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Optimal power allocation for residential network in islanded microgrid using capacity market demand response approach

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Abstract

This paper proposes a new demand response algorithm for load shedding and direct load control in smart homes with the goal of lowering peak-to-average ratios and enhancing power balance. The suggested algorithm makes use of two-way communication between distribution agents and smart homes (customers) to provide real-time load control, calculate percentage reductions, and produce distributed load consumption factors. An agent-based residential distribution network with four customers who owned smart appliances was modeled in MATLAB/SIMULINK to validate the technique. The findings show that the residential network is capable of reacting swiftly to supply changes and managing the grid's power balance through distributed load reduction, load shifting, and/or load adjustment, avoiding or limiting load shedding in the event of supply shortages.

Keywords: Microgrid; Demand Side Management; Demand Response; Home Energy Management; Load Shedding.

1. Introduction

Energy Demand Side Management (DSM) is a practical and cost-efficient method for closing the supply-demand gap in power networks. DSM entails the development, execution, and evaluation of methods and regulations intended to reduce power consumption. Customers can take part in demand response (DR) programs, which entail voluntarily changing their energy usage in reaction to changes in power pricing or incentive payments, to reduce peak demand and shift the peak in accordance with available generation. When the reliability of the system is in danger or wholesale market prices are high, DR can assist in reducing the amount of electricity used[1],[2].

In order to implement DR programs in DSM, it is necessary to have a centralized or decentralized control strategy that enables the system to adjust to changing conditions, as well as an intelligent and trustworthy Multi-Agent System (MAS) for bidirectional communication between the supply system and customers[3]. MAS are self-governing networks made up of multiple loosely connected agents that are distributed both physically and intellectually. In order to complete a challenging task, they are connected through cooperation and teamwork. These MAS can address difficult issues in smart grids as DR, microgrid operation and control, service restoration, spot market mechanisms, VPP control, and economic dispatch. Customers may be encouraged to change their energy use by DR for either financial or reliable reasons[4][5].

A specific kind of DR program called capacity market DR uses incentives to persuade consumers in the residential and small commercial sectors to use less energy[6]. In exchange for allowing the utility to remotely shut down, cycle, or vary their loads to fulfill reliability contingencies, customers receive rewards like rate savings and other incentives. This kind

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of DR program is helpful for lowering peak loads, reducing operational costs, and increasing utility profits while keeping customers satisfied[7][8].

2. Methodology

2.1. Proposed Agent Architecture

The proposed MAS architecture utilizes two agent layers for residential network management: the Action layer and the Control layer, as illustrated in Figure 1[2]. In order to create a power balance in the residential network, the action layer is made to monitor the supply and load demand of the network in real-time and to produce action signals for agents in the control layer. Based on the action signals produced by the action layer and the comfort level of the users, the control layer is in charge of managing the loads in the residential network. The suggested MAS architecture is developed in MATLAB using M-functions.

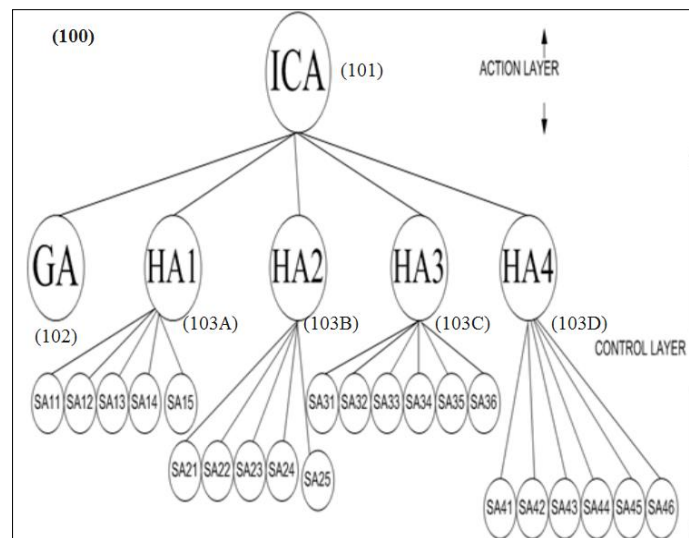


Figure 1 Agent architecture enabling Capacity Market-DR in residential network

The proposed decentralized hierarchical architecture for embedding Capacity Market DR in a residential network consists of several agents, such as the Intelligent Control Agent (ICA) in the action layer, and the Generator Agent (GA), Home (Customer) Agent (HA), and Smart Appliances Agent (SA) in the control layer.

