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Application of Multi Agent Systems in Automation of Distributed Energy Management in Micro-grid using MACSimJX

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ABSTRACT

The objective of this paper is to monitor and control a micro-grid model developed in MATLAB-Simulink through Multi Agent System (MAS) for autonomous and distributed energy management. Since MATLAB/Simulink is not compatible with parallel operations of MAS, MAS operating in Java Agent Development Environment (JADE) is linked with MATLAB/Simulink through Multi Agent Control using Simulink with Jade extension (MACSimJX). This allows the micro-grid system designed with Simulink to be controlled by MAS for realizing the advantages of MAS in distributed and decentralized micro-grid systems. JADE agents receive environmental information through Simulink and they coordinate to take best possible action, which is reflected in MATLAB/Simulink simulations. After validation and performance evaluation through dynamic simulations, the operations of the agents at various scenarios are practically verified by using the Arduino microcontroller. These validation and verification moves MAS closer to Smartgrid applications and takes micro-grid automation to a new level.

KEYWORDS

Multi Agent System; JADE; MACSimJX; Energy Management; Distributed Optimization

1. Introduction

The world today is witnessing a gradual transition in the form of generation and distribution of electricity. The liberalization of the energy industry, together with decarbonisation and inclusion of renewable energy sources, as well as ground-breaking Information and Communication Technologies (ICT) developments have huge consequences on the way sector works. We are moving rapidly towards a more decentralized, more sustainable, and smarter power system. The smart grid paradigm represents a transition towards an intelligent, digitally enhanced, two way power delivery grids (ME El-hawary, 2014). Micro-grid is a building block of smart grid and it plays a major role in adoption of renewable energy resources like solar and wind. However, their intermittent nature entails new challenges when integrating with grid and impacts the stability of the micro-grid. To meet these challenges, micro-grid should incorporate control strategies to achieve balance between generation and demand. Distributed energy management is necessary for the integration of renewable energy onto the micro-grid. MAS approach is used for distributed decision-making in a decentralised environment to improve responsiveness and stability. Energy management of micro-grid using MAS is discussed in Jun, Junfeng, Jie, & Ngan (2011). An agent-based modelling approach is used to model the micro-grid in Hatziargyriou (2014). The interaction between individual intelligent decision-makers in the micro-grid are analysed through MAS simulation in Reddy & Veloso (2011). Optimization of micro-grid with intermittent renewable energy resources using MAS is given in detail in Eddy & Gooi (2011). Here, MAS is simulated in JADE for making distributed decisions to improve performance. But, no attempt is made to go beyond JADE simulations. MAS controlling the main operations of micro-grid are discussed in Hatziargyriou & Dimeas (2005). Fully decentralized approach is considered here, which is not economical. The design and implementation details of MAS in micro-grid energy management are discussed in detail in Pipattanasomporn, Feroze, & Rahman (2009). Hierarchical approach of MAS is considered here, but facilitating MAS for practical implementation is not discussed. Real-time digital simulator is used for real-time operation of MAS on micro-grid is discussed in Logenthiran, Srinivasan, Khambadkone, & Aung (2012). The monitoring and control strategies are not discussed here. Multi-agent based distributed energy management for intelligent micro-grid is discussed in (no reference listed). Micro-grid management and market operations are discussed here, but practical implementation is not discussed. The various trends in micro-grid control are discussed in Olivares et al. (2014). The complete review of micro-grids in MAS perspectives is discussed in Gomez-Sanz, Garcia-Rodriguez, Cuartero-Soler, & Hernandez-Callejo (2014). Distributed online optimal energy management for smart grid is discussed in Liu, Zang, & Yu (2015). Unit commitments and demand side management for social welfare is discussed here, but hardware in loop simulations is not discussed. A detailed review on agent concepts applied to intelligent energy systems is given in Vrba et al. (2014). Coordination approach of micro-grids for resilient operation is discussed in Rivera, Farid, & Youcef-Toumi (2014). The electrical constraints of micro-grid are discussed here, but the details of implementation is not given here. Micro-grid control strategies are discussed in Logenthiran, Naayagi, Woo, Phan, & Abidi (2015). But, real time implementation is not discussed here. Two agents scheduling is discussed in Yin, Cheng, Cheng, Wu, & Wu (2013). Multiple agent scheduling applications is discussed in Yin (2016). In most of these references, MAS operations are simulated in JADE, but JADE simulations are not adequate for validation. MAS have to be

