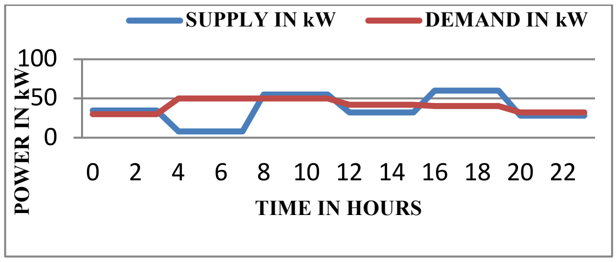

Figure 3. DG Supply and demand profile of the system.

- Case1: All customers have opted DR-O1
- Case 2: All customers have opted DR-O2
- Case3: All customers have opted DR-O3
- Case4: Customers have opted different DR options.

The simulations results from the proposed MGTADA and the earlier GTADA market trade mechanisms are obtained and are tabulated for these four cases.

1.Case 1: In this case, all the customers in the DN have opted DR-O1. Load clearing of customers is as follows.

- All the loads of the customers are cleared if their C_{CLP} is sufficient to meet the present load.
- In case of deficiency, LAs limits the consumption of the customers to their respective C_{CLP}. The loads are supplied based on the set priority.
- In case, C_{CLP} is lower than the uninterruptable load of a customer, the corresponding LA will meet the customer uninterruptable load requirement by initiating purchasing of the additional power from the global market.

Table 2 shows the two-phase market auction trading details in Case1. From Table 2, it is observed that, during time-blocks 1,3,4,5 and 6, LAs limit respective customer consumption to C_{CLP}, as per the priority to their loads. Unused C_{CLP} after energizing prioritized appliances, but which is not sufficient to energize the next preferred appliance will be 'given-up' to the local center.

Table 1. Generation availability and load profiles of microgrid.

Block	P_{MG} (kW)	DLCF	L1(kW) L_{AL}:20kW L_{UL}:4kW		L2(kW) L_{AL}:10kW L_{UL}:2kW		L3(kW) L_{AL}:5kW L_{UL}:1kW		L4(kW) L_{AL}:15kW L_{UL}:3kW		Total Demand(kW) L_{TAL}:50kW	Mis-match (kW)
			C_{CLP}	LR	C_{CLP}	LR	C_{CLP}	LR	C_{CLP}	LR		
1	35	0.7	14	12	7	6	3.5	3	10.5	9	30	+5
2	8	0.16	3.2	20	1.6	10	0.8	5	2.4	15	50	-42
3	55	1	20	20	10	10	5	5	15	15	50	+5
4	32	0.64	12.28	20	6.4	10	3.2	3	9.6	9	42	-10
5	60	1	20	16	10	8	5	4	15	12	40	+20
6	28	0.56	11.2	12	5.6	6	2.8	3	8.4	9	30	-2

#: + sign indicates surplus and – sign indicates deficits; LR: Load requirement

Table 2. Load Clearing of DN after Executing MGTADA and GTADA market trade mechanism for Case 1

