

RESEARCH ARTICLE

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CAPACITY MARKET-BASED DEMAND RESPONSE APPROACH FOR EFFICIENT POWER DISTRIBUTION IN RESIDENTIAL MICROGRID

Arunkumar P^{*1}, Chidurala Sai Prakash², Srikanth Velpula³, Manjunatha H M⁴

¹Research Scholar, Department of Electricaj and Electronics Engineering, SR University, Warangal, India-.

²Department of Electricaj and Electronics Engineering, SR University, Warangal, India-.

^{1,3}Department of Electrical and Electronics Engineering, Bapuji Institute of Engineering and Technology, Davanagere-577004 Karnataka, India.

¹<https://orcid.org/0009-0003-7145-4392>, ²<http://orcid.org/0000-0003-0544-8974>

³<http://orcid.org/0000-0003-2706-7136>, ⁴<https://orcid.org/0000-0001-6651-7131>

E-mail: *arunkumarp584@gmail.com, saiprakash.ace@gmail.com, srikvelpula@gmail.com, manjunath.hm1986@bietdvg.edu

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ABSTRACT

This paper presents a novel Demand Response algorithm based on a capacity market framework for efficient power management in residential microgrids. The primary objective is to minimize load shedding and enable effective direct load control in smart home environments. By establishing two-way communication channels between distribution agents and smart home customers, the proposed algorithm facilitates real-time load control decisions, accurate calculation of reduction percentages and the generation of home-specific Distributed Load Consumption Factors. An agent-based residential distribution network model was developed in MATLAB/Simulink, incorporating eight clients and integrated smart appliances to validate the algorithm's efficacy. Simulation results demonstrate that the network can maintain grid power balance through three key mechanisms: adaptive load adjustment, strategic load shifting and distributed load reduction. Under supply-constrained conditions, the approach effectively diminishes or even eliminates the necessity for load shedding. The capacity market-based paradigm proves highly advantageous for stand-alone microgrid systems, where optimal resource management is critical for ensuring system stability and enhancing customer satisfaction.



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I. INTRODUCTION

In modern power systems, Demand Side Management (DSM) has emerged as a crucial and cost-effective strategy to bridge the gap between electricity supply and demand. DSM encompasses the development and implementation of measures designed to optimize consumption patterns. Through Demand Response (DR) programs, consumers can adjust their energy usage in response to electricity price fluctuations or incentive signals, thereby reducing peak demand and shifting loads to align with available generation capacity. DR methods have proven particularly effective in lowering consumption during periods of high wholesale market prices or system reliability threats [1] [2]. Either centralized or decentralized control systems that facilitate dynamic system adaptability to evolving conditions are necessary for the effective implementation of DR programs within DSM frameworks. The use of intelligent and reliable Multi-Agent Systems (MAS), which facilitate two-way communication between the supply infrastructure and end users, is critical to this process. Loosely coupled, dispersed physically and functionally, autonomous networks consisting of multiple agents form MAS. Agents cooperate smoothly with each other to solve complex operation issues. For solving advanced issues related to DR mechanisms, microgrid operation and control strategies, service restoration process, spot market behaviour, Virtual Power Plant (VPP) management, and economic dispatch optimization, MAS structures have proven themselves to be exceptionally valuable in smart grid scenarios [3] [4]. Capacity market-based DR techniques offer potent solutions for residential microgrids, where resources are constrained and maintaining grid stability is paramount. These microgrids require sophisticated power allocation strategies to balance customer demands with supply limitations. The integration of smart home technologies, enabling precise load control and individual device management, significantly amplifies the effectiveness of capacity market DR [5] [6].

