

Multi Agent Systems based Distributed Control and Automation of Micro-grid using MACSimJX

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Abstract—The objective of this paper is to develop a model for distributed automation of micro-grid using Multi Agent System(MAS) for the advanced control and distributed energy management of a solar micro-grid. A grid connected solar micro-grid model, which contains two solar Photo Voltaic (PV) systems, one in department and other in hostel, each contains a local consumer, a solar PV system and a battery, is modelled in Simulink. Due to unstable nature of MATLAB, when dealing with multi threading environment, MAS operating in Java Agent Development Environment(JADE) is linked with the MATLAB using a middleware, Multi Agent Control using Simulink with Jade extension (MACSimJX). MACSimJX allows the solar micro-grid system designed with MATLAB to be controlled by solar micro-grid agents for realizing the advantages of decentralized approach of MAS. All the agents of solar micro-grid components are programmed in JADE and the results of the coordinated action of these agents are sent to the environment for distributed control and automation of the hardware. JADE leverages the advantage of MAS by its inherent features and hence the operational efficiency of solar micro-grid is further increased. Also the power exchange between main grid and solar micro-grid is optimized by effective demand side management. Simulation is designed to evaluate impact of autonomous operations of agents.

Index Terms—Solar microgrid; Multi Agent System; JADE; MACSimJX; Energy Management; Distributed Automation.

I. INTRODUCTION

Industrial automation in the power and energy domain has become more complex today. Actuators and sensors work together as a network of different devices, which become intelligent and can autonomously perform the task. MAS has received compelling attention in the recent times because of its capability to significantly improve the operational efficiency, reduce cost and increase degree of operational redundancy. Distributed control depending on only local operation of agents and their neighbors is a promising tool for handling MAS when compared to centralized controller, which is complex and expensive. The smart grid paradigm represents a transition towards an intelligent, digitally enhanced, two way power delivery grids [1]. Micro-grid is a the building block of smart grid and are poised to play a major role in enabling the widespread adoption of renewable, distributed energy resources. However, their integration into the micro-grid entails new challenges for control as the power generated is intermittent in nature, which impact the dynamics and stability of the micro-grid. To meet these challenges, micro-grid monitoring should incorporate communication and control to

achieve an optimal balance between generation, energy storage and load demand and also react quickly to changes. Dynamic energy management is a key enabler for the integration of renewable power generation onto the micro-grid.

An agent-based modeling approach is used to model the micro-grid and the interactions between individual intelligent decision-makers are analyzed through simulation in [2]. Optimization of micro-grid with intermittent renewable energy resources using MAS is given in detail in [3]. MAS controlling the main operations of micro-grid is discussed in [4]. The design and implementation details of MAS in micro-grid energy management is discussed in detail in [5]. Real-time digital simulator is used for real-time operation MAS on micro-grid is discussed in [6]. Multi-agent-based distributed energy management for intelligent micro-grid is discussed in [7]. The various trends in micro-grid control are discussed in [8]. The complete review of micro-grids in MAS perspectives is discussed in [9]. Distributed online optimal energy management for smart grid is discussed in [10]. A detailed review on agent concepts applied to intelligent energy systems is given in [11]. Real-time micro-grid control strategies are discussed in [12]. All the simulations in these references are implemented in JADE. A novel approach, MACSimJX, is introduced to link MATLAB with MAS to allow system designed with Simulink to be controlled by agents that operate in external program in JADE, a powerful development environment for modeling MAS is discussed in detail in [13]. The integration of JADE with Simulink using MACSimJX is discussed for energy management in Distributed Energy Resources (DER) of micro-grid in [14]. But in these papers, MAS was not implemented comprehensively, considering all the options available in a micro-grid for distributed control and automation in a dynamic distributed environment. Also because of its collaborating and negotiating behavior, MAS in JADE is not capable of performing real-time constrained control operation. So there is a need to analyze more comprehensively, considering all the logical options available in the micro-grid and also to investigate the linking of MAS in JADE with MATLAB Simulink using MACSimJX, which opens MATLAB to one of the most strongly supported open source agent development environments, allowing real-time hardware systems to be modeled alongside and interacting with software modeled as multi-agent systems, bringing MAS closer to practical implementation. MAS reduces the requirements of network

bandwidth due to decentralized approach and if large number of micro-grids are involved, the network bandwidth is further reduced by Software Defined Networks (SDN). Apart from extending network capabilities, SDN is used to automate the configuration of the routers and switches in a scalable manner to support rapid deployment of a large number of new applications, services, and infrastructure and manage the dynamic changes in the networks.