Bl.	P_{MG} (kW)		L1*		L2*		L3*		L4*		E/I of Grid Power* MCGSP/MCGBP		Microgrid profit			
													GTADA		MGTADA	
			GTADA	MGTADA	GTADA	MGTADA	GTADA	MGTADA	GTADA	MGTADA	GTADA	MGTADA	M_{PP}	MPP_{TB}	M_{PP}	MPP_{TB}
1	35	C_{CLP}/MCMGSP	14/12	14/10	7/12	7/10	3.5/12	3.5/10	10.5/12	10.5/10	-5/10	-5/10	1.71	239.4	0	0
		LC/LCP	12/11.66	12/10	6/11.66	6/10	3/11.66	3/10	9/11.66	9/10						
		C_{GP} /MCGBP I/MCGSP	-2/10	-2/10	-1/10	-1/10	-0.5/10	-0.5/10	-1.5/10	-1.5/10						
2	8	C_{CLP}/MCMGSP	3.2/12	3.2/10.4	1.6/12	1.6/10.4	0.8/12	0.8/10.4	2.4/12	2.4/10.4	**+2/14**	**+2/12.48**	**2**	**64**	**0.4**	**12.8**
		LC/LCP	4/12.4	4/10.81	2/12.4	2/10.81	1/12.4	1/10.81	3/12.4	3/10.81						
		C_{GP} /MCGBP I/MCGSP	+0.8/14	+0.8/12.48	+0.4/14	+0.4/12.48	+0.2/14	+0.2/12.48	+0.6/14	+0.6/12.48						
3	55	C_{CLP}/MCMGSP	20/12	20/10	10/12	10/10	5/12	5/10	15/12	15/10	-5/10	-5/10	1.81	400	0	0
		LC/LCP	20/12	20/10	10/12	10/10	5/12	5/10	15/12	15/10						
		C_{GP} /MCGBP I/MCGSP	0	0	0	0	0	0	0	0						
4	32	C_{CLP}/MCMGSP	12.28/12	12.28/10	6.4/12	6.4/10	3.2/12	3.2/10	9.6/12	9.6/10	-2/10	-2/10	1.87	240	0	0
		LC/LCP	12/11.95	12/10	6/11.95	6/10	3/11.95	3/10	9/11.95	9/10						
		C_{GP} /MCGBP I/MCGSP	-0..28/10	-0.28/10	-0.4/10	-0.4/10	-0.2/10	-0.2/10	-0.6/10	-0.6/10						
5	60	C_{CLP}/MCMGSP	20/12	20/10	10/12	10/10	5/12	5/10	15/12	15/10	-20/10	-20/10	1.33	320	0	0
		LC/LCP	16/11.5	16/10	8/11.5	8/10	4/11.5	4/10	12/11.5	12/10						
		C_{GP} /MCGBP I/MCGSP	-4/10	-4/10	-2/10	-2/10	-1/10	-1/10	-3/10	-3/10						
6	28	C_{CLP}/MCMGSP	11.2/12	11.2/10	5.6/12	5.6/10	2.8/12	2.8/10	8.4/12	8.4/10	-8/10	-8/10	1.42	160	0	0
		LC/LCP	8/11.2	8/10	4/11.2	4/10	2/11.2	2/10	6/11.2	6/10						
		C_{GP} /MCGBP I/MCGSP	-3.2/10	-3.2/10	-1.6/10	-1.6/10	-0.8/10	-0.8/10	-2.4/10	-2.4/10						

#: - sign indicates customer give-up power from their allotted C_{CLP} /Exporting power to grid and + sign indicates importing power from grid
*:Units of load in kW; P: units of cost in INR/kWh; LC: Load consumption; E/I: Export or Import

In time block 2, C_{CLP} of all the customers is not sufficient to energize their uninterruptable loads. At this situation, as discussed in DR-O1, LAs will initiate purchasing of additional power from global market to energize their uninterruptable loads. Figure 4 shows the LCP of all the loads in Case 1. From the last column in Table 2, it is observed that, the microgrid make profit in all the time blocks when GTADA protocol is used. However, in the proposed MGTADA protocol, the microgrid makes profit only when there is a deficit power in the DN. Further, the profit margin of the microgrid in MGTADA is lesser than GTADA (e.g.: during the time block 2, MPP_{TB} is 64 INR/Time block in GTADA and 12.8 INR/Time block in MGTADA). Thus the proposed MGTADA is beneficiary for consumers).The details of these values are summarized in Fig.5.

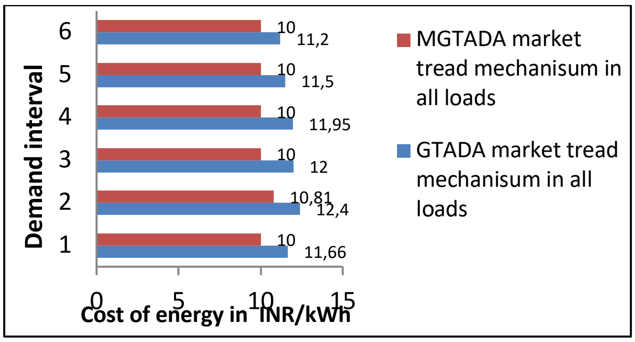

Figure 4. LCP of all loads in Case 1.