This paper introduces a novel DR algorithm designed to address load shedding and direct load control within smart home environments of residential microgrid systems [7]. The algorithm leverages bidirectional communication between distribution agents and smart home consumers to enable real-time load control decisions, accurately compute reduction percentages and generate tailored Distributed Load Consumption Factors (DLCF). Extensive research has been conducted in areas intersecting microgrid operation, demand response and optimization algorithms. Key related works include:

- Market-Based Microgrid Operation with DR: Research on optimal market-based microgrid operation explores balancing price signals, renewables, storage, and DR resources using risk-based stochastic models, demonstrating cost reduction and uncertainty mitigation [8] [9].
- DR in Residential and Smart Grid Contexts: Comprehensive reviews discuss residential DR challenges and design strategies, highlighting load scheduling techniques supported by Information and Communication Technology (ICT) to better match demand with generation [10] [11].
- Algorithms and Optimization Techniques: Studies on distributed market clearing methods integrate large-scale DR using decomposition techniques, improving convergence and reducing communication overhead [12]. Event-based DR algorithms have also been proposed for rapid decision-making during microgrid contingencies.
- DR in Capacity Markets: Preliminary work on DR planning within capacity markets indicates that microgrid participation can reduce transmission costs and enhance capacity selling profitability [13] [14].

II. METHODOLOGY

The proposed Capacity Market-Based DR approach is built upon and extends the intelligent residential network model presented in [15] [16] [17]. The system architecture is designed to validate the algorithm's performance in managing power distribution efficiently. Figure 1 depicts the block diagram of the proposed intelligent residential network, comprising a power source, an Intelligent Power Distribution System, and eight smart homes. Figure 2 illustrates the Multi-Agent System (MAS) architecture for the residential microgrid, consisting of an Action Layer and a Control Layer. This hierarchical structure enables advanced management of power balance. The Action Layer provides a real-time view of supply and load, generating actionable signals for the Control Layer agents, which oversee load management in response to these signals and user comfort preferences. The entire MAS was implemented in MATLAB using specialized M-functions [18].

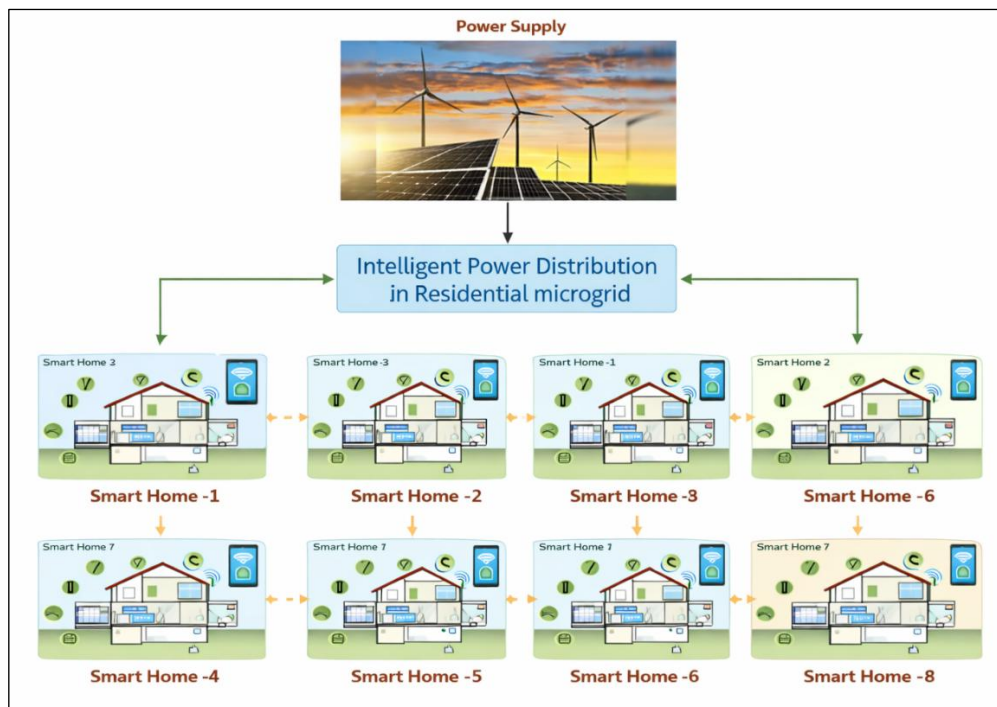


Figure. 1: Block diagram of the proposed intelligent residential network.

