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RESEARCH ARTICLE

Auction-Based Single-Sided Bidding Electricity Market: An Alternative to the Bilateral Contractual Energy Trading Model in a Grid-Tied Microgrid

HIREKERI MALLESHAPPA MANJUNATHA[1], GARIGHATTA KRISHNAIAH PURUSHOTHAMA[2], YASHWANTH NANJAPPA[3], (Senior Member, IEEE), AND RAGHAVENDRAPRASAD DESHPANDE[4]

[1]Department of Electrical and Electronics Engineering, Bapuji Institute of Engineering and Technology, Davanagere, Karnataka 577004, India
[2]Department of Electrical and Electronics Engineering, Malnad College of Engineering, Hassan, Karnataka 573202, India
[3]Department of Electronics and Communication Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka 576104, India
[4]Department of Electrical and Electronics Engineering, GSSSIETW, Mysuru, Karnataka 570016, India

Corresponding author: Yashwanth Nanjappa (yashwanth.n@manipal.edu)

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ABSTRACT An auction-based single-sided bidding energy transaction mechanism in a grid-connected microgrid (MG) using a multi-agent system allows for better profit sharing for all stakeholders. This can replace existing bilateral contractual trade between the stakeholders. In the bilateral contractual energy trade model, energy transactions are either long-term, medium-term, or short-term agreements or bilateral negotiations between the stakeholders based on physical limits. Whereas in an auction-based mechanism, the energy transaction is in real time based on bidding strategies and supply-demand mismatches among the stakeholders. This work proposes a single-sided auction mechanism (SSAM) to clear the market based on the asking price of the seller and the supply-demand mismatch of the microgrid. In addition, the new two bidding algorithms, namely the linear bidding algorithm (LBA) and the fuzzy logic-based bidding algorithm (FLBA), are developed for sellers to select the 'ask' quotes. The proposed auction-based, single-sided bidding energy transaction mechanism is tested and validated in the existing Malnad College of Engineering (MCE) grid-tied MG (bilateral contractual) trading model, Hassan-573201, Karnataka, India. The energy market simulation results yield promising findings, highlighting the advancement of proposed SSAM and bidding strategies in boosting the profit margin of sellers.

INDEX TERMS Microgrid, multi-agent system, bidding strategies, energy trading.

NOMENCLATURE

μ_{bp}^{g}	MG buying power from the grid in kW.
μ_{sp}^{g}	MG selling power to grid in kW.
l_{cp}	Market cleared load clearing price.
M_{bp}^{g}	Market cleared grid buying Price.
M_{la}^{b}	Market cleared LA buying price.
M_{sp}^{g}	Market cleared grid selling price.
M_{sp}^{Ps}	Market cleared DGA selling price.
T_{MCE}^{l}	Total load demand of MCE campus.
W_{lp}^{g}	Weighted average of limiting prices of grid.
AP_{S}	Ask price of SPV.
CF	Control factor.
DERs	Distributed energy recourses.
DGA	DG/SPV agent.
DGs	Distributed generation.
DN	Distribution Networks.
EB	Export power bill to utility grid.
FLBA	Fuzzy logic-based bidding algorithm.

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G_{bp}	Quoted Grid buying Price.
GDF	Generation difference factor.
G_{sp}	Quoted grid selling price.
IMO	Independent Market Operator.
LA	Load/MCE campus agent.
LBA	Linear bidding algorithm.
MCE	Malnad College of engineering.
MG	Microgrid.
MIAA	Microgrid intelligent aggregator agent.
SPVB	SPV bill of a day.
SPVSLB	SPV share on load bill.
S_{RC}	Rated capacity of SPV.
SSAM	Single-sided auction mechanism.
TLB	Total MCE/load bill.
UGA	Utility Grid Agent.
UGSLB	Utility grid bill share on MCE/load bill.
ΔP	Supply-demand mismatch of the MG.
Ps	Day-ahead real-time generation of SPV.

I. INTRODUCTION

A. MOTIVATION AND BACKGROUND

The increasing deployment of Distributed Energy Recourses (DERs) and deregulation of electricity has set the stage for private sector active engagement in electricity markets at the Distribution Networks (DN) level. This allows stakeholders such as Prosumers, Consumers, Distribution Generations (DGs), Distribution Storage (DS), and Distribution Companies to form direct trading agreements that maximize profit sharing without the need for intermediate brokers. The incorporation of more than one of these participants into a traditional DN setup brings forth economic, environmental, and security improvements, forming what we call a Microgrid (MG) [1]. This MG is a subsection of the main grid and may work in either an islanded or grid-tied mode [2].

The integration of non-dispatchable stakeholders such as (DERs) and variable loads in an MG poses additional challenges in the area of trading and management [2]. The emergence of DG units with non-dispatchable characteristics creates a supply-demand mismatch in the MG, which has a significant impact on the management of the grid. To resolve these problems, MG needs distributed intelligent frameworks with agents that use soft computing approaches to conduct market auctions for the benefit of stakeholders. The power balance is even more equal if the DN is a grid-tied MG with bidirectional energy flow [3]. Additionally, energy trading between the utility grid and the MG as well as among MG and stakeholders may be advantageous [4].

Agents are discrete entities that respond to environmental changes, execute various tasks, and communicate with other coexisting agents [5]. A Multi-Agent System (MAS) is a system created using a number of these agents [6], [7]. A centralized [8], decentralized [9], or mixed control technique [10] can be used by MAS to coordinate. One control agent manages all control actions in the centralized control approach. In the decentralized control method, each agent can carry out regional responsibilities and communicate with other agents. The MG and the MAS should be able to communicate in real time so that the agents may access the pertinent data within the permitted delay for starting the required tasks.

Different parts of the world operate energy trading models depending on the local policies and structures. The Single-Buyer Model, the Bilateral Contracts Model, and the Power Pool Model (Spot market) [11] are the three most common models seen. The Single Buyer Model works by having an entity, typically a trader, purchase power from all generators based on a medium- or long-term agreement, and then resell the power to distribution companies or large consumers [12]. The Bilateral Contracts Model allows sellers to directly sell electricity to distributors and large consumers without an intermediary buyer but at a contracted price. The Power Pool Model forwards the controller role to an Independent Market Operator (IMO). Sellers and buyers, typically distributors or large consumers, submit their ask and bid prices for the IMO to account for their generation and demand when clearing the market. This model is meant to increase competition between sellers and buyers to access the benefits of an open market [13]. In IMO, intermediate brokers plays an important role in energy trading. Intermediate brokers in electricity trading connect buyers, sellers, and other market participants, facilitating transactions and ensuring market liquidity. They monitor market conditions for price discovery, negotiate contracts, and manage documentation, scheduling, and settlement processes. Additionally, they help manage risks and ensure regulatory compliance, playing a vital role in optimizing electricity trading strategies. Overall, their expertise enhances market efficiency, enabling efficient electricity trade mechanisms.

In India, power trading is done through direct bilateral trading, trading with intermediaries, and power exchanges through structured auctions [14]. Additionally, based on different bidding models, electricity markets can be classified into Single Sided Bidding electricity markets [15] and Double-Sided Bidding electricity markets [16], [17].