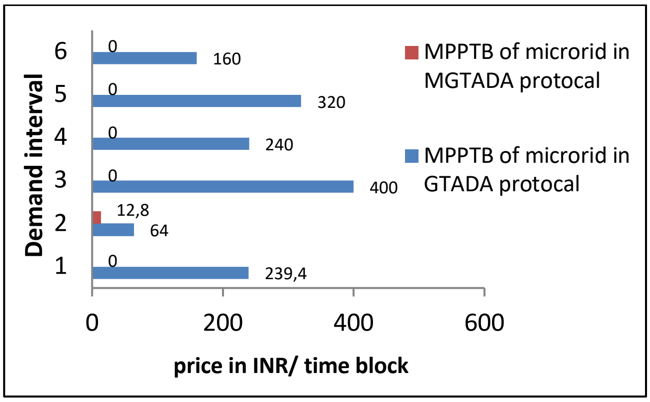

Figure 5. Comparison of MPP_{TB} of microgrid in GTADA and MGTADA of Case 1.

2.Case 2: In this case, all the customers in the DN have opted DR-O2, load clearing of customers in DN is affected using DR-O2 as follows.

- If the actual demand of the customer is within C_{CLP}, all the loads are cleared for that customer.
- In case, actual demand of the customer is more than C_{CLP}, then LA will meet the customer load requirement by initiating purchasing the additional power from the global market.

Table 3 shows the two-phase market auction trading details in case 2. From the Table 3, it is observed that during time blocks 1, 3 and 5 load requirement of the all customers

Table 3. Load Clearing of DN after Executing MGTADA and GTADA market trade mechanism for Case 2

Bl.	P_{MG} (kW)		L1*		L2*		L3*		L4*		E/I of Grid Power* MCGSP/MCGBP		Microgrid profit			
													GTADA		MGTADA	
			GTADA	MGTADA	GTADA	MGTADA	GTADA	MGTADA	GTADA	MGTADA	GTADA	MGTADA	M_{PP}	MPP_{TB}	M_{PP}	MPP_{TB}
1	35	C_{CLP}/MCMGSP	14/12	14/10	7/12	7/10	3.5/12	3.5/10	10.5/12	10.5/10	-5/10	-5/10	1.71	239.4	0	0
		LC/LCP	12/11.66	12/10	6/11.66	6/10	3/11.66	3/10	9/11.66	9/10						
		C_{GP} /MCGBP I/MCGSP	-2/10	-2/10	-1/10	-1/10	-0.5/10	-0.5/10	-1.5/10	-1.5/10						
2	**8**	C_{CLP}/MCMGSP	**3.2/12**	**3.2/12**	**1.6/12**	**1.6/12**	**0.8/12**	**0.8/12**	**2.4/12**	**2.4/12**	**+42/14**	**+42/14**	**2**	**64**	**2**	**64**
		LC/LCP	**20/13.68**	**20/13.68**	**10/13.68**	**10/13.68**	**5/13.68**	**5/13.68**	**15/13.68**	**15/13.68**						
		C_{GP} /MCGBP I/MCGSP	**+16.8/14**	**+16.8/14**	**+8.4/14**	**+8.4/14**	**+4.2/14**	**+4.2/14**	**+12.6/14**	**+12.6/14**						
3	55	C_{CLP}/MCMGSP	20/12	20/10	10/12	10/10	5/12	5/10	15/12	15/10	-5/10	-5/10	1.81	400	0	0
		LC/LCP	20/12	20/10	10/12	10/10	5/12	5/10	15/12	15/10						
		C_{GP} /MCGBP I/MCGSP	0	0	0	0	0	0	0	0						
4	32	C_{CLP}/MCMGSP	12.28/12	12.28/11.3	6.4/12	6.4/11.3	3.2/12	3.2/11.3	9.6/12	9.6/11.3	+10/14	+10/13.56	2	256	1.3	166.4
		LC/LCP	20/12.40	20/11.81	10/12.40	10/11.81	3/11.86	3/11.21	9/11.86	9/11.21						
		C_{GP} /MCGBP I/MCGSP	+7.2/14	+7.2/13.56	+3.6/14	+3.6/13.56	-0.2/10	-0.2/10	-0.6/10	-0.6/10						
5	60	C_{CLP}/MCMGSP	20/12	20/10	10/12	10/10	5/12	5/10	15/12	15/10	-20/12	-20/10	1.33	320	0	0
		LC/LCP	16/11.5	16/10	8/11.5	8/10	4/11.5	4/10	12/11.5	12/10						
		C_{GP} /MCGBP I/MCGSP	-4/10	-4/10	-2/10	-2/10	-1/10	-1/10	-3/10	-3/10						
6	28	C_{CLP}/MCMGSP	11.2/12	11.2/10.04	5.6/12	5.6/10.04	2.8/12	2.8/10.04	8.4/12	8.4/10.4	+2/14	+2/12.05	2	224	0.4	44.8
		LC/LCP	16/12.6	16/10.64	8/12.6	8/10.64	2/11.2	2/10.024	6/11.2	6/10.024						
		C_{GP} /MCGBP I/MCGSP	+4.8/14	+4.8/12.05	+2.4/14	+2.4/12.05	-0.8/10	-0.8/10	-2.4/10	-2.4/10						