Source: Authors, (2026).

II.1 AGENT ARCHITECTURE FOR RESIDENTIAL NETWORK MANAGEMENT

The MAS comprises four primary agent types:

- Intelligent Control Agent (ICA): The central DR coordinator.
- Generator Agent (GA): Monitors and reports available power supply.
- Home Agent (HA): Interfaces with consumer systems and manages smart appliances within a home.
- Smart Appliance Agent (SA): Represents individual appliances with specific characteristics (dimnable, programmable, static).

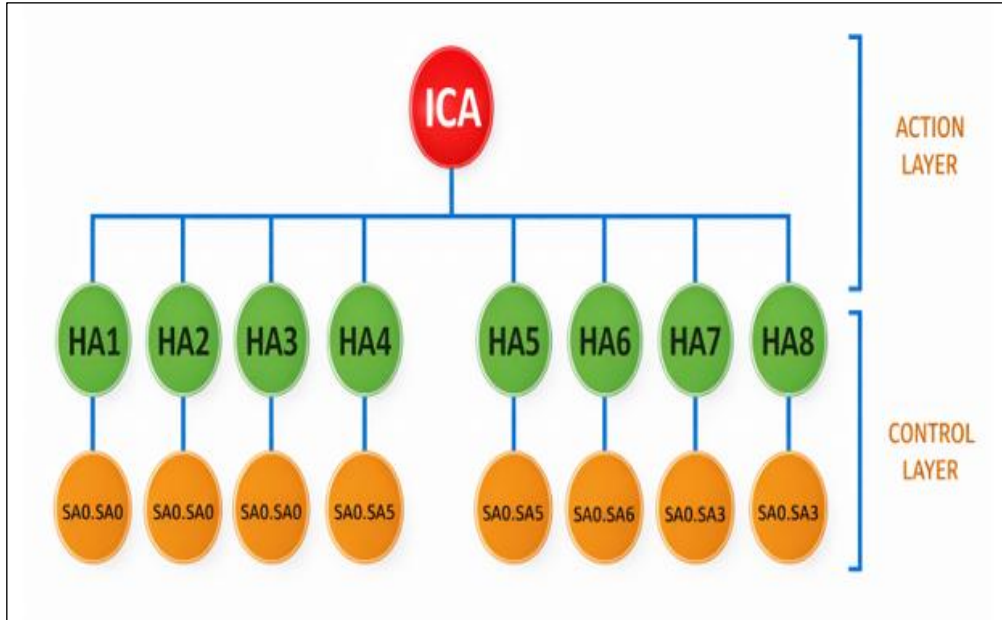


Figure 2: Multi-Agent System architecture enabling Capacity Market-DR.
Source: Authors, (2026).

The standardized naming patterns are followed by delegates such as Home Agents (HA) and Smart Appliance Agents (SA). The individual home agents are referred to as HAx where "x" specifies the corresponding home position in the network. SAxy is one of the agents of smart appliances (x means home and y means the appliance). The details of this mapping will depend on specific configuration choices, for example HA1 would be the first home agent and SA11 would be the first smart appliance agent for the first home [11-13]. Home Agents gather information about what consumers like and send this data to the ICA. In addition to their role in gathering this data, these Home Agents are equipped with intelligent features that allow them to manage the smart devices. This management is crucial to ensure that the network operates smoothly, even when conditions change unexpectedly. The Generator Agent keeps gathering and sending power supply data from home networks to the ICA. This up-to-the-minute information allows the ICA to set up the right Distributed Load Reduction Percentage (DLRP) factors also called set points. This helps to keep the system running when supply conditions change.