2.1.1. Agents for homes and smart appliances

HAX and SAxy, respectively, are the agents for homes and smart appliances. The subscripts "x" and "xy" denote the position and affiliation of the corresponding agents, respectively. For instance, SA₁₁ denotes the first smart appliance agent of load one, while HA₁ denotes the first home agent. The HAs gather consumer demand and update the ICA. HAs have the intelligence to control their smart appliances to fulfill specified points (balancing conditions) in order to preserve the dependability of the household network in addition to gathering consumer preferences.

Generator agent: The generator agent gathers information on the supply power of residential networks and relays this information to the ICA. The ICA sets the Distributed Load Reduction Percentage (DLRP), also known as the set point, in order to ensure the system's dependability.

Intelligent Control Agent: The ICA functions as a DR agent, continuously calculating the Distributed Load Reduction Potential (DLRP) and Distributed Load Consumption Factor (DLCF) based on the supply and demand of the residential network. These numbers are utilized to modify client consumption habits in line with the state of the power balance. Based on real-time data on load demand and supply power, DLRP and DLCF are computed.

$$DLRP = \frac{\text{SupplyPower} - \text{LoadDemand}}{\text{LoadDemand}} \times 100 \quad (1)$$

$$\left. \begin{array}{l} \text{If Supply Power} < \text{Actual Demand} \\ \text{DLCF} = \frac{\text{Supply Power}}{\text{Actual Demand}} \\ \text{If Supply Power} > \text{Actual Demand} \\ \text{DLCF} = 1 \end{array} \right\} \quad (2)$$

The clearing supply power (CSP) of each user on the home network is likewise determined by ICA. The entire connected load of the residential network is assumed in the current analysis to be less than or equal to the current supply power.

$$\text{CSP} = \frac{\text{Supply Power} \times \text{Connected load of customer}}{\text{Connected Load of Residential Network}} \quad (3)$$

2.2. Proposed Algorithm

Figure 2 depicts the suggested Capacity Market DR algorithm. For load clearing of the home network under diverse supply-demand conditions, it offers the best or nearly best option. It starts with:

- Real-time monitoring of the home network's load demand and supply of power.
- DLRP, DLCF, and CSP calculations utilising (1), (2), and (3) respectively.
- In order to establish power balance, the home network's loads are then appropriately chosen to start the load clearing process.