To facilitate strategic bidding in electricity markets, different researchers have proposed models which utilize dynamic programming [18], [19], stochastic optimization [20], [21], Two-level optimization [22], Lagrangian relaxation [23], genetic algorithm, fuzzy approach [21], and game theory. These various methods can typically be divided into three categories: (i) Those based on estimating the market clearing price; (ii) Those based on game theory; and (iii) Those based on estimation of competitors' bidding behaviour from their past bidding data. However, there is still the need for a more practical and systematic approach to strategic bidding.

Optimizing efficiency and guaranteeing a consistent supply of energy are the goals of a bilateral contractual energy trading mechanism in a grid-tied microgrid. These techniques involve mathematical algorithms that analyze various factors such as demand forecasts, available energy resources, and pricing mechanisms to optimize energy flows between interconnected entities [24], [25]. Risk management strategies [26], [27] are also essential for reducing the risks that come with trading energy, such as changes in supply and demand, price volatility, and possible disruptions. The microgrid's resilience and sustainability are eventually enhanced by the use of strategies including hedging, diversification of energy sources, and real-time monitoring systems, which reduce risks and improve the stability of energy trading operations.

B. RELATED WORK

Anees et al. [28], developed a bilateral energy trading scheme and a new technique for setting a price for both seller and buyer. The devised approach and energy trading scheme are more efficient than previous methods, requiring fewer rounds of negotiations between sellers and buyers to reach an appropriate mutual bilateral price. Additionally, discuss two bilateral energy trading scenarios: single seller single buyer and single seller multiple buyers, with the latter offering greater benefits for both parties. Morstyn et al. [29] propose bilateral contract networks for peer-to-peer energy trading. It introduces real-time and forward markets and develops utility-maximizing preferences for the different energy trading agents. Energy balance, market uncertainty, and other energy trading aspects are discussed. In [30] Algarvio et al. discuss bilateral contracting and price-based demand response in multi-agent power markets, focusing on time-of-use tariffs. Bilateral contracting involves long-term private negotiations for electrical energy purchases or sales. Price-based demand response involves consumers actively participating in power markets by altering consumption based on tariffs. The study examines how time-of-use pricing, curtailment, and shifting methods affect energy quantity and cost. Bompard et al. [31], presents a bilateral trade model and complex network theory, taking into account the strategic interactions found in bilateral contracts as well as the physical limits of the network. Karandikar et al. [32], introduced risk-constrained methodology for bilateral contract evaluation in competitive power markets, estimation of payoffs and risk quantification for electricity retailers and designed a framework for retailers to choose optimal bilateral contracts for risk-constrained payoff. A novel utility-based and adaptive agent-tracking strategy was presented by Imran et al. [33] for bilateral negotiations. Empower GenCo agents to swing bilateral negotiation results in their favor. With increased negotiation frequency, attain 7% higher payout than utility-based technique.

From the literature, it is observed that, in the existing bilateral contract energy trading models, energy trading is done either by long-term or short-term fixed bilateral contractual price, bilateral negotiations between the stakeholders are based on available physical limits, and sellers are empowered to swing bilateral negotiation results in their favor. It is also observed that in the existing bilateral contract energy trading models, the market cleared price is not based on the real-time supply-demand mismatch factor of the stakeholders. Considering this one as a challenge, the author Manjunatha et al., in their previous work [15], introduced a single seller, single buyer (SSSB) energy trading model where the market is conceived as two groups: a local market and a global market. A novel linear bidding algorithm (LBA) is used to decide the ask quotes for sellers in a single-sided bidding electricity market based on the generation capacity of the seller. This approach is aimed at increasing the profit margin of sellers by basing the market cleared prices on the variation in supply-demand mismatch factor rather than on bilateral contractual prices.

Inspired by this literature, this research study proposes a novel bidding strategy called FLBA, where ask price of the seller (Genco) is decided based on the variation in power generation and the supply-demand mismatch factor of the stakeholders in auction energy trading model. Auction-based single-sided bidding electricity market as an alternative to the bilateral contractual energy trading model in a grid-tied microgrid using a multi-agent approach. Auction systems promote fair and transparent energy transactions, stakeholder participation, and optimal energy exchange decision-making.

C. CONTRIBUTIONS AND ORGANIZATION

The existing bilateral contractual trading model (SPV powered MCE grid-tied MG) has been modified to an SSAM energy trading model. In this study, where the seller's offer (Ask) price is established by the LBA [15] based on the variation in power generation and proposed FLBA based on the variation in power generation and the supply-demand mismatch factor in the MG. The Market Clearing Prices in this SSAM trading model are based on the variation in supply-demand mismatch factor of MG, instead of the fixed bilateral contractual prices.

In the proposed SSAM energy trading model the market is conceived as two groups: a local market; and a global market. The local market consists of the aggregator, local vendors (DGs), and local purchasers (big consumers). The global market consists of aggregators and the main grid. In the proposed SSAM, aggregator is designed to conduct both local and global market auction to balance supply-demand in MG. The aggregator in MG consistently seeks to balance the local demand by utilizing local generation in the local market (without the assistance of the main grid) as far as possible. Deficit or surplus electricity is only traded with the main grid in the global market when power balance is not attainable in the local market. In this work MCE campus itself acts as both aggregator and consumer.

In the rest of the paper, Section II presents a representative grid-tied MG used as the test system to verify the proposed method followed by the architecture of the MAS with the working of each agent in the SSAM energy trading model is discussed. Section III discusses the proposed bidding strategies of stakeholders. Section IV presents an SSAM energy trading model trade mechanism. Section V presents simulation results for a test system using the suggested energy trade mechanism and bidding techniques. SSAM energy trading

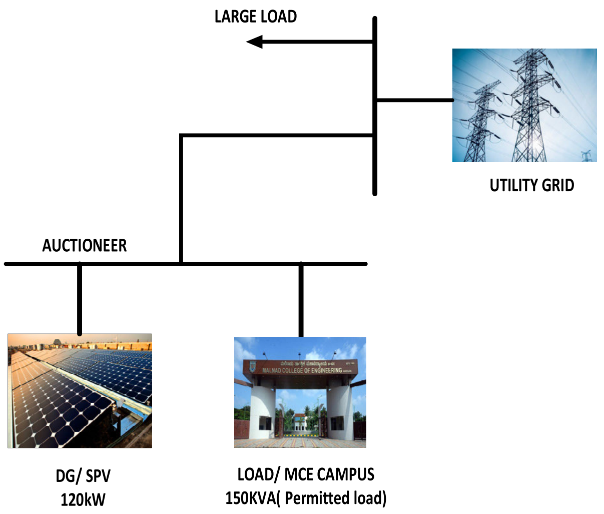

FIGURE 1. MCE grid-tied MG.

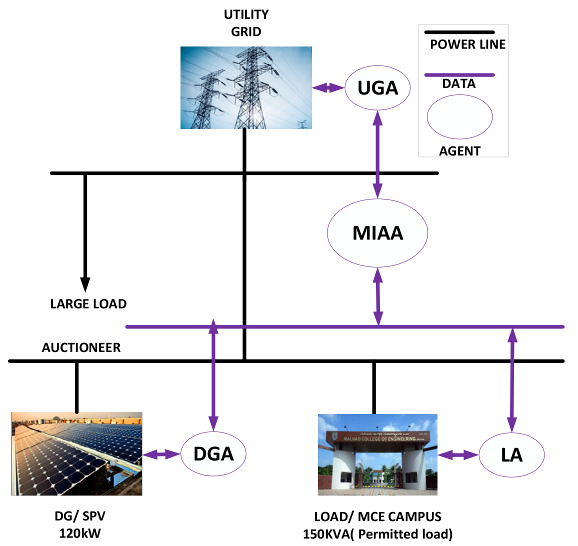

FIGURE 2. MAS architecture for MCE-MG.

model comparisons for different bidding strategies are in Section VI. Conclusions are in Section VII.