The ICA functions as the primary demand response agent within the system, continuously calculating two critical parameters:

- Distributed Load Reduction Percentage (DLRP).
- Distributed Load Consumption Factor (DLCF).

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

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

The real-time analysis of network supply and demand dynamics underpins these estimates. These settings influence consumer behavior to maintain power equilibrium throughout the system. The ICA further computes the Clearing Supply Power (CSP) for each network user. The total connected load of the residential network is now restricted to remain at or below the available supply power.

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

II.2 CAPACITY MARKET DR ALGORITHM

The suggested Capacity Market DR algorithm shown in Figure 2 gives either the best or almost the best choices for clearing the load in a lot of different supply-and-demand situations. The method works in three stages:

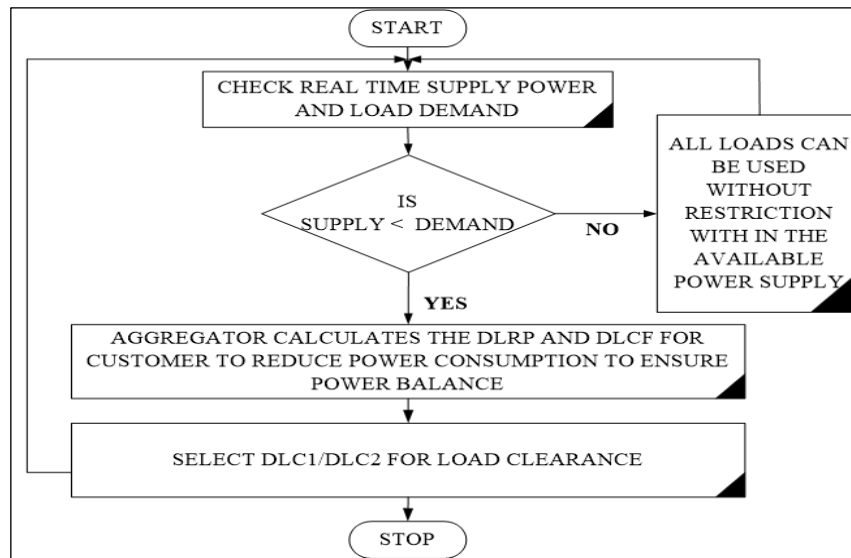


Figure 3: Flowchart of the proposed Capacity Market DR algorithm.
Source: Authors, (2026).

- Real-Time Monitoring: Continuous assessment of residential network load demand and power supply.
- Parameter Calculation: Computation of DLRP, DLCF, and CSP using equations (1), (2), and (3) respectively.
- Load Selection: Strategic identification of appropriate loads to initiate the clearing process for power balance maintenance.

The algorithm implementation follows two distinct Direct Load Control (DLC) operational scenarios:

II.2.1 Scenario 1: Fixed Programmable Loads (DLC1)

Programmable loads in this arrangement are handled as fixed, non-adjustable objects. Only modulation of dimmable loads allows one to perform power balance modifications, so offering a more limited but consistent working environment.

II.2.2. Scenario 2: Flexible Programmable Loads (DLC2)

This more dynamic method lets programmable loads be temporally moved, hence improving the peak-to average ratio of the network. While keeping system stability, this offers more demand management options. Maintaining equilibrium between power demand and supply is both Capacity Market DR method's principal goal. They guarantee quick response capacity for unforeseen or emergency modifications in either supply availability or demand requirements. The ICA sends reduction signals to the Home Automation (HA) system in reaction to supply fluctuations, therefore lowering the dimmable appliance power consumption to specified comfortable levels (e.g., 50% of rated capacity). Should this decrease prove inadequate, the HA uses pre-defined preferences to start load shifting or shedding for less-priority equipment. For a 20% consumption reduction signal, for instance, the HA first lowers dimmable appliance power usage; then, if needed, it moves running schedules for programmable appliances to reach the target reduction level.