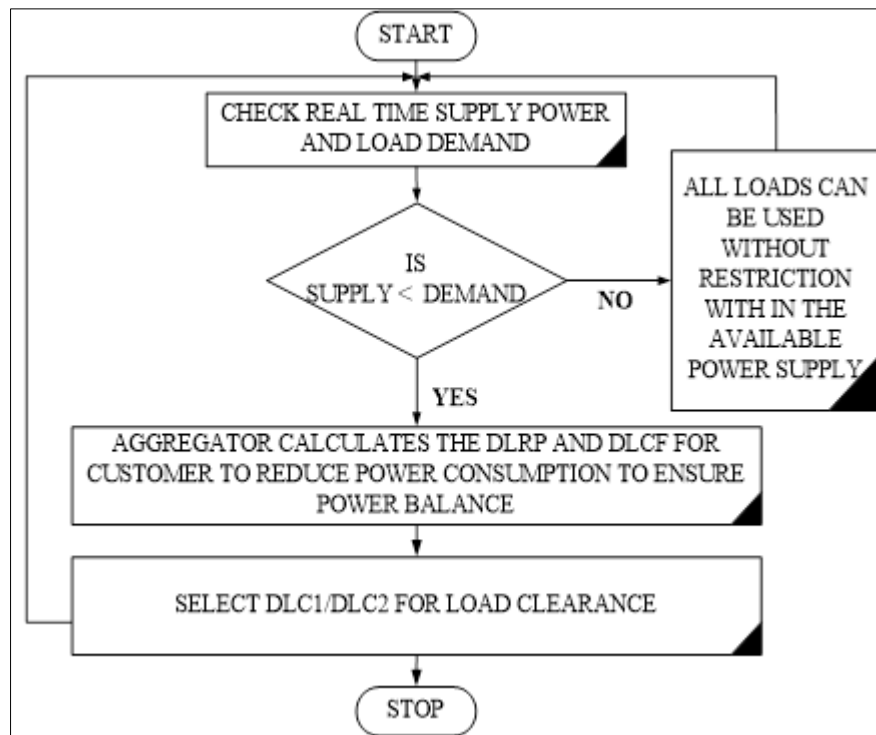


Figure 2 Flow chart of the Capacity Market DR algorithm

The capacity market DR method comes in two forms. In the first scenario, programmable loads are viewed as fixed static loads, and dimmable loads are the only ones that can be used to change the power balance. In the second scenario, the programmable loads can be moved to improve the network's peak-to-average ratio.

The goal of DR strategies is to keep the demand for and supply of power in balance. Additionally, it guarantees a prompt response to unanticipated and urgent changes in the supply and demand for power. The Home Automation (HA) system will receive a reduction signal from the ICA in the event of such a change, causing the power consumption of dimmable appliances to be reduced to a convenient level (for example, 50% of their rated power). In the event that this is insufficient, HA will move or shed some of the lower-priority loads. For instance, if HA receives a signal to cut consumer usage by 20%, it will do so by cutting the power used to run dimmable appliances and, if necessary, shifting the appliances' operating hours.

2.3. System Simulation

The MATLAB/SIMULIK modeling program is used in this section to simulate the prototype of an intelligent multi-agent residential network. Figures 3 and 4 present, respectively, the MATLAB/SIMULINK and schematic models of the home network. To verify the effectiveness of the suggested method, the residential network is employed.