II. MAS ARCHITECTURE FOR SSAM

In this work existing bilateral contractual energy trading grid-tied MG located in MCE Hassan, Karnataka, India is considered as a test network to validate proposed bidding strategies and SSAM energy trade mechanism. Figure 1 illustrates the MCE grid tied MG. The MG has one load terminal (MCE Campus) with a 150 kVA capability and a 120 kW SPV plant. The SPV plant sold power to the MCE campus at INR 4.5/kWh, while the MCE campus bought and sold its deficit/surplus power from/to the utility grid at a rate of INR 8/kWh, functioning as an aggregator.

The MCE-MG test network's MAS architecture includes the Microgrid DG/SPV Agent (DGA), Load/MCE campus Agent (LA), Utility Grid Agent (UGA), and Microgrid Intelligent Aggregator Agent (MIAA), These agents represent different entities in the MG scenarios and are depicted in Figure 2.

MIAA is the brain of the MAS, where all the agents communicate real time date to MIAA, and act according to the decision taken by the MIAA based on real-time data and proposed SSAM market auction. The brief operation flow of the proposed MAS architecture is s as follows:

- UGA possesses the limiting prices i.e., Quoted Grid Selling Price (G_{sp}) and Quoted Grid buying Price (G_{bp}) of the grid. This information is communicated to the MIAA. It continuously monitors the real-time imbalance condition of MG and is responsible for purchasing/selling of surplus/deficit power from/to MG at the market cleared Grid Selling Price (M^{g}_{sp}) and Grid buying Price (M^{g}_{bp}) from the proposed SSAM energy trading model.
- LA holds the load consumption data of their owner (MCE Campus) and communicates the same to MIAA.
- DGA holds the day ahead real-time generation of SPV (P_S). It determines the asking price of SPV(AP_S) from the proposed LBA and FLBA and communicates the same to MIAA.
- MIAA monitors in real-time the Ps and Total load demand of MCE campus (T^{l}_{MCE}) and calculates the supply-demand mismatch of the MG (ΔP), communicating it to the DGA. Furthermore, it uses G_{sp}, G_{bp}, A_{PS} and ΔP to calculate the market cleared DGA selling (M^{Ps}_{sp}), LA buying (M^{b}_{la}), grid selling (M^{g}_{sp}) and grid buying prices (M^{g}_{bp}) from the proposed SSAM energy trading model.

III. BIDDING STRATEGIES OF STAKEHOLDERS

In the present work, the bidding quotes of the stakeholders are determined using one of the following

A. BILATERAL CONTRACTUAL PRICES

In this method, bilateral contractual price (fixed price) between SPV and MCE load is used as a quote price of SPV for all the time intervals in the market, irrespective of variation in SPV generation and MCE load demand.

B. LINEAR BIDDING ALGORITHM

A new bidding algorithm, known as LBA, is proposed in this work to analyse the behavior of bidders in an electricity market. LBA is based on a linear supply/demand function model. A more details of LBA can be found in [4] and [15]. In a grid-tied MG environment, the LBA will determine SPV asking prices.

The ask price AP_S is determined as:

$$AP_S - G_{bp} = \frac{(W^{g}_{lp} - G_{bp})}{(S_{RC} - 0.5S_{RC})} (P_S - 0.5S_{RC}) \quad (1)$$

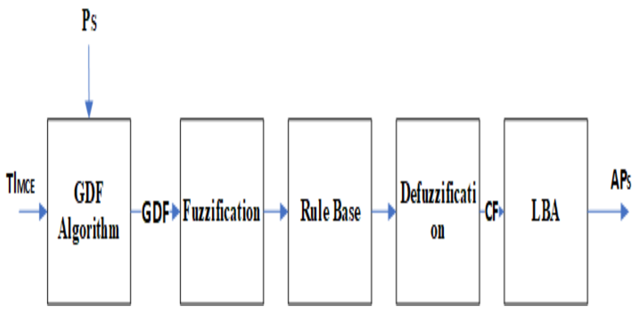

FIGURE 3. Block diagram of a SPV fuzzy control bidding system.

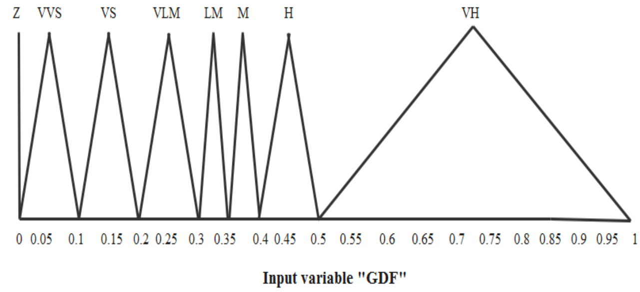

FIGURE 4. Input fuzzy sets used in fuzzy reasoning in SPV fuzzy controller bidding system.

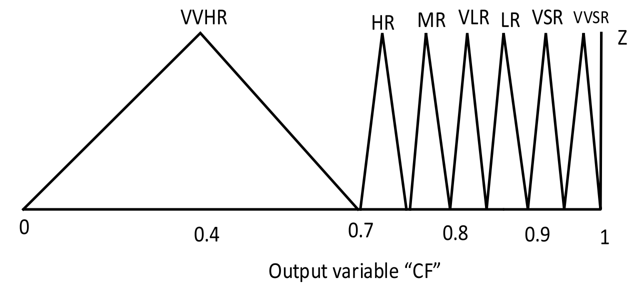

FIGURE 5. Output fuzzy sets used in fuzzy reasoning in SPV fuzzy controller bidding system.

where, S_{RC} be the rated capacity of SPV and W^{g}_{lp} be the Weighted Average of Limiting Prices of Grid.

$$W^{g}_{lp} = \frac{G_{sp} - G_{bp}}{2} \tag{2}$$

Here, the AP_S of SPV is varied from S_{RC} to 50% of S_{RC} from W^{g}_{lp} to G_{bp}. If the $P_S$is less than 50% of the S_{RC}, then the AP_S is limited to G_{bp} in order ensure minimum profit to the seller. This variation of bid prices introduces more dynamic into the market auction compared to prior bidding protocols.