are less than C_{CLP}. Unused power of the customer will be automatically given-up to the local center which will be exported to the grid.

During the time blocks 4 and 6, C_{CLP} of Customer 1 and Customer 2 are not sufficient to energize their regular load requirement and load requirement of the Customer 3 and Customer 4 are less than their C_{CLP}. Unused C_{CLP} of LA3 and LA4 will be given-up to the local center for suitable incentives. In these intervals, the ICA of microgrid purchases the difference power requirement from the global market. In time block 2, C_{CLP} of all the customers are not sufficient to energize their regular load requirements, the deficit power is purchased from the global market. Figure 6 shows the LCP of all loads in Case 2. Figure 7 summarized the comparison of MPP_{TB} of microgrid in GTADA and MGTADA of Case 2.

3.Case 3: In this case, all the customers in the DN have opted DR-O3, load clearing of customers in DR-O3 is similar to DR-O2. The energy cost for the customers is slightly higher than DR-O2 rate as a penalty to unprecedented load changes from customer.

Table 4 shows the two-phase market auction trading details in case 3. Figure 8 shows the trading statistics of all loads in Case 3. Figure 9 summarized the comparison of MPP_{TB} of microgrid in GTADA and MGTADA of Case 3.

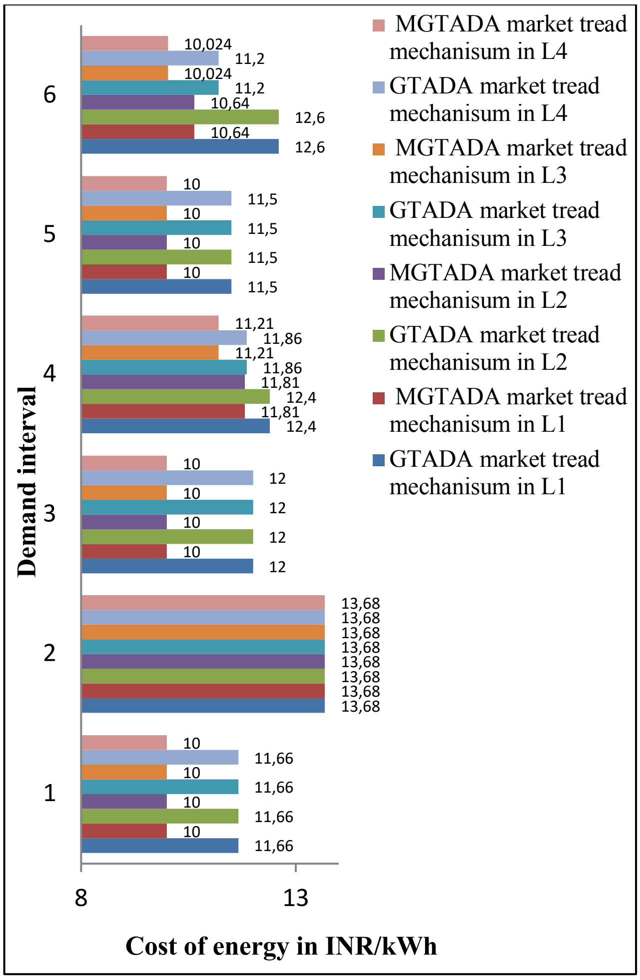

Figure 6. LCP of all loads in Case 2.

