Heuristic Multi-Agent Control for Energy Management of Microgrids with Distributed Energy Sources

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***Abstract*—The increased integration of distributed Renewable Energy Sources (RESs) and adoption of Electric Vehicles (EVs) require appropriate control and management of energy sources and EV charging. This becomes critical at the distribution system level, especially at a microgrid (MG) level. This control is required not only to mitigate the negative impacts of intermittent generation from RESs but also to make better use of available energy, reduce carbon footprint, maximize the overall profit of microgrid and increase energy autonomy by effective utilization of battery storage. This paper proposes a heuristic multi-agent based decentralized energy management approach for grid-connected MG. The MG comprises of active (controlled) and passive (uncontrolled) electrical loads, a photovoltaic (PV) system, battery energy storage system (BESS) and a charging post for electric vehicles. The proposed approach is aimed at optimizing the use of local energy generation from photovoltaic and smart energy utilization to serve electrical loads and EV as well as maximizing MG profit. The aim of the energy management is to supply local consumption at minimum cost and less dependency on the main grid supply. Utilizing energy available from RESs (PV and BESS), customers satisfaction (fulfilling local demand), considering uncertainty of renewable generation and load consumption and also taking into account technical constraint are the main strengths of the presented framework. Performance of the proposed algorithm is investigated under different operating conditions and its efficacy is verified.**

Keywords—Multi-agent control, energy management, distributed energy, storage system, electric vehicle

I. INTRODUCTION

Microrgrids (MGs) present an excellent environment for deployment and increased utilization of renewable energy sources, resulting in a sustainable energy supply [1, 2]. MGs focus on combining local generations with cluster of loads in a geographical proximity usually self-governed or controlled as a single controllable entity, serving as an integral part of a smart grid. The cost associated with the enhancement of current power system infrastructure and the global environmental concerns necessitate the development of a smart grid infrastructure that is capable of meeting existing and future energy demands. To this end, MGs present one of the best solutions to meet local energy demand from local renewable energy sources (RESs); thus, reduce or even eliminate the need for grid reinforcement (extra grid capacity) to meet the continuous increase in energy demand [3]. MGs allow better utilization of RESs, storage systems and participation of consumers in the optimal management of power system operation.

In the micro-grid, local renewable generation resources, such as photovoltaic (PV) systems, are utilized to supply part or all the electricity demand reducing the dependency on the grid infrastructure and traditional energy sources. The storage assets on the other hand are essential to time shift energy/power to compensate for the time mismatch between demand and generation, and in some cases to maximize the system profit by following varying electricity tariff. Thus, providing the degree of freedom that is required to optimize the utilization of the grid and implement advanced control strategies. However, the penetration RESs affects the system dynamics and also increases the complexity due to their intermittent and largely unpredictable nature. Therefore, the control strategies that can ensure optimum, dynamic and smooth system operation are required [2]. The energy management system in a MG is required to (a) support the grid by maintaining demand–supply balance, b) deal with intermittent nature of RES generation, (c) increase energy autonomy, (d) increase MG profit, and (e) ensure system reliability and flexibility.

The centralized control scheme (CCS) focuses on using a central controller for energy management of various sources in a MG (such as batteries and renewable energy sources etc.). The CCS however may experience a single-point failure affecting the overall operation of power system, reducing thus the reliability and also increases the measurements and communication links. The decentralized approach (DCS) on the other hand considers each unit in the system as a separate agent having intelligence of making decisions and control actions and presents improved fault tolerance and controllability. In this way, multi-agent system (MAS) distributed solve problems in a system by splitting subtasks and allocating it to individual unit [4]. Consequently, it helps in dealing with the unpredictable nature of RESs while satisfying the varying load demand with minimum cost and dependency on the main grid.

Many studies suggesting the use of MAS for power system has been discussed by earlier researchers. The application of multiagent systems for power system operation and control is discussed and summarized in [4-6]. Energy management based on multiagent control for addressing the problem of energy imbalance in a MG and sharing of resources among various MGs is discussed in [7]. A genetic algorithm (GA) for energy management of grid-connected MG is discussed in [8] for agent-based control. Economic dispatch using optimization based multiagent algorithm for distributed RES is presented in [9]. Energy management of RES using a two-level framework for multiple MGS is discussed in [10]. Multi-agent-based control and energy management approaches for multi-energy integrated system is discussed in [11]. A layered based multiagent control is proposed in [12], where at first power balance is enabled using PV and after that the main controllable components are diesel generators. However, the storage systems are not involved in the energy management and EV allocation is not discussed. A MAS controlling battery and load agents based on uncontrolled PV and wind is discussed in [13] for energy management in a MG with considering cost. A framework supplying load via uncontrolled wind and controlled PV is presented in [14] for limiting the power usage from the grid. However, storage system is not included in the formulation and energy provision. A decentralized MAS is presented in [15] for managing MG cluster and within each MG power dispatch with the objective of minimizing power exchange with the grid. The PV and wind systems however are not utilized to their full potential.