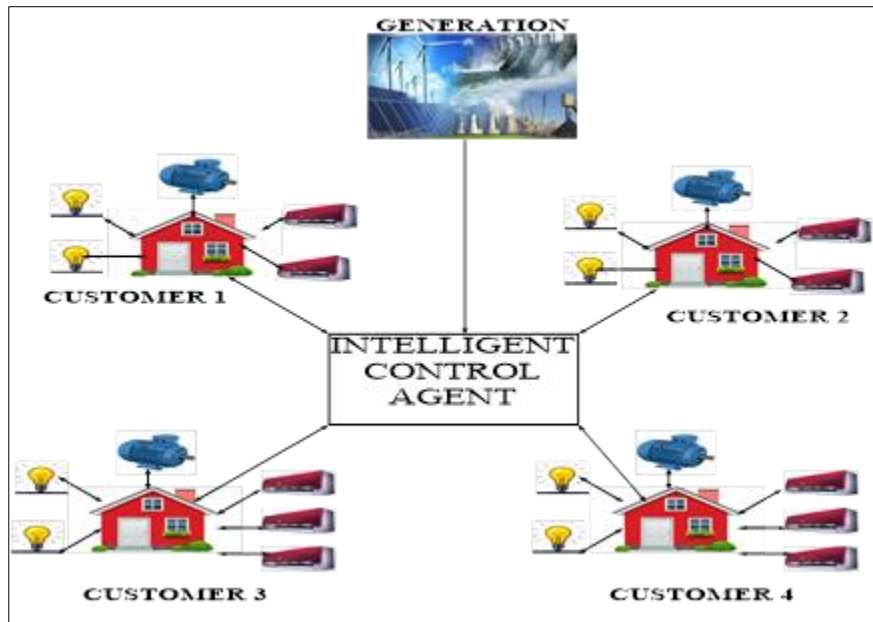


Figure 3 Intelligent residential networks

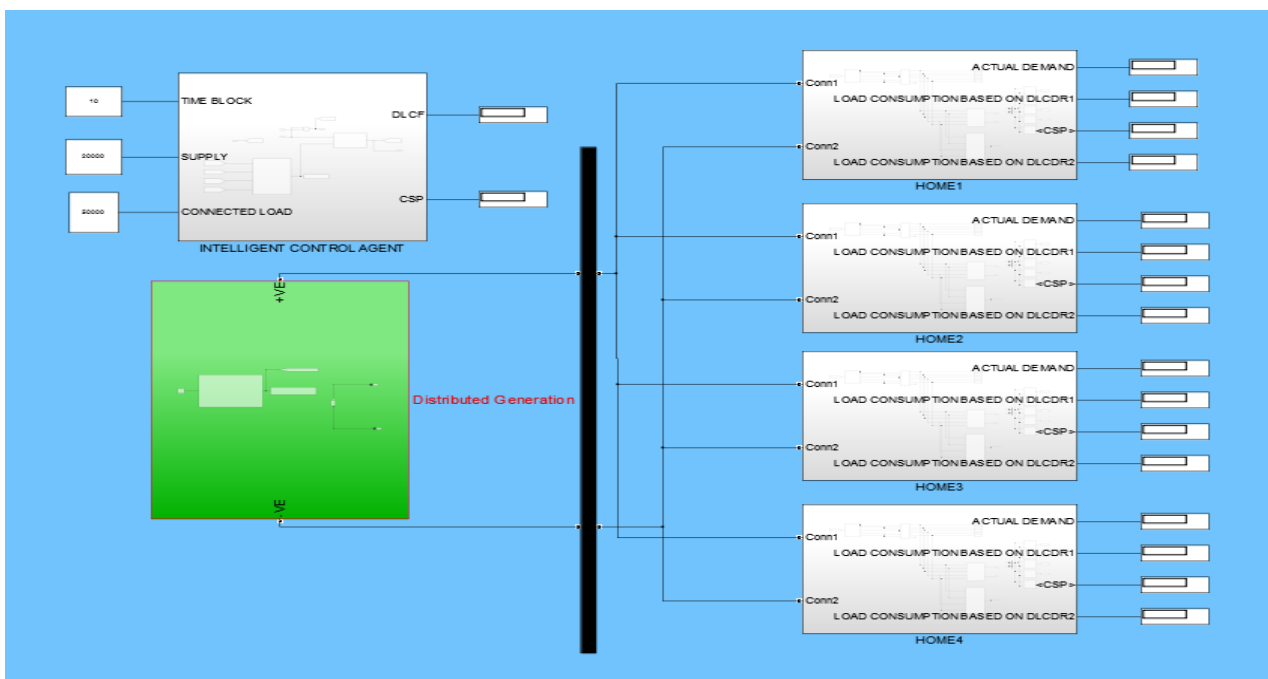


Figure 4 MATLAB/SIMULINK model of intelligent residential network

Using M-Functions, a multi-agent home network is modelled in MATLAB/SIMULINK. It is made up of a generator unit (GA), four "smart homes" (HA) with smart appliances standing in for the loads (customers), and an intelligent controller (ICA). The ICA and HA establish bidirectional communication, enabling real-time observation and management. For the purpose of determining the DLRP, DLCF, and CSP, which are then conveyed to the HAs, the ICA continuously checks the supply that is now available from the GA and the actual load demand of the home network. In order to achieve power

balance in the residential network, the HAs then start clearing load by picking the smart appliances in the best way possible depending on the customer's priority.

The four "smart homes" serve as the distribution network's loads (customers). In order to replicate various circumstances, each smart home is given a certain amount of total power and has five to six appliances that combine static, dimmable, and programmable components.

3. Results

In the current study, 10kW of electricity are assigned to HA1 and HA2 (representing Customers 1 and 2) in the residential network, and they are further divided into 5 separate load units, each of which is 2kW. These five loads consist of two static, one programmable, two dimmable, and one static load. The 15kW electricity allotted to the HA3 and HA4 (representing Customers 3 and 4) is further divided into 6 distinct load units. These loads include one programmable load of 2kW, one static load of 2kW, three dimmable loads of 3kW each, two static loads of 2kW each, and three dimmable loads of 3kW. Dimmable load reductions are only permitted to a maximum of 50% of their overall power consumption (presuming a minimal level of comfort). As a result, the home network's total connected load is 50kW. By making various supply and demand assumptions for specific time blocks, numerous situations are simulated. The reduction in active customers' power outages after the deployment of DLC is evident in the data.