C. FUZZY LOGIC BASED BIDDING ALGORITHM

In FLBA, the factors considered to determine AP_S are: P_S and S_{RC} of the SPV, and W^{g}_{lp} of the main grid. The fuzzy mechanism is used to determine the ask prices in the bidding mechanisms. A factor called Generation Difference Factor (GDF) for SPV is defined based on supply demand mismatch in MG as given in (4). This factor is used in the fuzzy mechanism as input. Fuzzified, rule base is applied, and the resulting fuzzy output is defuzzified to obtain a crisp output which is referred to as the corresponding Control Factor (CF). This CF is then used in LBA to determine AP_S of SPV using (5). The block diagram representation of a SPV fuzzy control bidding system is shown in Figure 3. The input GDF to the fuzzy controller is obtained by the GDF Algorithm. Figures 4 and 5 shows the input and output fuzzy sets used in fuzzy reasoning in SPV fuzzy controller bidding system. The range of fuzzy membership functions is determined through a trial and range procedure. The inference system operations used is 'Centroid' type of defuzzification. Table 1 contains eight IF-THEN structured fuzzy rules generated from linguistic input and output variables. Each having eight linguistic values. Input linguistic values are Zero (Z),Very Very small(VVS), Very Small (VS), Very Low Medium (VLM), Low Medium (LM), Medium (M), High (H) and Very High (VH). Output linguistic values are Very Very High Reduction (VVHR), High Reduction(VH), Medium Reduction (MR), Very Low Reduction (VLM), Low Reduction (LR), Very Small Reduction (VSR), Very Very Small Reduction (VVSR) and No Reduction (NR).

$$\Delta P = \frac{P_S}{T^{l}_{MCE}} \tag{3}$$

TABLE 1. Fuzzy rule base for SPV.

SL.NO	RULES			
1	IF	(GDF is Z)	THEN	(CF is NR).
2	IF	(GDF is VVS)	THEN	(CF is VVSR).
3	IF	(GDF is VS)	THEN	(CF is VSR)
4	IF	(GDF is VLM)	THEN	(CF is LR)
5	IF	(GDF is LM)	THEN	(CF is VLR)
6	IF	(GDF is M)	THEN	(CF is MR)
7	IF	(GDF is H)	THEN	(CF is HR)
8	IF	(GDF is VH)	THEN	(CF is VVHR)

$$\left\{ \begin{array}{l} \boldsymbol{IF}\ (T^{l}_{MCE} is > P_S) \\ GDF = \frac{(T^{l}_{MCE} - P_S)}{P_S} \\ \boldsymbol{IF}\ (T^{l}_{MCE} is \leq P_S) \\ \quad GDF = 0 \end{array} \right\} \tag{4}$$

$$AP_S - G_{bp} = \frac{(W^{g}_{lp} - G_{bp})}{(1 - 0.5)}(CF - 0.5) \tag{5}$$

IV. SSAM ENERGY TRADING MODEL

In the proposed SSAM trade mechanism, the MIAA holds market auctions between DGA (SPV plant) and LA (MCE Campus); as well as between LA and UGA. MIAA continuously monitors day-ahead:

- P_S and load demand of MCE campus (T^{l}_{MCE}) to compute ΔP, μ^{g}_{sp} and μ^{g}_{bp}.

$$\mu^{g}_{sp} = (P_S - T^{l}_{MCE}) \tag{6}$$

$$\mu^{g}_{bp} = \left(T^{l}_{MCE} - P_S\right) \tag{7}$$

- G_{sp}, G_{bp}, AP_S and ΔP to use them to calculate M_{sp}^{Ps}, M_{la}^{b} and M_{sp}^{g}/M_{bp}^{g}.

$$\left\{\begin{array}{c} IF\,\Delta P > 1 \\ M_{sp}^{Ps} = M_{la}^{b} = M_{bp}^{g} = G_{bp} = AP_S \\ IF\,\Delta P < 1 \\ M_{sp}^{Ps} = M_{la}^{b} = M_{bp}^{g} = \\ \left\{\frac{AP_S+[(1+(1-\Delta P))*AP_S]}{2}\right\} \end{array}\right\} \quad (8)$$

$$\left\{\begin{array}{c} IF\,\Delta P > 1 \\ M_{sp}^{g} = \frac{AP_S+G_{sp}}{2} \\ IF\,\Delta P < 1 \\ M_{sp}^{g} = \left[\begin{array}{c}(1+(1-\Delta P)) * \\ \frac{AP_S+G_{sp}}{2}\end{array}\right] \end{array}\right\} \quad (9)$$

- Based on M_{la}^{b} and M_{sp}^{g} in the respective time intervals, MIAA determines the Load Clearing Price (l_{cp}) as

$$l_{cp} = \left[\frac{(P_S * M_{la}^{b}) + (\mu_{bp}^{g} * M_{sp}^{g})}{T_{MCE}^{l}}\right] \quad (10)$$

V. MARKET SIMULATION

The MAS architecture of MCE-MG illustrated in Fig. 2 is simulated in MATLAB/SIMULINK to validate the proposed bidding strategies and SSAM energy trading model. The simulation divides a day into 24 time blocks, and each time block is taken into consideration as one hour. The length of these time blocks can be changed as necessary. The change time blocks necessitate to take average of kWh per hour of consumption based on number of time blocks within an hour. The change in time blocks not make any potential impact on the analysis, but it needs to make little bit modification in the process of calculating the kWh for respective time blocks.

The proposed SSAM energy trading model is simulated for three different cases considering contractual price as a fixed AP_S of SPV irrespective of variation in P_S, AP_S of SPV from LBA and AP_S of SPV from proposed FLBA respectively. These results are also compared with the load profile and corresponding bill of MCE campus without SPV and the existing bilateral contractual trading model between the SPV plant and the MCE campus.

A. MCE CAMPUS WITHOUT SPV (SUPPLY FROM GRID ONLY)

This is an illustration of the conventional one-way DN and fixed tariff market. Before the signing of the bilateral agreements between the SPV plant and the MCE campus, all power demands of the latter were provided by the utility grid at G_{sp} (INR 8/kWh). Table 2 outlines the one day load profile and corresponding bill of the MCE campus. The total bill paid by MCE to utility grid of a day is INR 8440.

B. EXISTING BILATERAL CONTRACTUAL TRADING MODEL OF MCE-MG

This case covers active MG with SPV integration. A simulation of the existing bilateral contractual trading model with MCE and SPV units being integrated using the existing contractual prices (G_{sp}/G_{bp}) as the fixed market cleared price. Where MCE G_{bp} is the bilateral contractual fixed trade price between SPV and MCE, and G_{sp} is the bilateral contractual fixed trade price between MCE and utility grid. Table 3 shows the hour-wise actual P_S of the SPV Plant, the load profile of the MCE campus, and the respective market cleared prices/kWh for the day of the simulation with the existing bilateral contractual trading model. This is the base case.

For the base case, the limiting prices of the grid, i.e., G_{sp}, are taken as INR 8/kWh and G_{bp}, as INR 4.5/kWh (Contractual SPV trading price to MCE campus) for market analysis. (e.g.: In time block 13, MIAA buys 90kW from SPV at INR 4.5/kWh and 20kW of deficit power from grid at INR 8/kWh to meet 110kW of demand. In this time block l_{cp} from existing bilateral contractual trade mechanism is INR 5.136/kWh). In this case SPVB is INR 2655, bill paid by MCE to utility is INR 3720 (difference of UGSLB and EB) and total bill of the MCE of the day is INR 6262.50 (difference of TLB and EB).

C. SSAM MARKET AUCTION USING BILATERAL CONTRACTUAL PRICE AS AP_S OF SPV

In this case, the market is simulated using bilateral contractual price (G_{bp}) as quote price (AP_S) of SPV plant and, G_{sp} and G_{bp} as a limiting price of grid for all time intervals in SSAM market auction. The SSAM market auction trading details are summarized in Table 4. When P_S is not available (time intervals 1 to 7 and 19 to 24), the MIAA purchase required power from the grid at M_{sp}^{g} to meet the load demand of LA.