In this paper, a heuristic multiagent approach aimed at maximizing the use of energy from photovoltaic together with a battery storage are proposed to serve electrical loads and EV charging. The proposed approach continuously monitors the time of the day and respective electricity prices, and in this way, smart energy utilization is enabled, and MG profit is maximized. The primary aim of energy management is to supply the consumption of customer agents with minimum operational cost of the microgrid and less dependency on the main grid.

The main contributions of this paper are:

1. Developing a decentralized MAS based energy management approach for grid-connected MG considering distributed energy sources and local electrical loads, thus enhancing the performance of the MG.
2. Development of a decentralized control of converters (for connecting distributed energy sources), considering each entity as a separate agent.
3. Considering the technical constraints of RES generations and storage batteries as well as the stochastic behavior of RES generations and demand of all customer agents, concurrently.
4. Online smart energy management framework to support balance between supply and demand.
5. Intelligent energy management to supply agents' (customers') energy demand with minimum cost and less dependency on the main grid.
6. Development of a Simulink model for the MG system to analyze the performance of proposed multi-agent controller.

The paper is organized as follows: Section II describes the microgrid modelling, its configuration, and specifications along with technical constraints; Section III elucidates the proposed multiagent control and energy management of microgrid. The simulation results are presented in Section IV and paper concludes in Section V.

II. MICROGRID MODELLING

The schematic diagram of different agents in a MG is shown in Fig. 1. The MG comprises of photovoltaic system, electrical battery energy storage system (BESS), electric vehicle, and active and passive electrical loads. All the agents are connected to the AC grid at the point of common coupling (PCC) via a three-phase link. The DC-sides of the agents are independent of each other. The power generation by the PV agent follows the maximum power point tracking (MPPT) control and is uncontrolled by the MG user. The power generated by PV is consumed locally and any surplus is exported to the grid. There are two types of load agents in the MG that need to be met; uncontrollable AC loads (e.g. lighting, TV, etc.) and controlled active loads (e.g. washing machine, dishwasher, etc.). Due to the uncertainties of power production from RES and customers' energy demand, MGs usually need to exchange electrical power with the main grid. The active loads are unidirectional (modelled using power electronic converter and batteries) and allow load curtailment in case of lower local generation to meet the demand. The EV agent is modelled as a battery with bi-directional power flow control via power electronic converter (charger). This allows control of flow of power considering user requirements, such as required state of charge (SOC) or target miles as well as operation in Vehicle to Grid (V2G) mode, where the EV supply power to the MG [16, 17]. The storage agent allows bi-directional power flow and helps to support the grid by

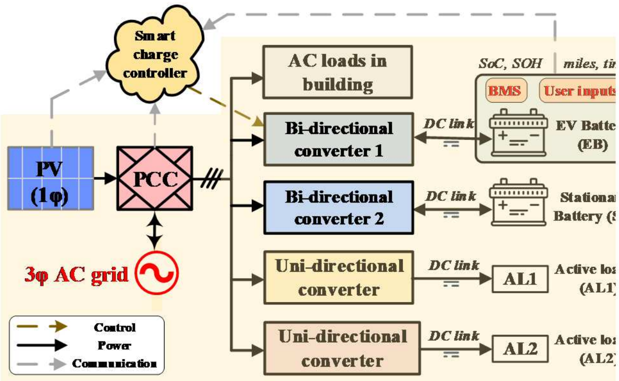

Fig. 1: Schematic diagram of the microgrid under investigation.

either absorbing or delivering power, depending on generation-demand balance.

The interaction of various sources and loads in MG necessitates the development of appropriate multiagent control so as to manage the use of energy in a way to maximize the overall profit of microgrid and increase its energy autonomy. The proposed control algorithm ensures that the energy is optimally utilized based on power availability from local PV generation, EV user requirements, MG constraints and energy prices. The aim of energy management is to supply the consumption of customer agents with minimum cost and less dependency on the main grid.