Table 4. Load Clearing of DN after Executing MGTADA and GTADA market trade mechanism for Case 3

Bl.	P_{MG} (kW)		L1*		L2*		L3*		L4*		Grid Power* MCGSP/MCGBP		Microgrid profit			
													GTADA		MGTADA	
			GTADA	MGTADA	GTADA	MGTADA	GTADA	MGTADA	GTADA	MGTADA	GTADA	MGTADA	M_{PP}	MPP_{TB}	M_{PP}	MPP_{TB}
1	35	C_{CLP}/MCMGSP	14/12	14/10.9	7/12	7/10.9	3.5/12	3.5/10.9	10.5/12	10.5/10.9	+15/14	+15/13.08	2	280	0.9	126
		LC/LCP	20/12.6	20/11.554	10/12.6	10/11.554	5/12.6	5/11.554	15/12.6	15/11.554						
		C_{GP} /MCGBP I/MCGSP	+6/14	+6/13.08	+3/14	+3/13.08	+1.5/14	+1.5/13.08	+4.5/14	+4.5/13.08						
2	8	C_{CLP}/MCMGSP	3.2/12	3.2/12	1.6/12	1.6/12	0.8/12	0.8/12	2.4/12	2.4/12	+42/14	+42/14	2	64	2	64
		LC/LCP	20/13.68	20/13.68	10/13.68	10/13.68	5/13.68	5/13.68	15/13.68	15/13.68						
		C_{GP} /MCGBP I/MCGSP	+16.8/14	+16.8/14	+8.4/14	+8.4/14	+4.2/14	+4.2/14	+12.6/14	+12.6/14						
3	55	C_{CLP}/MCMGSP	20/12	20/10	10/12	10/10	5/12	5/10	15/12	15/10	-5/10	-5/10	1.81	400	0	0
		LC/LCP	20/12	20/10	10/12	10/10	5/12	5/10	15/12	15/10						
		C_{GP} /MCGBP I/MCGSP	0	0	0	0	0	0	0	0						
4	32	C_{CLP}/MCMGSP	12.28/12	12.28/11.3	6.4/12	6.4/11.3	3.2/12	3.2/11.3	9.6/12	9.6/11.3	+18/14	+18/13.56	2	256	1.3	166.4
		LC/LCP	20/12.72	20/11.82	10/12.72	10/11.82	5/12.72	5/11.82	15/12.72	15/11.82						
		C_{GP} /MCGBP I/MCGSP	+7.72/14	+7.2/13.56	+3.6/14	+3.6/13.56	+1.8/14	+1.8/13.56	+5.4/14	+5.4/13.56						
5	60	C_{CLP}/MCMGSP	20/12	20/10	10/12	10/10	5/12	5/10	15/12	15/10	-10/10	-10/10	1.666	400	0	0
		LC/LCP	20/12	20/10	10/12	10/10	5/12	5/10	15/12	15/10						
		C_{GP} /MCGBP I/MCGSP	0	0	0	0	0	0	0	0						
6	28	C_{CLP}/MCMGSP	11.2/12	11.2/11.94	5.6/12	5.6/11.94	2.8/12	2.8/11.94	8.4/12	8.4/11.94	+22/14	+22/14	2	224	1.94	217.28
		LC/LCP	20/12.88	20/12.84	10/12.88	10/12.84	5/12.88	5/12.84	15/12.88	15/12.84						
		C_{GP} /MCGBP I/MCGSP	+8.8/14	+8.8/14	+4.4/14	+4.4/14	+2.2/14	+2.2/14	+6.6/14	+6.6/14						