TABLE 2. Load profile of MCE campus without SPV (supply from grid only).

Sl. No	TIME BLOCK	MCE LOAD PROFILE	
		Load*/G_{sp}	BILL/hour
1	1	20/8	160
2	2	20/8	160
3	3	20/8	160
4	4	20/8	160
5	5	20/8	160
6	6	20/8	160
7	7	15/8	120
8	8	15/8	120
9	9	15/8	120
10	10	70/8	560
11	11	70/8	560
12	12	100/8	800
13	13	110/8	880
14	14	80/8	640
15	15	120/8	960
16	16	100/8	800
17	17	110/8	880
18	18	15/8	120
19	19	15/8	120
20	20	20/8	160
21	21	20/8	160
22	22	20/8	160
23	23	20/8	160
24	24	20/8	160

*: kW; Bill paid by MCE to utility = INR 8440

TABLE 3. Generation and load profile of existing bilateral contractual trading model of MCE-MG.

Sl.No	TIME BLOCK	SPV		LOAD PROFILE						EXPORT POWER TO GRID	
				SPV POWER* CONSUMPTION		GRID POWER * COSUMPTION		TOTAL LOAD* CONSUMPTION			
		P_S/CQP	SPV BILL	P_S /CQP	SPV-BILL	UG/G_{sp}	UG-BILL	TL/l_{CP}	TL-BILL	E/G_{bp}	E-BILL
1	1	0/4.5	0	0	0	20/8	160	20/8	160	0	0
2	2	0/4.5	0	0	0	20/8	160	20/8	160	0	0
3	3	0/4.5	0	0	0	20/8	160	20/8	160	0	0
4	4	0/4.5	0	0	0	20/8	160	20/8	160	0	0
5	5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
6	6	0/4.5	0	0	0	20/8	160	20/8	160	0	0
7	7	0/4.5	0	0	0	15/8	120	15/8	120	0	0
8	8	20/4.5	90	15/4.5	67.50	0	0	15/4.5	67.50	5/8	40
9	9	25/4.5	112.5	15/4.5	67.50	0	0	15/4.5	67.50	10/8	80
10	10	40/4.5	180	40/4.5	180	30/8	240	70/6	420	0	0
11	11	50/4.5	225	50/4.5	225	20/8	160	70/5.5	385	0	0
12	12	80/4.5	360	80/4.5	360	20/8	160	100/5.2	520	0	0
13	13	90/4.5	405	90/4.5	405	20/8	160	110/5.136	565	0	0
14	14	75/4.5	337.5	75/4.5	337.5	5/8	40	80/4.75	377.5	0	0
15	15	70/4.5	315	70/4.5	315	50/8	400	120/5.958	715	0	0
16	16	70/4.5	315	70/4.5	315	30/8	240	100/5.55	555	0	0
17	17	45/4.5	202.5	45/4.5	202.5	65/8	520	110/6.56	722.5	0	0
18	18	25/4.5	112.5	15/4.5	67.50	0	0	15/4.5	67.50	10/8	80
19	19	0/4.5	0	0	0	15/8	120	15/8	120	0	0
20	20	0/4.5	0	0	0	20/8	160	20/8	160	0	0
21	21	0/4.5	0	0	0	20/8	160	20/8	160	0	0
22	22	0/4.5	0	0	0	20/8	160	20/8	160	0	0
23	23	0/4.5	0	0	0	20/8	160	20/8	160	0	0
24	24	0/4.5	0	0	0	20/8	160	20/8	160	0	0
		SPVB =INR 2655		SPVSLB = INR 2542.5		UGSLB= INR3920		TLB= INR 6462.5		EB= INR 200	

1. Bill paid by MCE to utility grid = UGSLB – EB = INR 3920 - INR 200 = INR 3720.
2. Total bill paid by MCE = TLB-EB = INR 6462.5 –INR 200 =INR 6262.50

(e.g.: during time block 2, MIAA purchase 20kW from grid at INR 8/kWh). Similarly, when there is -surplus power (time interval 8,9 and 18), the MIAA sell the surplus power to the grid at M^{g}_{bp}(e.g.: In time block 8, MIAA sell 10kW of surplus power to grid at INR 4.5/kWh). During the time intervals 10 to 17, MIAA purchase the deficit power from the grid at M^{g}_{sp} (e.g.: In time block 13, MIAA buys 90kW from SPV at INR 4.90/kWh and 20kW of deficit power from grid at INR - 7.386/kWh to meet 110kW of demand. In this time block l_{cp} from proposed SSAM trade mechanism is INR 5.35/kWh). In this case SPVB is INR 2952.59, bill paid by MCE to utility is INR 3778.425 and total bill of the MCE of the day is INR 6618.51.

D. SSAM MARKET AUCTION USING AP_S OF SPV FROM LBA

In this case, the LBA is used to compute the AP_S of SPV for all time intervals in the SSAM market auction. Table 5 summarizes the SSAM market auction trading details with respect to SPV plant and load (MCE campus). It can be seen from Table 5 that the power trading manner is similar to SSAM market auction for a bilateral contractual price, except that M^{Ps}_{sp}, M^{b}_{la}, M^{g}_{bp}, M^{g}_{sp} and l_{cp} are determined by the SSAM market auction for LBA based quote prices. (e.g.: In time block 13, MIAA buys 90kW from SPV at INR 5.864/kWh and 20kW of deficit power from grid at INR 7.903/kWh to meet 110kW of demand. In this time block l_{cp} from proposed SSAM trade mechanism is INR 6.23/kWh). In this case SPVB is INR 3163.32, bill paid by MCE to utility is INR 3796.92 and total bill of the MCE of the day is INR 6847.74.

E. SSAM MARKET AUCTION USING AND AP_S OF SPV FROM PROPOSED FLBA

In this case, AP_S of SPV plant for all time intervals in SSAM market auction are calculated by proposed FLBA. Table 6 provides details regarding the power trading in the market auction using the FLBA-based quote prices. This is similar to the SSAM market auction with a bilateral contractual price as quote prices; however, M^{Ps}_{sp}, M^{b}_{la}, M^{g}_{bp}, M^{g}_{sp} and l_{cp} are now determined by the FLBA-based quote prices. (e.g.: In time block 13, MIAA buys 90kW from SPV at INR 5.982/kWh and 20kW of deficit power from grid at INR 7.172/kWh to meet 110kW of demand. In this time block l_{cp} from proposed SSAM trade mechanism is INR 6.19/kWh). In this case SPVB is INR 3316.25, bill paid by MCE to utility is INR 3707.84 and total bill of the MCE of the day is INR 6920.14.

VI. COMPARATIVE ANALYSIS OF SSAM ENERGY TRADING MODEL FOR PROPOSED BIDDING STRATEGIES

Figure 6 summarizes the comparison of AP_S and M^{Ps}_{sp} of SPV in SSAM market auction for bilateral contractual price LBA and FLBA based quote prices. During the intervals 1 to 7 and

TABLE 4. Generation and load profiles of MCE-MG in SSAM market auction using bilateral contractual price as AP_S of SPV.