For the MG, the electrical power balance at each time (*t*) must be satisfied to supply load consumption, expressed as:

$$P_t^{load} + \alpha_t^{EV} P_t^{EV} = P_t^{RES} + P_t^{BESS} + P_t^{grid} \qquad (1)$$

where, $P_t^{RES} = P_t^{PV}$ is the power from renewable energy at time *t*, P_t^{EV} is the EV power required (negative when in charging mode and positive for discharging mode) and α_t^{EV} represents the EV status (it has a value of 1 when EV is connected to the MG and charging, and zero when it is not connected), P_t^{BESS} is BESS power (positive when discharging ($BESS^{+}$) and negative when charging ($BESS^{-}$)) and P_t^{grid} is grid power. The P_t^{load} represents the overall load in the system, which is comprised of passive and active loads. The active loads are used for load curtailment and participate in the demand side management. The positive value of P_t^{grid} represents the power dispatched to the load and the negative P_t^{grid} indicates that power is sent back to the grid. The BESS stores the surplus energy generated by the RES system. The stored energy is later used (discharged) to meet the load demand when there is a power shortage from the local renewable energy generation.

There are two types of electrical constraints for the BESSs and EVs, one on the minimum and maximum state of charge (SOC) of the battery and the other is the limit on the maximum charge/discharge power rating of the battery (and associated converter). Usually, the battery SOC for both BESS and EV is maintained between a maximum of 80-90% and a minimum of 10-20% of its Ampere-hour capacity so as to prevent over or undercharging and improve the life of the battery, as expressed in (2). Likewise, there are upper limits on the charging power of EV battery and charging/ discharging power of BESS, as expressed in (3). The maximum charge and discharge power of battery is limited to about 10-20% of its capacity (i.e., 0.1-0.2 C_{rate}), and this is to reduce the battery degradation.

$$SOC_{min}^{BESS,EV} \leq SOC_t^{BESS,EV} \leq SOC_{max}^{BESS,EV} \qquad (2)$$

$$\left|P_t^{BESS\pm}\right| \leq \frac{0.1 Q^{BESS} V^{BESS}}{\Delta t} \; and \; \left|P_t^{EV-}\right| \leq \frac{0.1 Q^{EV} V^{EV}}{\Delta t} \qquad (3)$$

where, P_t^{BESS+} and P_t^{BESS-} are discharging and charging powers of storage in kW, P_t^{EV-} is EV charging power in kW, V^{BESS} represents AC link battery voltage, $Q^{BESS\ or\ EV}$ represents the battery maximum Ah capacity (for the BESS or EV), and Δt indicates the time step.

III. PROPOSED MULTI-AGENT HEURISTIC CONTROL

This paper proposes a multi-agent based decentralized energy management approach for grid-connected MG aimed at maximizing energy use from local renewable energy generation (photovoltaic) and minimizing energy import from the grid by using the battery storage and PV to serve local electrical loads and provide economic benefits for the MG owner as well as support the grid. The primary aim of the energy management system is to supply the consumption of customer agents with minimum operational cost of the microgrid and less dependency on the main grid.

A decentralized control of converters considering each entity as separate agent is developed. The multi-agent controller finds and specify the appropriate set points for the BESS, EV battery and active loads, at each time *t*, considering PV output power, available battery SOC, electricity price and load demand. The controller setpoints aim to maximize the economic benefits of MG, while at the same times maintains the constraints for EV and battery storage system to preserve their lifetime.

The flow diagram of the proposed multi-agent control algorithm is presented in the Fig. 2 and is explained as follows:

1. The algorithm starts by calculating the total load power demand in the MG network at time *t*, that is P_t^{load}.
2. The available power generation in the MG is analyzed and the algorithm assesses if the generated PV power (which is the generating source in the MG) is sufficient to support the load power, that is, $\Delta P_t = P_t^{load} - P_t^{PV}$ is either greater than zero or otherwise.
3. In case of excess power ($\Delta P_t < 0$), the extra power can be used to charge the EV battery or the stationary BESS, or it can be sent to the grid. This is decided based on the status signal (α_t^{EV}) from the EV (which is priority in this work). So, if $\alpha_t^{EV} = 1$, this means that the EV is connected to the network at PCC and thus, the residual power is supplied to the EV until it reaches the user specified SOC level (SOC_t^{EV*}). When the EV battery reaches the set (reference) SOC (SOC_t^{EV*}), the remaining power is supplied to a battery storage until it reaches it maximum SOC limit. Finally, if still there is excess power, it is exported to the utility grid. On the other hand, if the residual power is not enough for charging the EV battery, with a specific reference power (P_t^{EV*}), the remaining power is requested from the battery storage or grid (as necessary and if the cost constraint is satisfied). This is expressed as follows, in (4).