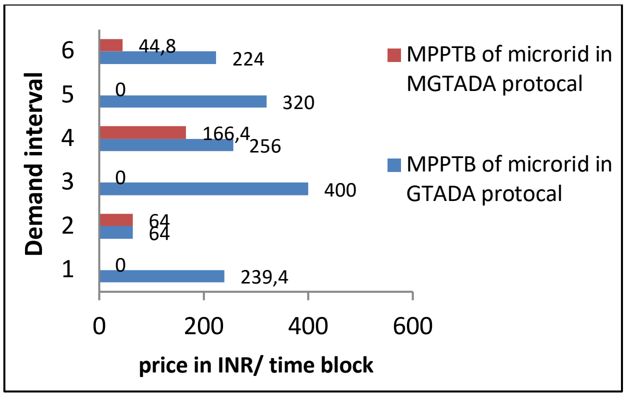

Figure 7. Comparison of MPP_{TB} of microgrid in GTADA and MGTADA of Case 2

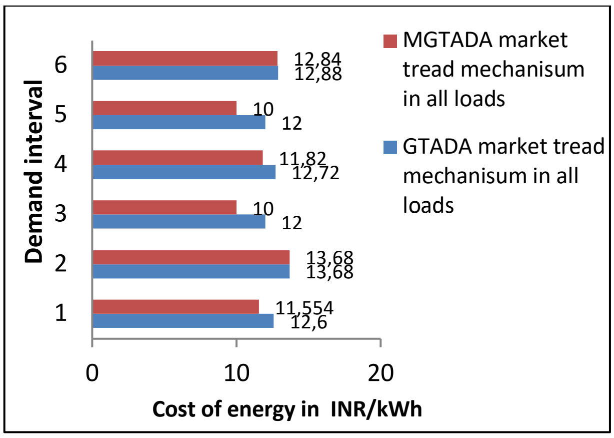

Figure 8. LCP of all loads in Case 3.

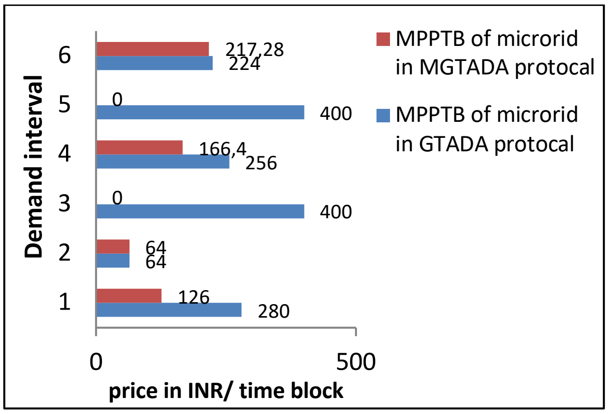

Figure 9. Comparison of MPP_{TB} of microgrid in GTADA and MGTADA of Case 3.

4.Case 4: In this case, the customers have opted different DR-Os. Hence the effects of combination of different DR-Os on load clearing of the customers in the DN can be observed. Customer 1 and Customer 3 have opted DR-O1, Customer 2 has opted DR-O2 and Customer 4 has opted DR-O3.

Table 5 shows the two-phase market auction trading details in Case 4. From the Table 5, it is observed that in time block 1, load requirements of the Customer 1, Customer 2 and Customer 3 are less than their C_{CLP} and Customer 4 is more than their C_{CLP}. The deficit power after considering the local given-up power will be imported from the global market. In a similar manner power balance is maintained in

Table 5. Load Clearing of DN after Executing MGTADA and GTADA market trade mechanism for Case 4