Sl.No	TIME BLOCK	SPV			MCE LOAD PROFILE						EXPORT POWER TO GRID	
					SPV POWER* CONSUMPTION		GRID POWER* COSUMPTION		TOTAL LOAD* CONSUMPTION			
		P_S/AP_S	P_S/M_{sp}^{Ps}	SPV-BILL	Ps/M_{la}^{b}	SPV-BILL	UG/M_{sp}^{g}	UG-BILL	TL/l_{cp}	TL-BILL	E/M_{bp}^{g}	E-BILL
1	1	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
2	2	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
3	3	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
4	4	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
5	5	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
6	6	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
7	7	0/4.5	0/4.5	0	0	0	15/8	120	15/8	120	0	0
8	8	20/4.5	20/4.5	90	15/4.5	67.50	0	0	15/4.5	67.50	5/4.5	22.50
9	9	25/4.5	25/4.5	112.5	15/4.5	67.50	0	0	15/4.5	67.50	10/4.5	45
10	10	40/4.5	40/5.375	215	40/5.375	215	30/8	240	70/6.50	455	0	0
11	11	50/4.5	50/5.143	257.15	50/5.143	257.15	20/8	160	70/5.95	417.15	0	0
12	12	80/4.5	80/4.95	396	80/4.95	396	20/7.5	150	100/5.46	546	0	0
13	13	90/4.5	90/4.90	441	90/4.90	441	20/7.386	147.72	110/5.35	588.72	0	0
14	14	75/4.5	75/4.641	348.07	75/4.641	348.07	5/6.641	33.205	80/4.76	381.27	0	0
15	15	70/4.5	70/5.375	376.25	70/5.375	376.25	50/8	400	120/6.46	776.25	0	0
16	16	70/4.5	70/5.175	362.25	70/5.175	362.25	30/8	240	100/6.02	602.25	0	0
17	17	45/4.5	45/5.375	241.87	45/5.375	241.87	65/8	520	110/6.92	761.87	0	0
18	18	25/4.5	25/4.5	112.5	15/4.5	67.50	0	0	15/4.5	67.50	10/4.5	45
19	19	0/4.5	0/4.5	0	0	0	15/8	120	15/8	120	0	0
20	20	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
21	21	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
22	22	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
23	23	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
24	24	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
		SPVB=INR2952.59			SPVSLB=INR2840.09		UGSLB=INR 3890.925		TLB=INR 6731.01		EB= INR112.50	

1. Bill paid by MCE to utility grid = UGSLB – EB = INR 3890.925 - INR 112.50 = INR 3778.425.
2. Total bill paid by MCE = TLB-EB = INR 6731.01 - INR 112.5=INR 6618.51

19 to 24, P_S is zero; hence SPV plant is not participating in SSAM market auction. During the time intervals 8, 9 and 18, P_S of SPV is higher than load demand; therefore, M_{sp}^{Ps} is same as AP_S/Gbp (INR 4.5/kWh) for all the three bidding methods. During the time intervals 10 to 17, demand is higher than P_S. In such intervals, M_{sp}^{Ps} will vary differently for contractual price as a fixed AP_S of SPV irrespective of variation in P_S, AP_S of SPV from LBA and AP_S of SPV from proposed FLBA respectively. (M_{sp}^{Ps} are between Gbp and W_{lp}^{g} based on ΔP).From this, it is observed that, in the time interval 10 to14 and 16, M_{sp}^{Ps} from FLBA based AP_S are higher than LBA based AP_S, while at the time interval 15 and 17, M_{sp}^{Ps} from FLBA based AP_S are lesser than LBA based AP_S. This is because, in LBA AP_S depends on variation in SPV generation, whereas in FLBA AP_S is depends on ΔP of MG. The corresponding M_{sp}^{Ps} from the proposed SSAM trading model depends on AP_S and ΔP for both LBA and FLBA. From the overall comparison, it is observed that, the proposed FLBA based quote prices in SSAM market auction increases the profit margin of SPV compared to bilateral contractual price and LBA based quote prices. It is also observed that the difference between AP_S and M_{sp}^{Ps} is lesser in FLBA based quote prices in SSAM market auction compared to bilateral contractual price and LBA based quote prices. Thus, the proposed FLBA based quote prices in SSAM market auction conduct ethical trading between the stakeholders.

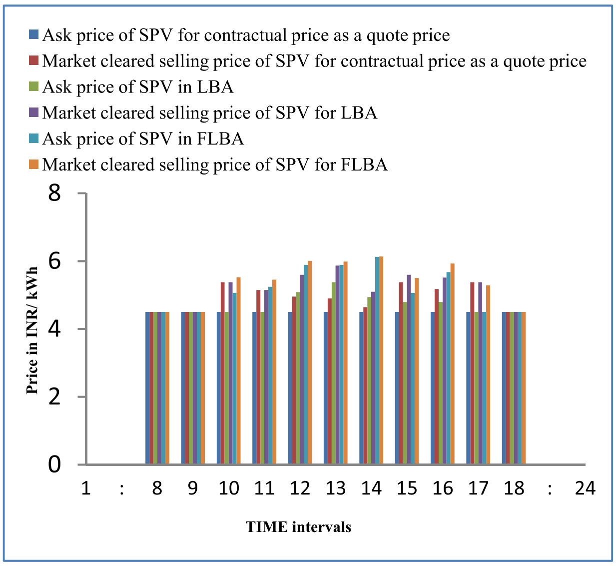

FIGURE 6. Comparison of AP_S and M_{sp}^{Ps} in SSAM market auction for bilateral contractual price, LBA and FLBA based quote prices.

Figure 7 presents the comparison of M_{sp}^{g} of the load for contractual price, LBA and FLBA based quote prices in the SSAM market auction. During the time intervals 1 to 7 and 19 to 24, SPV plant generation is zero and hence load demand is met by purchasing the power from the grid at M_{sp}^{g}

TABLE 5. Generation and load profile of MCE-MG in SSAM market auction using AP_S of SPV from LBA.

Sl. No	TIME BLOCK	SPV			MCE LOAD PROFILE						EXPORT POWER TO GRID	
					SPV POWER* CONSUMPTION		GRID POWER* COSUMPTION		TOTAL LOAD* CONSUMPTION			
		P_S/AP_S	P_S/M_{sp}^{Ps}	SPV-BILL	Ps/M_{la}^{b}	SPV-BILL	UG/M_{sp}^{g}	UG-BILL	TL/l_{cp}	TL-BILL	E/M_{bp}^{g}	E-BILL
1	1	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
2	2	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
3	3	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
4	4	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
5	5	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
6	6	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
7	7	0/4.5	0/4.5	0	0	0	15/8	120	15/8	120	0	0
8	8	20/4.5	20/4.5	90	15/4.5	67.5	0	0	15/4.5	67.5	5/4.5	22.5
9	9	25/4.5	25/4.5	112.5	15/4.5	67.5	0	0	15/4.5	67.5	10/4.5	40
10	10	40/4.5	40/5.375	215	40/5.375	215	30/8	240	70/6.5	455	0	0
11	11	50/4.5	50/5.143	257.15	50/5.143	257.15	20/8	160	70/5.95	417.15	0	0
12	12	80/5.083	80/5.592	447.36	80/5.592	447.36	20/7.85	157	100/6.04	604.36	0	0
13	13	90/5.375	90/5.864	527.76	90/5.864	527.76	20/7.903	158.06	110/6.23	685.82	0	0
14	14	75/4.938	75/5.092	381.9	75/5.092	381.9	5/6.873	34.365	80/5.20	416.26	0	0
15	15	70/4.792	70/5.594	391.58	70/5.594	391.58	50/8	400	120/6.59	791.58	0	0
16	16	70/4.792	70/5.51	385.7	70/5.51	385.7	30/8	240	100/6.25	625.7	0	0
17	17	45/4.5	45/5.375	241.87	45/5.375	241.87	65/8	520	110/6.92	761.87	0	0
18	18	25/4.5	25/4.5	112.5	15/4.5	67.5	0	0	15/4.5	67.5	10/4.5	40
19	19	0/4.5	0/4.5	0	0	0	15/8	120	15/8	120	0	0
20	20	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
21	21	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
22	22	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
23	23	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
24	24	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
		SPVB=INR 3163.32			SPVSLB=INR 3050.82		UGSLB=INR 3909.425		TLB=INR 6960.24		EB= INR 112.5	