$$P_t^{EV} = \begin{cases} PV & \Delta P_t > P_t^{EV*} \\ PV + BESS & \Delta P_t < P_t^{EV*}, \quad SOC_t^{BESS} > SOC_{min}^{BESS} \\ PV + Grid & \Delta P_t < P_t^{EV*}, \quad SOC_t^{BESS} < SOC_{min}^{BESS} \end{cases} \qquad (4)$$

4. In case excess load demand, i.e., low photovoltaic generation ($\Delta P_t > 0$), power can be taken from stationary battery as long as the cost constraint is fulfilled and also there is enough energy in the battery (i.e., $SOC_t^{BESS} > SOC_{min}^{BESS}$) and until the battery is fully discharged to minimum SOC level. This happens for example during nighttime when PV generation is not available to cater and fulfil the load power. Thus, if RE system configurations cannot cater, storage batteries (BESS and/or EV battery) help in maintaining the power balance by supplying the load demand.

5. Once battery energy storage is fully drained ($SOC_t^{BESS} \leq SOC_{min}^{BESS}$) or a certain period of cost restrictions apply, non-critical loads (active loads in this work) are shed, i.e., $P_t^{AL1}, P_t^{AL2} = 0$. Especially during peak hours, the non-critical loads are shed.

6. In case, BESS is supplying the load and if still the load demand is not satisfied by the BESS because the load is either higher than the capacity of battery or battery is entirely drained, power is obtained from the main grid. The algorithm always gives priority to meeting the energy demand of the loads and EV, even if the power from PV and battery energy storage system is not available.

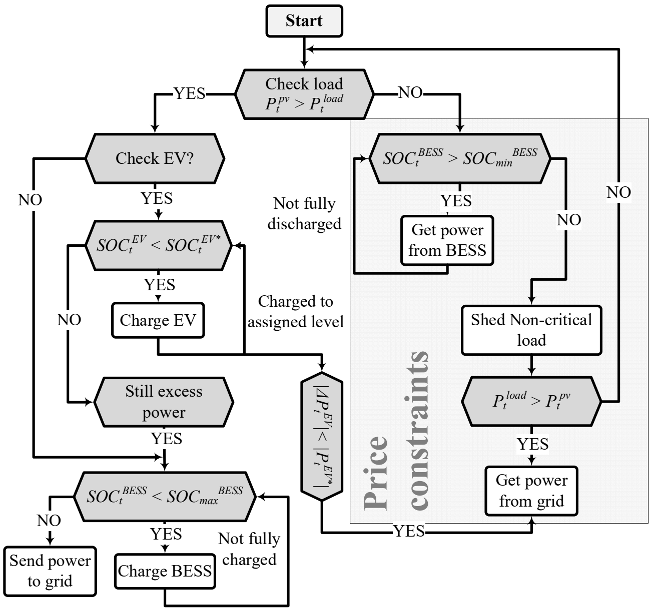

Fig. 2: Flow chart of the proposed multi-agent control algorithm for MG energy management.

7. The algorithm also takes into consideration the price of electricity defined based on three periods of day, i.e., peak time, off-peak time, and standard period. These times of operation and their corresponding prices are listed in Table 1 [18]. These operating periods and their respective electricity prices help in defining the effective usage of BESS for increasing MG profit. The peak time prices are usually higher as load demand increase during this period, thus in this case, the available BESS is fully utilized for fulfilling the load demand, the active loads are shed, and also the excess BESS power is exported to the grid. Thus, effectively reducing the energy import cost by using less or zero energy from grid during these hours and in addition, to earn profit for selling excess energy for higher price. The off-peak period is used to charge the battery so as to store energy to be used during peak hours for example. Lastly, the standard time is the longest duration of the day and thus, the BESS is used only when its SOC is greater than 50%. The usage of BESS is restricted during standard period so as to save energy for peak hours. Unlike off-peak period, the BESS is only used in discharging mode for both peak and standard times. This is expressed as follows:

$$P_t^{BESS*} = \begin{cases} \bar{P}_t^{BESS+} & t = t_p & SOC_t^{BESS} > SOC_{min}^{BESS} \\ \bar{P}_t^{BESS+} & t = t_{sd} & SOC_t^{BESS} > SOC_{50}^{BESS} \\ \bar{P}_t^{BESS-} & t = t_{op} & SOC_t^{BESS} < SOC_{max}^{BESS} \end{cases} \tag{5}$$

where, $\bar{P}_t^{SB-}$ and $\bar{P}_t^{SB+}$ are the BESS maximum charging and discharging powers, respectively. The SOC_{50}^{BESS} represents the 50% SOC of BESS.