Bl.	P_{MG} (kW)		L1*		L2*		L3*		L4*		Grid Power* MCGSP/MCGBP		Microgrid profit			
													GTADA		MGTADA	
			GTADA	MGTADA	GTADA	MGTADA	GTADA	MGTADA	GTADA	MGTADA	GTADA	MGTADA	M_{PP}	MPP_{TB}	M_{PP}	MPP_{TB}
1	35	C_{CLP}/MCMGSP	14/12	14/10.01	7/12	7/10.01	3.5/12	3.5/10.01	10.5/12	10.5/10.01	+1/14	+1/12.01	2	280	0.01	1.4
		LC/LCP	12/11.66	12/10.008	6/11.66	6/10.008	3/11.66	3/10.008	15/12.6	15/10.61						
		C_{GP} /MCGBP I/MCGSP	-2/10	-2/10	-1/12	-1/10	-0.5/10	-0.5/10	+4.5/14	+4.5/12.01						
2	8	C_{CLP}/MCMGSP	3.2/12	3.2/12	1.6/12	1.6/12	0.8/12	0.8/12	2.4/12	2.4/12	**+22/14**	**+22/14**	2	64	2	64
		LC/LCP	4/12.4	4/12.4	10/13.68	10/13.68	1/12.4	1/12.4	15/13.68	15/13.68						
		C_{GP} /MCGBP I/MCGSP	+0.8/14	+0.8/14	+8.4/14	+8.4/14	+0.2/14	+0.2/14	+12.6/14	+12.6/14						
3	55	C_{CLP}/MCMGSP	20/12	20/10	10/12	10/10	5/12	5/10	15/12	15/10	-5/10	-5/10	1.81	400	0	0
		LC/LCP	20/12	20/10	10/12	10/10	5/12	5/10	15/12	15/10						
		C_{GP} /MCGBP I/MCGSP	0	0	0	0	0	0	0	0						
4	32	C_{CLP}/MCMGSP	12.8/12	12.8/10.4	6.4/12	6.4/10.4	3.2./12	3.2/10.4	9.6/12	9.6/10.4	+8/14	+8/12.48	2	256	0.4	51.2
		LC/LCP	12/11.86	12/10.37	10/12.72	10/11.14	3/11.86	3/10.37	15/12.72	15/11.14						
		C_{GP} /MCGBP I/MCGSP	-0.8/10	-0.8/10	+3.6/14	+3.6/12.48	-0.2/10	-0.2/10	+5.4/14	+5.4/12.48						
5	60	C_{CLP}/MCMGSP	20/12	20/10	10/12	10/10	5/12	5/10	15/12	15/10	-12/10	-12/10	1.6	384	0	0
		LC/LCP	20/12	20/10	8/11.5	8/10	5/12	5/10	15/12	15/10						
		C_{GP} /MCGBP I/MCGSP	0	0	-2/12	-2/10	0	0	0	0						
6	28	C_{CLP}/MCMGSP	11.2/12	11.2/10.09	5/12	5/10.09	2.8/12	2.8/10.09	8.4/12	8.4/10.09	+3/14	+3/12.11	2	224	0.09	10.08
		LC/LCP	8/11.2	8/10.054	6/12.33	6/10.42	2/11.2	2/10.054	15/12.88	15/10.97						
		C_{GP} /MCGBP I/MCGSP	-3.2/10	-3.2/10	+1/14	+1/12.11	-0.8/10	-0.8/10	+6.6/14	+6.6/12.11						

all the time blocks. Figure 10 shows the LCP of all loads in Case 4. Figure 11 summarized the comparison of MPP_{TB} of microgrid in GTADA and MGTADA of Case 4.