1. Bill paid by MCE to utility grid = UGSLB – EB = INR 3909.425- INR 112.5= INR 3796.92
2. Total bill paid by MCE = TLB-EB = INR 6960.24 - INR112.5 = INR 6847.74

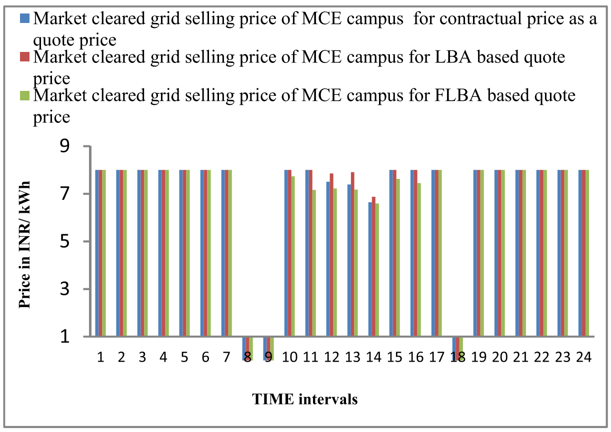

FIGURE 7. Comparison of M_{sp}^{g} of load/MCE campus.

(INR 8/kWh) for all the three bidding methods. During the time intervals 8, 9 and 18, P_S is higher than load demand; and hence no power from grid is required. During the time intervals 10 to 17, additional power is required from the grid. The corresponding M_{sp}^{g} (which is same as market cleared MG buying price) is different for the three bidding methods; among the three the M_{sp}^{g} based on FLBA is the least. (e.g.: In time interval 13, 20kW is additional power requirement from the grid, the corresponding M_{sp}^{g} are INR 7.386 /kWh,INR 7.906/kWh and INR 7.172/kWh from proposed SSAM trading model for contractual price as a fixed AP_S of SPV,AP_S of SPV from LBA and AP_S of SPV from proposed FLBA respectively).

The Figure 8 compares SPV plant bills (SPVB) of a day in the SSAM market auction for four different cases: existing fixed contractual price, and contractual price as a fixed AP_S of SPV, AP_S of SPV from LBA and AP_S of SPV from proposed FLBA respectively. The results show an increase in the seller's profit for the proposed SSAM market auction compared to the current fixed contractual trading model. Of the four cases presented, the highest profit is yielded when using the FLBA based quote price, which demonstrates the advantages of this trade mechanism.

Figure 9 compares the daily bills paid by MCE to the utility grid in the SSAM market auction for four different cases: existing fixed contractual price, and contractual price as a fixed AP_S of SPV, AP_S of SPV from LBA and AP_S of SPV from proposed FLBA respectively. The results show a increase in the purchase price from the utility grid in the proposed SSAM market auction for contractual price as a fixed AP_S of SPV and AP_S of SPV from LBA compared to the current fixed contractual trading model. Whereas there is a decrease in purchase price from the utility grid in the proposed SSAM market auction for AP_S of SPV from proposed FLBA compared to the current fixed contractual trading

TABLE 6. Generation and load profile of MCE-MG in SSAM market auction using AP_S of SPV from FLBA.

Sl.No	TIME BLOCK	SPV			MCE LOAD PROFILE						EXPORT POWER TO GRID	
					SPV POWER* CONSUMPTION		GRID POWER* COSUMPTION		TOTAL LOAD* CONSUMPTION			
		P_S/AP_S	P_S/M_{sp}^{Ps}	SPV-BILL	Ps/M_{la}^{b}	SPV-BILL	UG/M_{sp}^{g}	UG-BILL	TL/l_{cp}	TL-BILL	E/M_{bp}^{g}	E-BILL
1	1	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
2	2	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
3	3	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
4	4	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
5	5	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
6	6	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
7	7	0/4.5	0/4.5	0	0	0	15/8	120	15/8	120	0	0
8	8	20/4.5	20/4.5	90	15/4.5	67.5	0	0	15/4.5	67.5	5/4.5	22.5
9	9	25/4.5	25/4.5	112.5	15/4.5	67.5	0	0	15/4.5	67.5	10/4.5	45
10	10	40/5.058	40/5.286	211.44	40/5.523	211.44	30/7.728	231.84	70/6.6.46	452.76	0	0
11	11	50/5.238	50/5.452	272.6	50/5.452	272.6	20/7.159	143.18	70/5.93	415.78	0	0
12	12	80/5.885	80/6.003	480.24	80/6.003	480.24	20/7.22	144.4	100/6.24	624.64	0	0
13	13	90/5.885	90/5.982	538.38	90/5.982	538.38	20/7.172	143.44	110/6.19	681.82	0	0
14	14	75/6.122	75/6.134	460.05	75/6.134	460.05	5/6.59	32.95	80/6.16	493	0	0
15	15	70/5.058	70/5.497	384.79	70/5.497	384.79	50/7.62	381	120/6.38	765.79	0	0
16	16	70/5.672	70/5.928	414.96	70/5.928	414.96	30/7.451	223.53	100/6.38	638.49	0	0
17	17	45/4.5	45/5.286	237.87	45/5.286	237.87	65/8	520	110/6.88	757.87	0	0
18	18	25/4.5	25/4.5	112.5	154.5	67.5	0	0	15/4.5	67.5	10/4.5	45
19	19	0/4.5	0/4.5	0	0	0	15/8	120	15/8	120	0	0
20	20	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
21	21	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
22	22	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
23	23	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
24	24	0/4.5	0/4.5	0	0	0	20/8	160	20/8	160	0	0
		SPVB=INR 3316.25			**SPVSLB=INR 3302.83**		**UGSLB=INR 3820.34**		**TLB=INR 7032.64**		**EB= INR112.5**	

1. Bill paid by MCE to utility grid = UGSLB – EB = INR 3820.34 -INR 112.5 = INR 3707.84
2. Total bill paid by MCE = TLB-EB = INR7032.64 - INR112.5= INR 6920.14

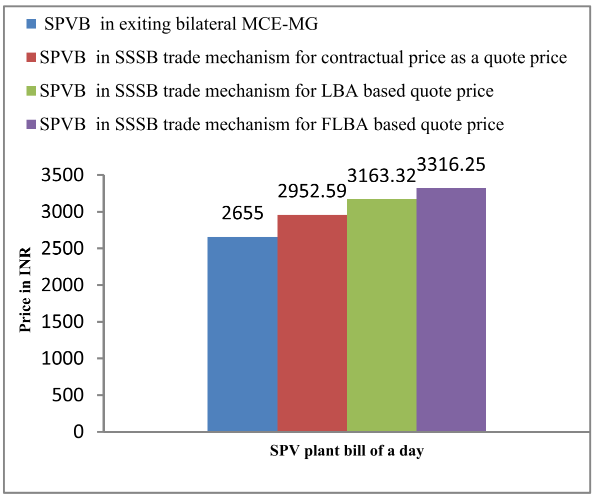

FIGURE 8. Comparison of SPV plant bill.