It is worth mentioning that the cost mainly affects the operation of proposed controller when generation from renewables (PV) is less than the load. Therefore, the flow of algorithm in Fig. 2 under $P_t^{PV} < P_{load}^{PV}$ is subject to cost as well and may toggle between BESS and grid based on the period of day. The proposed algorithm is smart and able to decide among the grid and BESS for supplying the demand at each time based on electricity prices and period of day.

Table 1: The period of day, and respective times and prices.

Time of day	Time (h)	Price (£/kWh)
Peak (t_p)	06:00-09:00 18:00-20:00	0.25
Standard (t_{sd})	09:00-18:00 20:00-22:00	0.072
Off-peak (t_{op})	22:00-06:00	0.045

IV. RESULTS AND DISCUSSION

In this section, the MG shown in Fig. 1 is used to evaluate the proposed multiagent control strategy for 24 hours scenarios considering various events. The simulation environment is MATLAB R2019a and the microgrid model is simulated using SimPowerSystem's phasor mode to perform faster simulation for a 24 h scenario. The control algorithm is implemented using Stateflow. The EV capacity assumed for 40 kWh Nissan Leaf battery and is plugged to the MG at 14:00 h. For the analysis a small building is assumed with several loads, BESS, PV system and one EV charging point. The technical details are listed in Table 2.

The results presented in Fig. 3 show the first case ($\mathbf{v}_{\mu grid}$ is the p.u. microgrid voltage), where the grid is supplying load starting from 00:00 h and continues powering until 05:00

h where battery is enabled to fulfil, together with the PV system, the load demand, which results in zero grid import power. However, after 08:00 h, PV generation becomes greater than the load demand and thus, the excess power is utilized for charging the battery energy storage system until 14:47 h, where battery maximum SOC of 80% is reached. The battery is kept idle until 18.00 h (to save its energy) and thereafter it is allowed to deliver maximum power to meet the load demand (to support peak demand, for example). Meanwhile, at 14.00 h, it is assumed that the EV is plugged in with an initial SOC of 40% and a target SOC (required by the driver) of 75%. Charging of the EV increases the overall load of the microgrid, which is now supplied by both the PV and the grid. Finally, the battery storage is charged from 23:00 h to 24:00. This case, however, does not consider the inclusion of price as constraint towards the use of BESS for energy management and switching of BESS setpoints is independent of day period/price. The overall cost of microgrid per day for the energy flow in Fig. 1 is 30.17 £/day.

Table 2: Technical details of test system.

MG agents	**Specifications**
PV system	75 kW
BESS	40 kW (rated power) 250 kWh (rated capacity)
Maximum load	35 kW (fixed load) 30 kW (variable load)
EV	6.6 kW (rated power) 40 kWh (rated capacity)

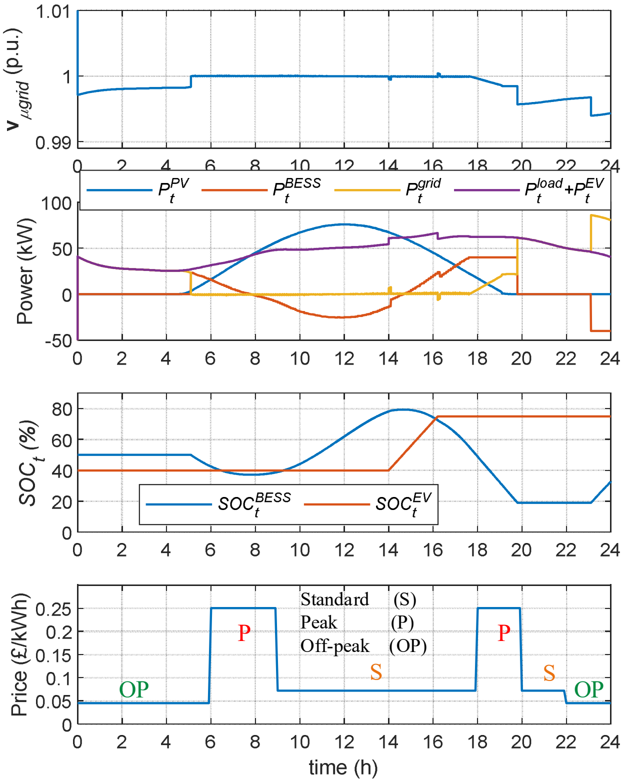

Fig. 3: Flow of power for various agents in the microgrid without the inclusion of cost as MAS constraint.