III. SYSTEM SIMULATION AND IMPLEMENTATION

In order to validate the suggested intelligent multi-agent home network architecture, we created a thorough simulation environment using MATLAB/SIMULINK. The home network's conceptual and execution models are depicted in Figures 3 and 4, respectively. Our suggested capacity market demand response strategy can be tested and its effectiveness assessed using this simulation framework. Real-time monitoring and control capabilities are made possible by the simulation's establishment of bidirectional communication links between the ICA and HAs. The ICA is able to continuously monitor the real load demand throughout the home network as well as the supply that is available from the GA. Critical metrics including the Distributed Load Consumption Factor (DLCF), Clearing Supply Power (CSP), and Distributed Load Reduction Percentage (DLRP) are computed by the ICA using this data and sent to the HAs. After obtaining these parameters, the HAs use complex load clearing algorithms to choose the best smart appliance operating states according to priorities specified by the client. This strategy maximizes consumer happiness while guaranteeing power balance maintenance.

III.1 RESIDENTIAL LOAD CONFIGURATION

Eight different "smart homes" are used in the simulation to simulate realistic loads in the distribution network. Every smart house has five to six appliances that are carefully categorized as follows and each is set up with a precise power allocation:

- Appliances having fixed power consumption profiles that cannot be adjusted are known as static loads.
- Appliances having changeable power consumption capabilities are known as dimmable loads. Dimmable load reductions are only permitted to a maximum of 50% of their overall power consumption (presuming a minimal level of comfort).
- Time-shifting appliances with adjustable running schedules are known as programmable loads.

The connected load profile of eight smart homes is summarized in Table 1.

Table 1: Load Profile of Eight Smart Homes in the Residential Microgrid.

Smart home	Allotted power in kW	Smart Appliances in kW					
		S1	S2	P1	D1	D2	D3
1	5	1	1	1	1	1	NA
2	10	2	2	2	2	2	NA
3	12	1	1	1	3	3	3
4	15	2	2	2	3	3	3
5	18	3	3	3	3	3	3
6	21	4	4	4	3	3	3
7	24	4	4	4	4	4	4
8	27	5	5	5	4	4	4

Source: Authors, (2026).

The Residential Microgrid total connected load is 132kW. 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.

IV. RESULTS AND DISCUSSION

One day is divided into 24-time blocks in order to evaluate the suggested DLC DR algorithms, with each hour representing one time block for carrying out load clearing actions. For analysis purposes, the 6 blocks are taken into account. For time blocks 1 through 6 of the home networks, the available supply, actual load demand, power mismatch, DLRP, and DLCF are tabulated in Table 2. To validation proposed DLC programs load HA3 is considered. The sub-hourly CSP, load demand, and mismatch for HA3 is shown in Table 3. Table 4 and 5 summaries the load consumption patron of HA3 after incorporating proposed DLC1 and DLC2 in residential network. From comparing the Tables 3,4 and 5, it is observed that:

- The supply demand mismatch in all the time blocks is reduced in HA3 after incorporating DLC 1 and DLC 2, whereas it is almost zero in DLC2 compared to DLC 1.
- In the time block 1, DLC 2 clear the P1, whereas it is not achieved in DLC1
- In time block 2 and 5, DLC 2 clear the S2, whereas it is not achieved in DLC1
- The Total load consumption of (TLC) of HA3 in DLC 2 is more compared to DLC1. It concludes DLC 2 program is most efficient compared to DLC1.

The Figure 4 summarise comparison of the total energy consumption of individual smart home residential microgrid for DLC1 and DLC2. From the figure 4, it is observed that, power consumption in DLC-2 is more compared to DLC-1. The Table 6 summarise the total energy consumption of residential microgrid for DLC1 and DLC2. Figure 5 shows the comparison of Supply, actual demand, Power Consumption of residential microgrid from six-time blocks in kW after incorporating DLC1 and DLC-2.