The rest of the paper is organized as follows. A detailed discussion on multi agent system approach and multi agent platform is given in section II. Implementation of MACSimJX is given in section III. Simulation of automation in dynamic energy management is given in Section IV. Case study, simulation and validation is given in section V. Conclusion is given in section VI.

II. MULTI AGENT SYSTEMS APPROACH

A. Multi Agent Systems

Autonomous components and coordination are the basic ingredients of any distributed system. Distributed systems that involve many heterogeneous entities have some major limitations.

- Interactions among participating entities are fixed by application developer while coding and hence they lack run-time adaptive behavior.
- Applications that have to operate in environments where maintaining continuous communication is expensive. So distributed systems with many ongoing interaction are almost infeasible.

These considerations have motivated the development of approaches to distributed system based on agents which provide ways for adaptation and ongoing interaction. A Multi Agent System (MAS) is a distributed system consisting of multiple software agents which form “a loosely coupled network”, to work together to solve problems that are beyond their individual capabilities or knowledge of each entity. The goal of MAS approach is used to control a very complicated system with minimum data exchange and minimum computational demands.

B. Multi Agent Systems in Micro-grid

Supervisory Control And Data Acquisition (SCADA) system is conventional system for automating electrical distribution systems. SCADA basically refers to a central control system that monitor and control equipment from a remote location. SCADA systems basically co-ordinate, communicate and control amongst remote sub-stations and control room. In the micro-grid, uncertainty in SCADA systems arises when sensor data or inferred knowledge cannot be deemed accurate due to intermittent nature of renewable energy resources. Applications must deal with inherent noise/error in sensor data or knowledge as well as uncertainty, incompleteness and inconsistent or conflicting data from multiple, heterogeneous sources. Humans have traditionally supervised such problems to reason and resolve issues in SCADA. Also SCADA is

complicated due to its centralized approach. A multi-agent Energy Management System (EMS) can cope with heterogeneity and give better, faster solution than SCADA. MAS can deal with disadvantages of SCADA and increase the operational efficiency of micro-grid due to its inherent characteristics and functionalities, taking the automation of micro-grid to the next level. The energy management system in micro-grid is tightly associated with the communications between stakeholders and entities (agents) to exchange information. Plug and play adaptability and connection to external grid is seamless in MAS based micro-grid. By nature MAS can be scaled up by adding other agents or by dispersing them in new environment with new resources and capacities.

III. IMPLEMENTATION OF MACSIMJX

We consider a grid-connected solar micro-grid system containing two solar Photo Voltaic (PV) systems, one in the department of the college and the other in a hostel, each of which contains a local consumer, a solar PV system and a battery. Considering all the possible options available for the solar micro-grid, a flow chart is drawn as shown in Fig. 1. The