One day is divided into 48 time blocks in order to evaluate the suggested DLC method, with each 30 minute interval representing one time block for carrying out load clearing actions. For analysis purposes, the first 10 blocks are taken into account. For time blocks 1 through 10 of the home network, the available supply, actual load demand, power mismatch, DLRP, and DLCF are tabulated in Table 1. The sub-hourly CSP, load demand, and mismatch for HA1 and HA2 are shown in Table 2, while the comparable data for HA3 and HA4 are shown in Table 3.

Table 1 Sub hourly Supply, Actual Load, Miss-match, DLRP and DLCF of residential network

Block	Supply(kW)	Demand(kW)	Missmatch (kW)	DLRP	DLCF
1	30	42	-12	-28.57	0.7143
2	30	36	-6	-20	0.8333
3	40	28	+12	+30	1
4	40	20	+20	+50	1
5	50	32	+18	+26	1
6	50	50	0	0	1
7	50	40	+10	+20	1
8	20	32	-12	-40	0.625
9	20	36	-16	-44.44	0.556
10	20	50	-30	-60	0.4
#: + sign indicates surplus and - sign indicates deficits					

The load clearance (distribution) pattern by the proposed DLC algorithm in the residential network is studied for two cases.

3.1. Case 1

In this instance, DLC1 is used to clear the load of customers in the home distribution network.

- If the supply power is sufficient to match the current load, all loads are cleared.
- When there is a shortage, the programme modifies the dimmable loads to achieve power balance.
- All loads are eliminated if the power balance is attained by reducing the power consumption of dimmable loads.
- If the power balance cannot be achieved despite the dimmable loads' reduced power consumption, then (according to the priority set) first the static loads and subsequently the programmable loads are not cleared.

The sub-hourly CSP, real demand, and corresponding clearing of static, programmable, and dimmable loads are shown in Tables 4 and 5 and are based on the supply and demand from consumers during the specific time block. Results for HA1 and HA2 are shown in Table 4, whereas those for HA3 and HA4 are shown in Table 5. Tables 4 and 5 show that some loads are shut down to achieve power balance at the intervals 1, 2, 8, 9, and 10. Because there is less demand during the intervals 3, 4, and 7, there is excess power that is not being used. The DLC programme in Case 2 recognises these circumstances; the programmable loads are moved to these intervals and are subsequently cleared and served.

Table 2 Sub hourly CSP and load profile of HA1 and HA2

Block	CSP of C1 and C2(kW)	S1 (kW)	S2(kW)	P1(kW)	D1(kW)	D2 (kW)	Total Demand of C1 and C2(kW)	Miss match (kW)
1	6	2	0	2	2	2	8	-2
2	6	0	0	2	2	2	6	0
3	8	0	0	2	2	2	6	+2
4	8	0	0	0	2	2	4	+4
5	10	2	0	0	2	2	6	+4
6	10	2	2	2	2	2	10	0
7	10	0	2	2	2	2	8	+2
8	4	0	0	2	2	2	6	-2
9	4	2	2	0	0	2	6	--2
10	4	2	2	2	2	2	10	-6

S1 and S2 are Static Loads, P1 is programmable Load and D1 and D2 are Dimmable Loads

Table 3 Sub hourly CSP and load profile of HA3 and HA4

Block	CSP of C1 and C2(kW)	S1 (kW)	S2(kW)	P1(kW)	D1(kW)	D2 (kW)	D3 (kW)	Total Demand of C1 and C2(kW)	Miss match (kW)
1	9	2	0	2	3	3	3	13	-4
2	9	2	2	2	3	3	0	12	-3
3	12	2	0	0	3	3	0	8	+4
4	12	0	0	0	3	3	0	6	+6
5	15	2	2	0	3	3	0	10	+5
6	15	2	2	2	3	3	3	15	0
7	15	2	2	2	3	3	0	12	+3
8	6	2	2	0	3	3	0	10	-4
9	6	2	2	2	0	3	3	12	-6
10	6	2	2	2	3	3	3	15	-9

S1 and S2 are Static Loads, P1 is programmable Load and D1, D2 and D3 are Dimmable Loads

Table 4 Case-1 Sub-hourly CSP, actual demand, DLCF and load clearing of HA1 and HA2