Table 2: Sub hourly Supply, Actual Load, Miss-match, DLRP and DLCF of residential network.

Block	SPV in Kw	DL in Kw	Mismatch in Kw	DLRP	DLCF	DSP	LC of DLC1 in Kw	LC of DLC2 in Kw
1	70	110	-40	-36.36	0.6363	0.530303	59	69.27
2	80	106	-26	-24.52	0.754	0.606061	55.71	65.36
3	132	68	64	94.11	1	1	52	52
4	90	46	44	95.65	1	0.681818	46	46
5	85	87	-2	-2.29	0.977	0.643939	54.94	58.38
6	132	91	41	0	1	1	91	91

Source: Authors, (2026).

Table 3: Sub hourly CSP, Actual Load, Miss-match of HA3.

Time block	CSP in kW	S1 in kW	S2 in kW	P1 in kW	D1 in kW	D2 in kW	D3 in kW	DL in Kw	Miss match in kW
1	6.36	1	0	1	3	3	3	11	-4.64
2	7.27	1	1	1	3	3	0	9	-1.73
3	12	1	0	0	3	3	0	7	-5
4	8.18	0	0	0	3	3	0	6	+2.18
5	7.72	1	1	0	3	3	0	8	-0.28
6	12	1	1	1	3	3	3	12	0

+ indicate surplus – indicate deficit

Source: Authors, (2026).

Table 4: Sub hourly CSP and load clearing of HA3 for DLC1.

Time block	CSP in kW	S1 in kW	S2 in kW	P1 in kW	D1 in kW	D2 in kW	D3 in kW	TLC in kW	Miss match in kW
1	6.3	0	0	0	1.90	1.90	1.90	5.72	+0.58
2	7.27	1	0	1	2.26	2.26	0	6.52	+0.75
3	12	1	0	0	3	3	0	7	+5
4	8.18	0	0	0	3	3	0	6	+2.18
5	7.72	1	0	0	2.93	2.93	0	6.86	0.86
6	12	1	1	1	3	3	3	12	0

Source: Authors, (2026).

Table 5: Sub hourly CSP and load clearing of HA3 for DLC2.

Time block	CSP in kW	S1 in kW	S2 in kW	P1 in kW	D1 in kW	D2 in kW	D3 in kW	TLC in kW	Miss match in kW
1	6.36	0	0	1	1.78	1.78	1.78	6.36	0
2	7.27	1	1	1	2.13	2.13	0	7.27	0
3	12	1	0	0	3	3	0	7	+5
4	8.18	0	0	0	3	3	0	6	+2.18
5	7.72	1	1	0	2.86	2.86	0	7.72	0
6	12	1	1	1	3	3	3	12	0

Source: Authors, (2026).

Table 6: Total energy consumption of residential microgrid for DLC1 and DLC2.

Block	SPV in Kw	Actual DL in Kw	Mismatch in Kw	LC of DLC1 in Kw	Mismatch in Kw after DLC1	LC of DLC2 in Kw	Mismatch in Kw after DLC2
1	70	110	-40	59	11	69.27	0.73
2	80	106	-26	55.71	24.29	65.36	14.64
3	132	68	64	52	80	52	80
4	90	46	44	46	44	46	44
5	85	87	-2	54.94	30.06	58.38	26.62
6	132	91	41	91	41	91	41

Source: Authors, (2026).