In the second case, shown in Fig. 4, the cost of energy price is included as part of the optimization algorithm. The BESS power flow is constrained and is enabled in accordance with (4) where BESS is used in full during peak hours (until it reaches minimum SOC), charged during off peak to its maximum and is used during standard time only if the SOC of the BESS is greater than 50%. The results are shown in Fig. 4. The BESS is charged mid-night as it is the Off-peak time. Later at 06:00 h, the BESS supply load together with PV and also the excess power is exported to the grid. At 08:00 h, the PV power is higher than the load, so the BESS is charged using the excess power from the PV. At 15:00, the load is greater than the PV generation and thus, the BESS is enabled to supply the load (as its SOC>50%). Later at 18:00 h, the BESS is discharged at maximum power limit and after 22:00, the BESS is charged taking advantage of the lower electricity tariff. This automation based on optimization of energy cost significantly reduces the cost to £19.58/day (which is 35.10% less than the first case). A further analysis for cloudy shows similar results of significant reduction in the cost of MG. This clearly demonstrate the effectiveness of the proposed multi-agent control in the energy management of the MG and the economic benefits it brings.

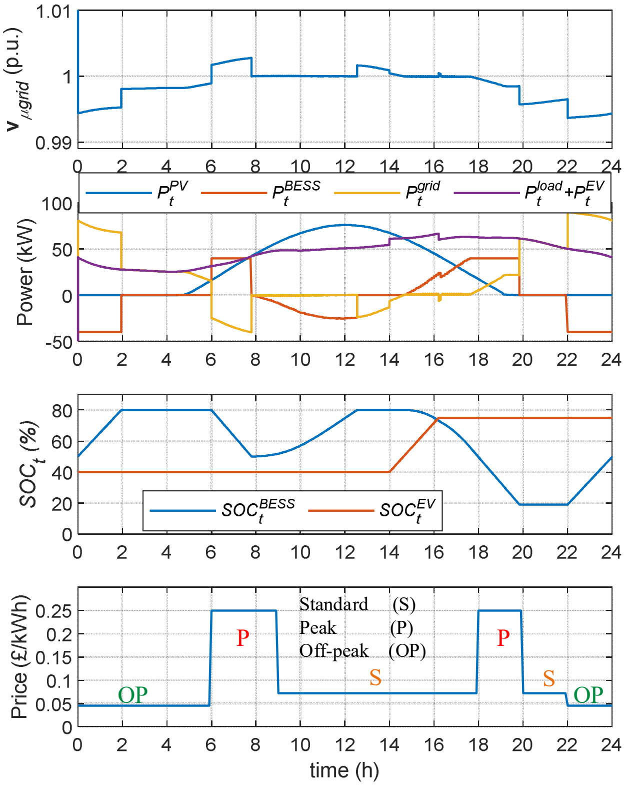

Fig. 4: Flow of power for various agents in the microgrid using proposed multi-agent control with the inclusion of cost as MAS constraint.

V. CONCLUSIONS

This paper proposes a multi-agent based decentralized energy management algorithm for grid-connected MG aimed at maximizing energy use from local renewable energy generation (photovoltaic) and minimizing energy import from the grid by using a battery energy storage system and a

PV system to serve local electrical loads and provide economic benefits for the MG owner as well as support the grid. The multi-agent controller determines the appropriate set points for different agents in the MG at each time *t*, considering PV output power, SOC of the battery energy storage system, electricity price and load demand. The significance of proposed multi-agent control towards energy management and its contribution to economic benefits of the MG are validated using MATLAB/Simulink simulation. The results show that by using the proposed controller, a reduction is the MG energy cost of up to 35.10% is achievable for normal weather and similar reduction to cloudy weather too. Thus, the proposed controller is suitable for effective utilization of MG resources towards MG economic benefit and energy autonomy. Future work includes analyzing the impact of different weather conditions (for example, cloudy, summer or winter etc.), several EVs as part of network and variable charging times, and involving battery degradation in the cost constraints of the MG.

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