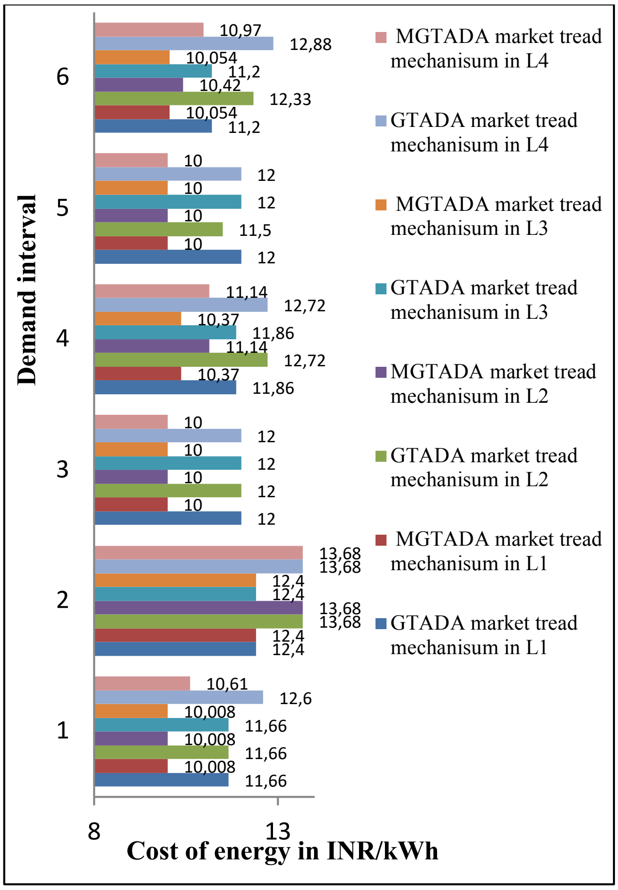

Figure 10. LCP of all loads in Case 4.

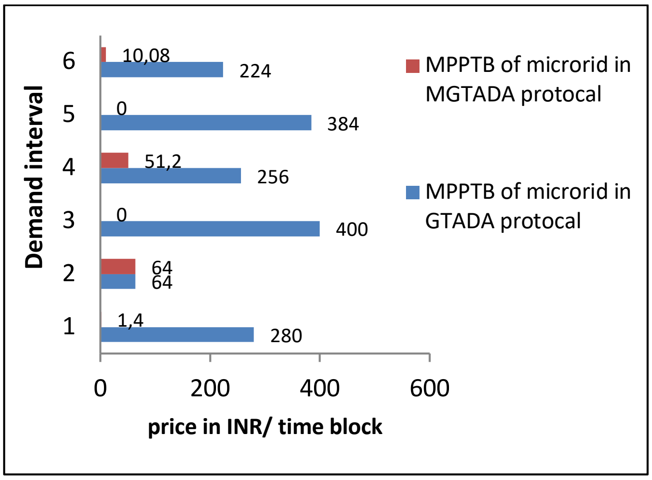

Figure 11. Comparison of MPP_{TB} of microgrid in GTADA and MGTADA of Case 4.

Thus, the MCMGSP of the customer is varied based on ΔP and the MGSP to benefit the customer in MGTADA. This price was based only on the weighted average of MGSP and GSP in GTADA. Similarly, MCGSP is varied based on ΔP and the weighted average of MGSP and GSP in MGTADA, where it is fixed at GSP in the GTADA. This will benefit the customer as the profit margin of the aggregator reduces as seen from Figures 5,7,9,11; resulting in lower energy charges (LCP) of the customer as seen from Figures 4,6,8,10. The effective uses of DR options have obviously reduced the power mismatch and hence resulted in reduced power trade between the microgrid and the grid as seen from Tables 2-5.

5. Conclusions

In this paper, a MEMF for trading and managing the power, including multiple DR options in a grid-tied microgrid is presented. A new trading mechanism MGTADA is introduced. The effects of DR programs on the market cleared energy prices from the two-phase market auction using the GTADA and the proposed MGTADA protocols are presented and compared. From the simulation results, it is clear that the proposed MEMF can effectively meet the load demand under any varying load conditions. Further, there is an increase in the profit margin of customers in the MGTADA protocol by minimizing the profit margin of the ICA/aggregator, as compared to the earlier GTADA protocol. The concept of prioritized load consumption within the C_{CLP} and regular load consumption patron based on previous history are proposed in the smart DN. As a future plan, the integration of dimmable loads and distribution storage system will be included in the test DN and its impact in the MEMF is investigated.

The main outcomes of this work can be summarized as follows:

1. A novel two-phase trade mechanism is designed for the grid integrated microgrid based on: (i) supply-demand mismatch of the microgrid; and (ii) the limiting prices of the grid. These will minimize the profit margin of the aggregator, thereby increasing the profit margin of the customers.
2. A new distribution management mechanism is introduced in the DN by introducing a factor called DLCF and C_{CLP} in the local market to proportionally allocate the locally available power to the customers.
3. The control to exercise the DR options is given to the customers, which is usually effected by the aggregator.
4. A novel 'give-up' policy is introduced for the customers. Further, the generally used incentive policy is also modified to yield more benefits to the customers when they are participating in DR-O1.

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