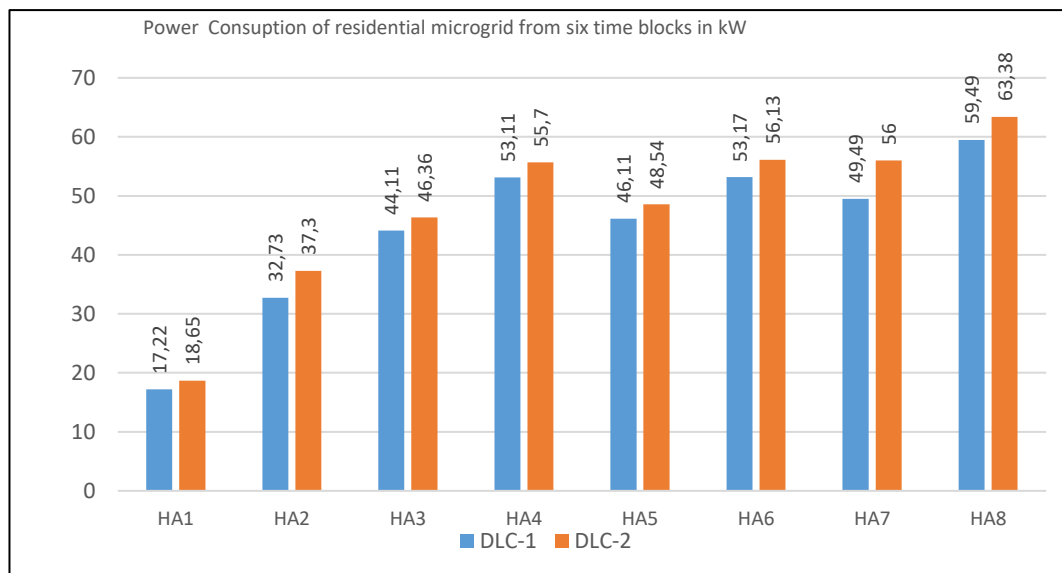


Figure 4: Comparison of the total energy consumption of individual smart home residential microgrid.

Source: Authors, (2026).

From the Table 6 and Figure 5, it is observed that:

- In all the time blocks supply demand mismatch is reduced in microgrid after incorporating DLC1 and DLC2, additionally DLC2 perform best compare to DLC1. (eg., In time block 1 actual supply demand mismatch is -40kW, where as it is 11kW in DLC1 and 0.73kW in DLC2) its clearly shows DLC2 clear the load by efficiently managing the available supply power.
- The total power consumptions of residential microgrid form six-time blocks in DLC-1 are 358.651kW, where as in DLC-2, it is 382.01kW