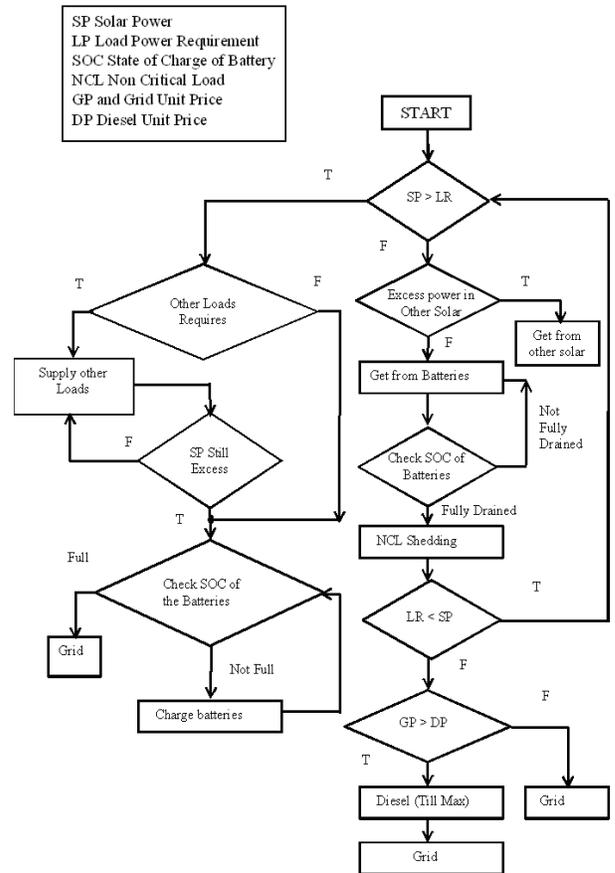


Fig. 1. Flowchart

solar power, load, state of charge (SOC) of the battery, non-critical loads, dynamic pricing of grid are monitored hourly,

and based these data, the agent takes best possible actions autonomously for dynamic energy management of the solar micro-grid in a distributed environment.

The Simulink model is designed for the solar micro-grid with solar power, load and battery. In Simulink, the S-functions are unable to handle multiple threads of execution, which is an essential characteristic of an MAS: they become unstable if several processes run concurrently inside Simulink. To overcome this problem, MACSimJX is used, which acts a middleware between Simulink models and the agents, bringing MAS closer to the practical applications. MACSimJX has a client-server architecture, separating the MAS from Simulink. Client is in the Simulink and the server is at the agent environment. Named pipes in windows are used for communication [15]. Two pipes are used, one for passing configuration information and the other for passing simulation information.

The MAS simulation framework has the following characteristics.

- A fixed-rate, discrete time, simulation with no explicit internal state.
- True multi-threading in parallel with Simulinks simulation cycle.
- The capability to synchronize with Simulink operations.

The complete model of MACSimJX is shown in Fig. 2 which shows how the signals are given from MACSim client to the MACSim server. Once simulation signals arrive at

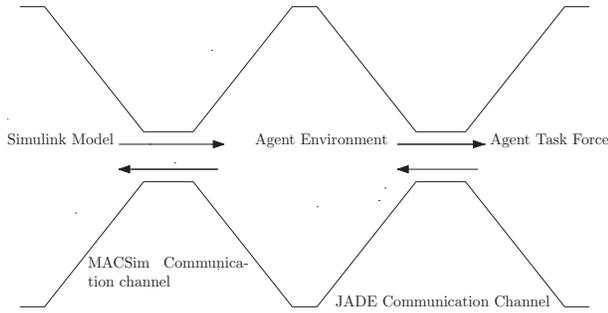


Fig. 2. A Complete Model of MACSimJX

the MACSim server, they are passed on to the agent model, which is divided into two parts, agent environment and Agent Task Force (ATF). The agent environment provides essential agent facilities such as coordination and messaging. The agent environment has an agent coordinator and an agent server. The agent coordinator posts messages to ATF which assigns the work to various agents, requesting them to carry out any operations necessary to prepare outputs for the specified time step. The ATF consists of all the agents that jointly operate on the data arriving from Simulink in order to accomplish the goal of automizing and optimizing the energy management of solar micro-grid. Then the computed outputs are passed back to the agent environment. Once the agent environment has the completion messages from all agents, the output values are passed to the pipe server to be returned to Simulink. The messaging, therefore, provides synchronization with Simulinks

simulation cycle so that they can be sent as command signals to the actuators for switching operation.