Block	CSP (kW)	Actual Demand(kW)	DLCF	S1(kW)	S2(kW)	P1(kW)	D1(kW)	D2(kW)	Total Load Consumption(kW)
1	6	8	0.7143	2	0	2	1	1	6

2	6	6	0.8333	0	0	2	2	2	6
3	8	6	1	0	0	2	2	2	6
4	8	4	1	0	0	0	2	2	4
5	10	6	1	2	0	0	2	2	6
6	10	10	1	2	2	2	2	2	10
7	10	8	1	0	2	2	2	2	8
8	4	6	0.625	0	0	2	1	1	4
9	4	6	0.556	0	0	2	0	2	4
10	4	10	0.4	0	0	2	1	1	4

Table 5 Case-1 Sub-hourly CSP, actual demand, DLCF and load clearing of HA3 and HA4

Block	CSP (kW)	Actual Demand (kW)	DLCF	S1(kW)	S2(kW)	P1(kW)	D1(kW)	D2(kW)	D3(kW)	Total Load Consumption(kW)
1	9	13	0.7143	2	0	2	1.667	1.667	1.667	9
2	9	12	0.8333	2	2	2	1.5	1.5	0	9
3	12	8	1	2	0	0	3	3	0	8
4	12	6	1	0	0	0	3	3	0	6
5	15	10	1	2	2	0	3	3	0	10
6	15	15	1	2	2	2	3	3	3	15
7	15	12	1	2	2	2	3	3	0	12
8	6	10	0.625	2	0	0	2	2	0	6
9	6	12	0.556	0	0	2	0	2	2	6
10	6	15	0.4	0	0	0	2	2	2	6

Table 6 Case-2 Sub-hourly CSP, actual demand, DLCF and load clearing of HA1 and HA2

Block	CSP (kW)	Actual Demand (kW)	DLCF	S1(kW)	S2(kW)	P1(kW)	D1(kW)	D2(kW)	Total Load Consumption(kW)
1	6	8	0.7143	2	0	2	1	1	6
2	6	6	0.8333	0	0	2	2	2	6
3	8	6	1	0	0	2	2	2	6
4	8	4	1	0	0	2	2	2	6
5	10	6	1	2	0	2	2	2	8
6	10	10	1	2	2	2	2	2	10
7	10	8	1	0	2	2	2	2	8
8	4	6	0.625	0	0	2	1	1	4
9	4	6	0.556	2	0	0	0	2	4
10	4	10	0.4	0	0	2	1	1	4

Table 7 Case-2 Sub-hourly CSP, actual demand, DLCF and load clearing of HA3 and HA4

Block	CSP (kW)	Actual Demand (kW)	DLCF	S1(kW)	S2(kW)	P1(kW)	D1(kW)	D2(kW)	D3(kW)	Total Load Consumption(kW)
1	9	13	0.7143	2	0	2	1.667	1.667	1.667	9
2	9	12	0.8333	2	2	2	1.5	1.5	0	9

3	12	8	1	2	0	2	3	3	0	10
4	12	6	1	0	0	2	3	3	0	8
5	15	10	1	2	2	2	3	3	0	12
6	15	15	1	2	2	2	3	3	3	15
7	15	12	1	2	2	2	3	3	0	12
8	6	10	0.625	0	0	2	2	2	0	6
9	6	12	0.556	0	0	2	0	2	2	6
10	6	15	0.4	0	0	0	2	2	2	6

4. Discussion

The sub-hourly available supply, real demand profile, and load clearing for the two cases are shown in Table 8 for the residential network. Table 8 shows that the total amount of supply across the ten intervals (time blocks) is 350kW, while the total amount of demand is 366kW. Out of this 366 kW, 290 kW total are cleared in case 1, and 310 kW total are cleared in case 2. It demonstrates the usefulness of programmable/shiftable loads in the DLC algorithm (Case2) to fully satisfy demand.