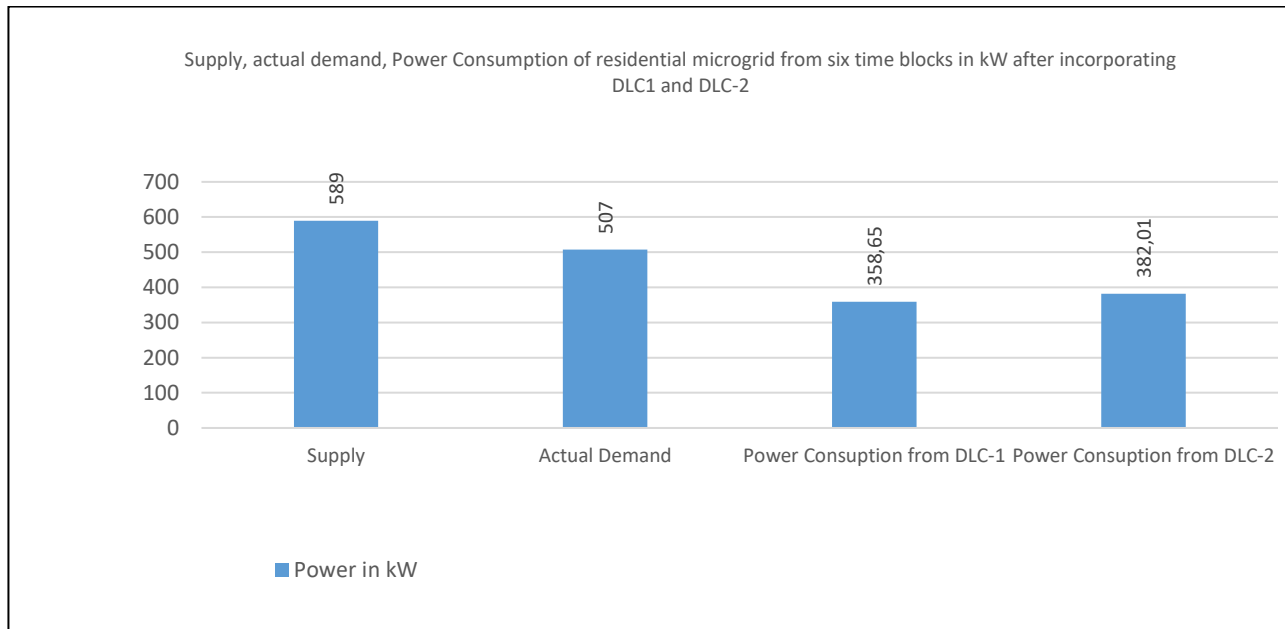


Figure 5: Supply, actual demand, Power Consumption of residential microgrid from six-time blocks in kW after incorporating DLC1 and DLC-2.

Source: Authors, (2026).

For detailed analysis, Home 3 (HA3) was examined. Table III shows HA3's CSP, appliance demand and mismatch before DR. Tables 4 and 5 detail the load-clearing results for HA3 under DLC1 and DLC2 respectively. Key Observations from Tables 3-5:

- The supply-demand mismatch is reduced in all time blocks for HA3 after implementing both DLC1 and DLC2.
- DLC2 outperforms DLC1, achieving zero mismatch in blocks 1, 2, and 5 by effectively clearing loads like P1 and S2, which DLC1 could not.
- The Total Load Consumption (TLC) of HA3 is higher with DLC2, indicating more efficient utilization of available supply power and superior customer comfort preservation.

Table 6 and Figure 4 provide a network-wide comparison. The total power consumption across the six blocks was 358.65 kW for DLC1 and 382.01 kW for DLC2, confirming DLC2's superior performance in maximizing energy delivery while minimizing mismatch (e.g., reducing mismatch from -40 kW to 0.73 kW in Block 1).

V. CONCLUSION

This paper presented a capacity market-based Demand Response (DR) framework for intelligent power distribution in residential microgrids. The proposed approach integrates a novel direct load control strategy through two operational modes, namely DLC1 and DLC2 designed to dynamically manage supply-demand imbalances in real time. Unlike conventional load shedding techniques, which indiscriminately disconnect loads during shortages, the proposed algorithm enables prioritized and optimized load management based on calculated Distributed Load Consumption Factors and reduction percentages for individual smart homes. By incorporating two-way communication between distribution agents and smart residential consumers, the system ensures rapid decision-making, accurate load adjustment, and effective resource allocation within the microgrid. The developed MATLAB/Simulink-based agent-driven model, comprising multiple smart home clients and controllable appliances, demonstrates that the proposed strategy successfully maintains power balance through adaptive load shifting, distributed load reduction, and strategic demand control. Simulation results confirm that the capacity market-based paradigm significantly reduces dependency on load shedding, enhances system reliability, and improves customer satisfaction. Under supply-constrained and emergency conditions, the microgrid responds efficiently by optimally clearing time-block loads while preserving critical demand. The proposed framework provides a robust and scalable solution for stand-alone and grid-connected residential microgrids, ensuring improved operational stability, enhanced reliability and efficient utilization of distributed energy resources.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Arunkumar P and Chidurala Sai Prakash.

Methodology: Arunkumar P and Chidurala Sai Prakash.

Investigation: Arunkumar P and Chidurala Sai Prakash.

Writing – Original Draft: Arunkumar P, Srikanth Velpula and Chidurala Sai Prakash.

Writing – Review and Editing: Arunkumar and Srikanth Velpula.

Resources: Arunkumar P and Chidurala Sai Prakash.

Supervision: Chidurala Sai Prakash.

Approval of the final text: Chidurala Sai Prakash and Manjunatha H M.

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