IV. SIMULATION OF AUTOMATION IN DYNAMIC ENERGY MANAGEMENT OF SOLAR MICROGRID USING MACSIMJX

The proposed approach considers a two layer framework comprising agent layer containing the agent based control and functional layer, where the physical infrastructure is simulated in MATLAB-Simulink. The behavior parts of the agents (i.e. decisions and control strategies) and coordinating functionalities are done in the agent layer aiming to optimize micro-grid operation and the simulation part, with the functional layer. This layer considers the model of the real solar micro-grid comprising solar units, load, batteries, diesel unit and grid. MACsimJX acts as a middleware linking these two. The functional layer requests services so that the agent layer can observe and take necessary actions for optimizing the solar micro-grid under dynamic environment. The agent layer needs to interact with the function layer to have a mean to test the control strategies. The agent layer considers gateways to translate semantics from agent world to services world. The quality of service and the dynamic, autonomous energy management and demand side management is done by proper control and management strategies, which accommodates different heterogeneous entities and also remain secure, sustainable and reliable. The abbreviations used are shown in Table I

TABLE I
ABBREVIATIONS

No	Abbreviations	Description
1.	SDP and LDP	Solar Department and Load Department
2.	SHP and LHP	Solar Hostel and Load Hostel
3.	BD and BH	Battery Department and Battery Hostel
4.	GRD and DSL	Grid and Diesel
5.	GPR and DPR	Grid and Diesel Unit Price
6.	CL and NCL	Critical Load and Non Critical Load
7.	LCDP and LCHP	Critical Load in Department and Hostel
8.	LNCDP and LNCHP	Non Critical Load in Department and Hostel
9.	CA	Control Agent
10.	SDA and SHA	Solar Department and Hostel Agents
11.	LDA and LHA	Load Department and Hostel Agents
12.	BDA and BHA	Battery Department and Battery Hostel Agent
13.	GA and DA	Grid Agent and Diesel Agent
14.	(DSL-LD-CA)	LD and DSL Switch controlled by CA
15.	(DSL-LH-CA)	LH and DSL Switch controlled by CA
16.	(GRD-LD-CA)	LD and GRD Switch controlled by CA
17.	(GRD-LH-CA)	LH and GRD Switch controlled by CA
18.	SD-BD	Switch connecting solar and battery in Department
19.	SD-BH	Switch connecting SDP and Battery in Hostel
20.	SD-GRD	Switch connecting solar Department and Grid
21.	BD-LD	Switch connecting Battery and Load in Department
22.	BD-LH	Switch connecting BD and Load in Hostel
23.	SH-BH	Switch connecting solar and battery in Hostel
24.	SH-BD	Switch connecting solar hostel and and BD
25.	SH-GRD	Switch connecting solar hostel and Grid
26.	SH-LD	Switch connecting solar hostel and and LD
27.	SD-LH	Switch connecting SD and Load in Hostel
28.	BH-LH	Switch connecting BH and Load in Hostel
29.	BH-LD	Switch connecting BH and Load in Department
30.	DSL-LD	Switch connecting Diesel unit and LD
31.	DSL-LH	Switch connecting Diesel unit and LH
32.	GRD-LD	Switch connecting grid and LD
33.	GRD-LH	Switch connecting grid and LH
34.	NCLD-SW, NCLH-SW	NCL Department and Hostel Switch

The Simulink model is developed for SD, LD, BD, SH, LH, BH, GRD and DSL. Three types of State Of Charge (SOC) are considered in the battery. Fully charged, SOC is

in between fully charge (100%) and fully drained (40%) and SOC is at fully drained (40%). The lesser the available power, the longer it takes for the battery to fully charge, and vice versa. Similarly, if more power is drawn, it discharges in short time and if less power is drawn it discharges for long time.

The input port and output ports are defined in simulation model of solar micro-grid as shown in Fig. 3. Eight input ports and 18 output ports are considered. These 18 output ports are connected to the actuators.