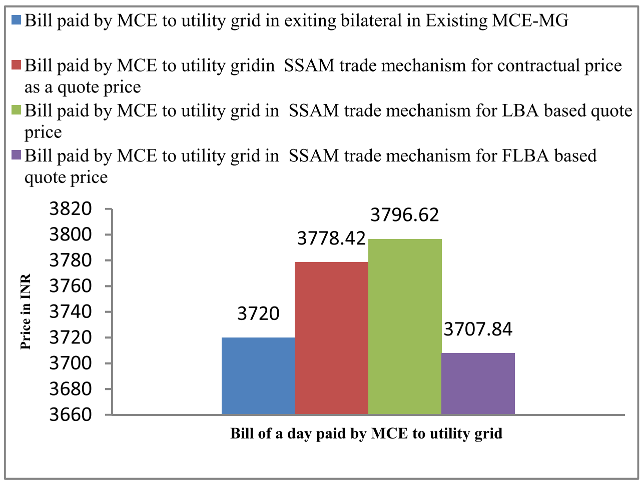

FIGURE 9. Comparison of Bill paid by MCE to utility.

model, which demonstrates the advantages of FLBA based SSAM trade mechanism.

Figures 6–9 highlight the advantages of the FLBA-based SSAM trade mechanism compared to other trade mechanisms in increasing the profit margin of SPV in all aspects. The boost in profit margin of SPV is mainly due to the proposed FLBA, because in FLBA both variation in power generation and supply-demand mismatch in MG are considered to compute the AP_S of SPV.

Figure 10 compares the total bill paid by MCE in different cases of market auctions. The overall bill of a day with an SPV plant is less than the bill without the SPV plant. The case with the existing fixed bilateral contract generates the lowest bill out of the three different cases: contractual price as a fixed AP_S of SPV, AP_S of SPV from LBA and AP_S of SPV from proposed FLBA in SSAM trading model respectively. These results indicate an improvement to the profit share of the SPV plant (seller) in MCE-MG. This improvement is due to the increase in SPVB from proposed SSAM trading model for different bidding strategies.

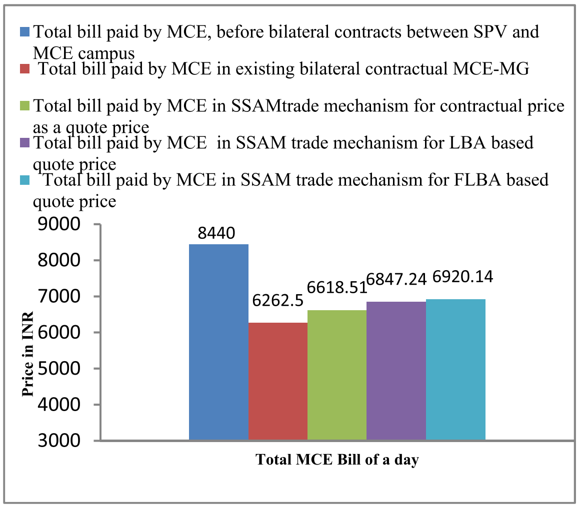

FIGURE 10. Comparison of total MCE bill.

VII. CONCLUSION

This paper explores the performance and effects of a proposed SSAM energy trading model on a grid-tied MG, using contractual, LBA, and FLBA based quote prices. To investigate its functionality in practice, a hybrid MAS system was designed to incorporate the required agents to simulate the model. Through the simulation, the performance of both existing energy transactions and those executed via the SSAM trading model were examined, considering the mean profit of the SPV seller. Results suggest that the proposed trading model boosts SPV profits in spite of competition limitations, as there is only a single seller and buyer. Overall, the simulation results are evidence of how effective the proposed bidding algorithms and SSAM trading model are at increasing SPV profits.

The outcome of this work can be summarized as follows:

- A novel SSAM energy trade mechanism has been designed to maximize the profit margin of the seller, by modifying the existing bilateral contractual model for the grid integrated MG, taking into account the supply-demand mismatch of the MG and the limiting prices of the grid.
- New strategic bidding algorithms: LBA based on variation in power generation and, FLBA based on variation in power generation and supply-demand mismatch in MG are developed to compute ask quotes of sellers for enhanced market dynamics.

The goal of the SSAM-based energy trade mechanism and single-sided bidding strategy is to boost the seller's profit margin. On the other hand, the implementation of double-sided bidding strategy and double-sided auction mechanisms will boost both the seller's and buyer's profit margin.

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HIREKERI MALLESHAPPA MANJUNATHA received the B.E. degree in electrical and electronics engineering, the M.Tech. degree in computer application in industrial drives, and the Ph.D. degree from Visvesvaraya Technological University, Belagavi, Karnataka, India, in 2009, 2012, and 2022, respectively.

He is currently an Assistant Professor with the Bapuji Institute of Engineering and Technology, Davanagere, affiliated to Visvesvaraya Technological University. His main research interests include power system operation and control, distribution automation, artificial intelligence tools applied to smart grids, and energy trading.

GARIGHATTA KRISHNAIAH PURUSHOTHAMA received the M.Tech. degree in electrical engineering from the Indian Institute of Technology, Madras (IITM), in 1992, and the Ph.D. degree from the Indian Institute of Science, Bengaluru, in 2001. He has worked at various academic positions with the Electrical and Electronics Engineering Department, Malnad College of Engineering, Hassan. He has over 60 international and national journal/conference research publications to his credit. His research areas are power system operation and control, AI tools in power systems, smart grids, and distribution networks.

YASHWANTH NANJAPPA (Senior Member, IEEE) received the B.E. degree in electronics and communication engineering from Visvesvaraya Technological University, Belagavi, in 2010, the M.Tech. degree in signal processing and VLSI from Jain University, Bengaluru, in 2012, and the Ph.D. degree from Visvesvaraya Technological University, in 2020. He is currently an Assistant Director (FDW) and an Assistant Professor (Senior Scale) with the Department of Electronics and Communication Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, where he is actively undertaking numerous administrative and academic roles. His primary research interests include wireless sensor networks, communication systems, antennas, VLSI technology, and cyber security.

RAGHAVENDRAPRASAD DESHPANDE received the Ph.D. degree from Visvesvaraya Technological University, Belagavi, Karnataka, India, in 2020.

He is an Associate Professor with the GSSS Institute of Engineering and Technology for Women, Mysuru, affiliated to Visvesvaraya Technological University. His areas of research interests include smart grids, power quality issues in DGs, renewable energy sources, machine learning techniques applied to smart grids, and digital signal processing applications to power systems.