Table 8 Sub hourly Supply, Actual Demand and load clearing of both the cases

Block	Supply (kW)	Actual Demand (kW)	Load Clearing In Case-I (kW)	Load Clearing In Case-II (kW)
1	30	42	30	30
2	30	36	30	30
3	40	28	28	32
4	40	20	20	28
5	50	32	32	40
6	50	50	50	50
7	50	40	40	40
8	20	32	20	20
9	20	36	20	20
10	20	50	20	20
Total power	350	366	290	310

The Fig.5 and Fig.6 shows the graphical representation of CSP, actual demand and load clearing of the HA1, HA2, HA3 and HA4 of both the cases. Fig.7 shows the sub-hourly available supply, actual demand profile and load clearing of the residential network for both the cases.

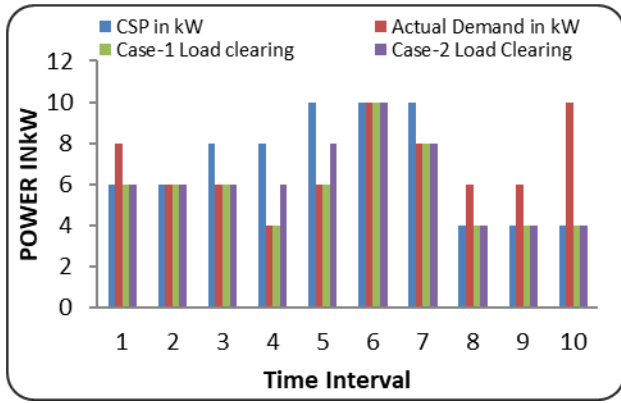


Figure 5 CSP, Demand, and Load clearing of HA1 and HA2.

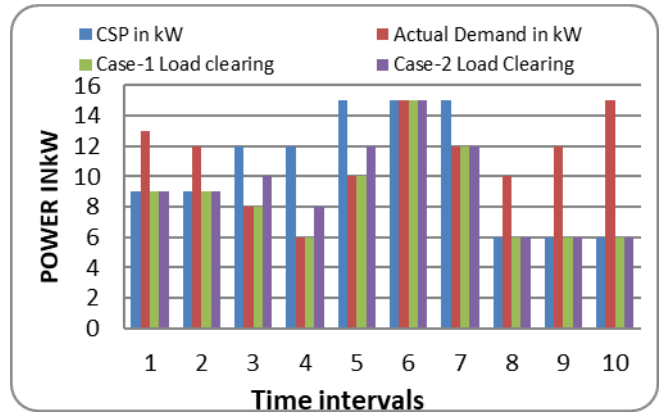


Figure 6 CSP, Demand, and Load clearing of HA3 and HA4.

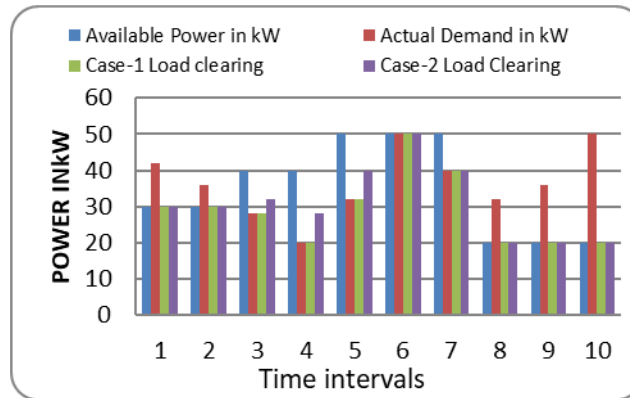


Figure 7 Supply, Demand, and Load clearing of the residential network

5. Conclusion

In the real-time control of smart distribution systems, DR is crucial. In this study, a brand-new algorithm for load shedding and direct load control is described. The proposed algorithm's primary goal is to decrease power outages, which will improve the supply system's dependability. While DLC is a potential alternative strategy for load shedding and increases customer reliability, load shedding alone is an ineffective way to handle rapid changes in supply. A time block's optimal load for a certain situation will be cleared. The simulation findings demonstrate that the residential network can efficiently manage the grid through distributed load reduction and respond rapidly to demand in emergency situations. In the event of a supply shortage, it aids in preventing load shedding. Although extra controllers and digital systems are needed for this operation, DSM techniques can be efficiently used when developing smart distribution systems to attain the highest levels of security and dependability.

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Compliance with ethical standards

Declaration of conflict of interest

No competing interests to be disclosed.

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