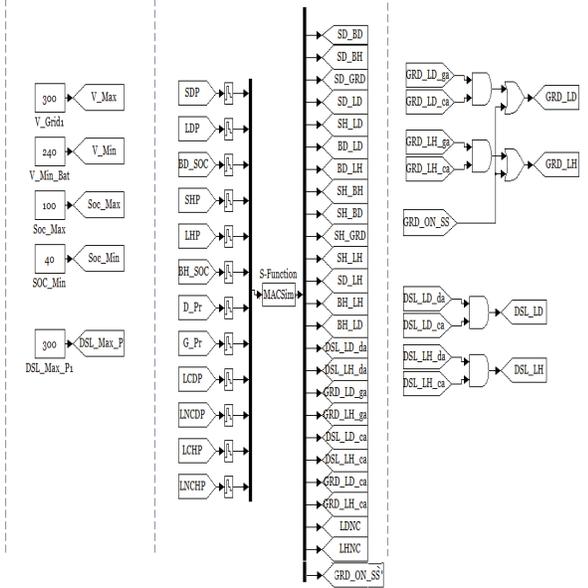


Fig. 3. Simulink Input output switching model of solar microgrid

A. Automation and Demand side Management

All possible conditions, due to intermittent nature of solar power and randomness of load are considered for optimal energy management. Based on values of the environment parameters, a 8 bit number is formed as shown in Fig. 4. The various combinations in the 8 bit number gives 256 possible states, from 0 to 255; 108 of these states are active and the remaining states are null states — they do not occur. The states are analyzed and the relevant output port switch operations for these states are identified. The load, solar power and battery agents for the two solar units (department and hostel) along with grid agent and diesel agent are programmed in JADE for incorporating the actions of solar micro-grid components. The switching operations corresponding to all the agents in ATF are identified. Then for these output port switch operation, the relevant states are consolidated. The state number is broadcast to all the agents, and by observing it, an agent decides the subset of switching operations it is expected to do. Each agent independently does the relevant switching operation for the dynamic energy management. In JADE, the switching operations of agents are done in parallel using multi threading in order to reduce the time of operations. The agents switching operations are described in Table II.

System State Number (SSN) - 8 Bit

WD	WH	X	Y _{D1}	Y _{D0}	Y _{H1}	Y _{H0}	Z
Example							
System State Number (SSN) Calculation	SDP-LDP		SHP-LHP		SDP-LDP + SHP-LHP		Z
	[+] W _D = 0	[+] W _H = 1	[+] W _D = 1	[+] W _H = 1	[+] X = 0	[+] X = 1	
SSN	[1] SOC _{BD} = 100		[2] SOC _{BD} < 100 & > 40		[3] SOC _{BD} = 40		Z
	[1] SOC _{BH} = 100		[2] SOC _{BH} < 100 & > 40		[3] SOC _{BH} = 40		
	[1] Y _D = 00	[2] Y _D = 01	[3] Y _D = 10	[1] Y _H = 00	[2] Y _H = 01	[3] Y _H = 10	
DSL _{Pr} > GRD _{Pr}		DSL _{Pr} > GRD _{Pr}		DSL _{Pr} > GRD _{Pr}		Z	
[+] Z = 0		[+] Z = 0		[+] Z = 0		[+] Z = 1	
245	1	1	1	1	0	1	0

Fig. 4. System State Numbe(SSN)

TABLE II
SWITCHING OPERATION OF AGENTS

No	Agent Name	Switches Controlled	Service
1.	SDA	SD_BD, SD_BH, SD_GRD	Give Power
2.	LDA	SD_LD, SD_SH	Receive Power
3.	BDA	BD_LD, BD_LH	Give Power
4.	SHA	SH_BH, SH_BD, SH_GRD	Give Power
5.	LHA	SH_LD, SD_LH	Receive Power
6.	BHA	BH_LH, BH_LD, SH_GRD	Give Power
7.	DA	DSL_LD, DSL_LH	Give Power
8.	GA	GRD_LD and GRD_LH	Give Power

These agents function in the system layer. The control agent at the control layer is used for NCL shedding at LDA and LHA. The agent operations are done based on the various environmental states, as reflected in the 8 bit number, and the output from ATF are sent to activate these switches through Simulink.

B. Automation and Demand Side Management with Non Critical Load

Along with the 8 agents already mentioned, control agent is also included in the ATF, which specifically controls the NCL. Two layers of agents are formed: the control layer contains control agent for NCL control and the system layer contains all the other agents for controlling the critical load. The necessary parameter communication between these two layers are established for micro-grid control switching operations. Changes are made in the input port and output port in Simulink model to include NCL control operations. Four additional inputs (LCDP, LCHP, LNCDP, LNCHP) are included in the input and 6 additional outputs (DSL-LD-CA, DSL-LH-CA, GRD-LD-CA, GRD-LH-CA, LNCDP, LNCHP) are included in output of simulink model. Control layer agent does the switching operation of LDNC, LHNC, GRD_LD, GRD_LH, DSL_LD and DSL_LH to control the NCL load for demand side management. Control layer agent acts in coordination with system layer agents for controlling NCL. Only when the conditions in the two layers are favoring, the grid or diesel is connected to the loads after the shedding of NCL. When the

system layer agents decide to go for grid, the control layer agent does the NCL shedding, and if the power deficiency is managed in post shedding, it switches off the grid. If the power is required in post shedding, the control layer agent will switch on the external resources and the system layer decides on grid or diesel based on the unit price at that point of time. For control agent actions, separate state model is worked out and a 6 bit number is generated based on the conditions as shown in Fig. 5.

Control State Number (CSN) - 6 Bit						
	W	X ₂	X ₁	X ₀	Y	Z
Example						
Control State Number (CSN) Calculation	[SDP-LCDP] > [SHP-LCHP]	[LNCDDP + LNCCHP]	[Yes] W = 0	[No] W = 1	[SDP-LCDP] > [SHP-LCHP]	[Yes] X ₂ = 0
			[Yes] X ₂ = 0	[No] X ₂ = 1	[SHP-LCHP] > [SDP-LCDP]	[Yes] X ₁ = 0
			[Yes] X ₁ = 0	[No] X ₁ = 1	[SDP-LCDP] > 0	[Yes] X ₀ = 0
			[Yes] X ₀ = 0	[No] X ₀ = 1	[SDP-LCDP] > [SHP-LCHP]	[Yes] Y = 0
			[Yes] Y = 0	[No] Y = 1	[SDP-LCDP] > [SHP-LCHP]	[Yes] Z = 0
			[Yes] Z = 0	[No] Z = 1		
CSN	W	X ₂	X ₁	X ₀	Y	Z
47	1	0	1	1	1	1

Fig. 5. Control State Number(CSN)

The 6 bit number generates 64 states, 50 of which are active and the remaining are null states. The operation of the specific switches for the states are identified. The state numbers are consolidated for the specific switch operations. The consolidated state numbers for the specific switch operations are programmed in control agent.

V. CASE STUDY

The Simulink modeling is implemented for solar power unit, load and batteries of the department and hostel, and grid and diesel power. Here BD and BH refer to department and hostel battery SOC. SDP, LDP, SHP and LHP refer to solar power and load values of the department and hostel. D_PR and G_PR refer to the diesel price and grid price in INRS (Indian Rupees). The input values taken every hour for the case study are shown in Table. III. After the coordinated operations of agents, the simulation output for these input values is shown in Fig. 6.

TABLE III
CASE STUDY VALUES (KW)

Time	SDP	LDP	SHP	LHP	DPR	GPR
0	400	200	300	100	10	8
1	200	400	300	100	10	8
2	400	200	100	200	8	10
3	200	400	100	300	8	10
4	200	400	100	300	10	8
5	200	300	300	100	10	8
6	400	200	100	200	8	10
7	200	300	100	200	8	10
8	200	300	100	200	8	10
9	200	400	100	300	10	8

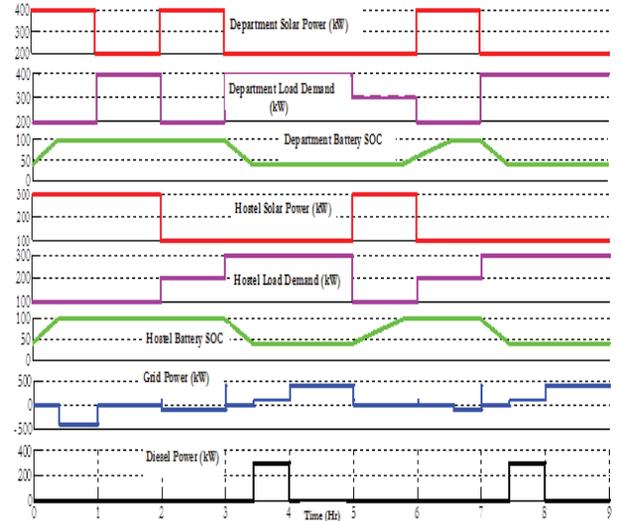


Fig. 6. Simulation of Dynamic Energy Management of Solar Microgrid

In this simulation model output, initially department and hostel solar powers are 200kW more than the corresponding load demand and so the department and hostel batteries are charged with the total excess power of 400kW for a specific period and then this power is given to the grid. In the 2nd hour, the load in the department is 200kW more than the solar power, and in the hostel, the solar power is 200kW more than the load. Since battery SOC is continued from previous state, both are fully charged. So the excess solar power 200kW in the hostel is given to the department load. In the 3rd hour, the department solar has excess power of 200kW and the hostel solar has 100kW deficit than their respective loads. Out of the 200kW excess power, the department solar gives 100kW to the hostel load and the remaining 100kW is given to the grid. In the 4th hour, both the department and hostel units are in deficit by 200kW, and therefore the power in the batteries are discharged to the corresponding loads till it reaches the cut-off value and then 300kW is taken from diesel (full capacity is 300kW) and remaining 100kW from grid as the diesel price is greater than the grid price. In the 5th hour, in the same scenario, with diesel price more than the grid price, the required total power of 400kW is taken from grid. In the 6th hour, there is 100kW deficiency in the department unit and 200kW excess in the hostel unit. So, hostel battery is charged first and then department battery is charged. In the 7th hour, we have 200kW excess in the department unit and 100kW deficient in the hostel unit. Department unit gives 100kW to the hostel unit and the remaining 100kW is used for charging the department battery till it is fully charged, and after that the 100kW is given to the grid. Here the hostel battery was fully charged in the previous hour. In the 8th hour, the department and hostel have a deficiency of 100kW each and so both the batteries are discharged till the cut-off and then the required 200kW is received from diesel unit as diesel price is less than grid price. In the 9th hour, the department and hostel units have a deficiency of 100kW each and the batteries are drained

in the previous state. Therefore, the required 200kW is taken from the diesel unit as diesel price is less than grid price. In the 10th hour, the department and hostel units have a deficiency of 200kW each. The required power of 400kW is received from grid as the grid price is less than diesel price. Every hour noncritical loads are defined and so before it goes to grid or diesel it sheds the non critical loads.

VI. CONCLUSION

A Simulink solar micro-grid model is developed in MATLAB/Simulink and it is linked with JADE using MACSimJX for realizing the practical implementation of MAS in dynamic energy management and demand side management of solar micro-grid, to achieve the lowest possible cost under intermittent nature of solar power and randomness of load. The proposed framework gives the intelligent consumer the ability to explore all possible logical sequences of options, understand the stochastic environment, and select the optimal energy management actions autonomously to increase operational efficiency in a distributed environment, bringing MAS closure to real-time implementation. The limitation of this approach is, it is very difficult to evaluate the information management functionality of the system. Future work will focus on extension to multiple agents integrating diverse renewable generators (solar and wind) with several intelligent consumers with conflicting requirements. Furthermore, the proposed approach can be implemented in actual micro-grids by sending the command signals from MACSimJX through the communication network interface and Internet Of Things (IOT) technology.

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