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linked with MATLAB for a comprehensive simulation, which can be validated. But MATLAB does not support parallel operations, which is essential for a decentralized approach of MAS. 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 modelling MAS (Robinson & Peter, 2010). Although many micro-grid research activities involving MAS have been reported, all of them implement MAS in JADE platform and generates the basic simulations, which can only be used for theoretical proof of demonstration. Because of its collaborating and negotiating behaviour, MAS in JADE is not capable of performing real-time constrained control operation of micro-grid. So, there is a need to investigate the linking of MAS in JADE with MATLAB Simulink, which opens MATLAB to agent development environments for modelling real-time hardware systems alongside and interacting with multi-agent systems. This brings MAS closer to practical implementation. So an attempt has been made in this paper to use MACSimJX for autonomous energy management of solar micro-grid, considering the intermittent nature of solar power, randomness of load, dynamic pricing of grid and control of Non-Critical Load (NCL) for demand side management. The rest of the paper is organized as follows: A detailed discussion on multi agent system approach is given in Section 2. MACSimJX is explained in Section 3. Section 4 deals with implementation of dynamic energy management of solar micro-grid using MACSimJX. Case study, simulation and validation are given in Section 5. Practical verification of demand side management of solar micro-grid using Arduino is discussed in Section 6. Conclusion is given in Section 7.

2. Multi Agent Systems Approach

Autonomous actions and coordination are the basic ingredients of any distributed system. The limitations of distributed systems are that they lack run-time adaptive behaviour and require continuous communication. These considerations have motivated the development of approaches to a distributed system based on agents, which provide ways for adaptation and on-going interaction. A Multi Agent System (MAS) is a distributed system consisting of multiple agents, which form a loosely coupled network to work together to solve problems that are beyond their individual capacities. Multi-agents overlay a way to elaborate systems that are decentralized, emergent, and concurrent. MAS have inherent benefits such as extensibility, autonomy and reduction in problem complexity. Agents have certain behaviours and tend to satisfy certain objectives using their resources, skills and services. With a decentralized approach, MAS has its own perception of the environment, goal and agenda and they try to achieve the best for themselves, while behaving strategically. Plug and play adaptability and connection to external grid are seamless in MAS based micro-grid energy management. By nature MAS can be scaled up by adding other agents or by dispersing them in new environment with new resources and capacities. MAS are particularly useful for designing distributed systems requiring autonomy of their entities.

3. Multi Agent Control using Simulink with Jade extension (MACSimJX)

MAS are implemented in JADE framework for energy management of a micro-grid. MATLAB is not compatible with parallel operation, which is an essential characteristic of MAS; it becomes unstable if several processes run in parallel. To overcome this problem, a middleware, MACSimJX, is used as an interface between Simulink models and the agents in JADE, bringing MAS closer to the physical models through hardware in loop simulations. The agent considers the environment values received from the micro-grid devices and takes best possible actions autonomously for dynamic energy management of the solar micro-grid in a distributed environment. MACSimJX has client-server architecture. Client is in the Simulink and the server is at the agent environment. Communication between client and the server is done through windows named pipes (Mendham, 2005). Configuration information and simulation information are passed through separate pipes allowing the two processes to be run asynchronously. Queries are sent by the client and responded by the server. Simulation signals are passed on to the agent model. The agent environment facilitates coordination and messaging. It assigns the work to various agents for executing the operations. The result of agents operations or the command signals are given back to the agent environment. After receiving the completion information from all the agents, the agent environment sends the output to the Simulink through the windows pipe server. The resulting actions of agents are synchronized with Simulink simulation cycle for hard ware in loop simulations.

4. Implementation of Dynamic Energy Management of Solar Micro-grid using MACSimJX

A grid-connected micro-grid system containing two solar Photo Voltaic (PV) systems, one in the department of the college premises and the other in a hostel is considered. Each PV system consists of local consumer, a solar PV system and a battery. The Simulink model is developed for the department and hostel solar power, load, and batteries along with grid and diesel (SDP, SHP, LDP, LHP, BD, BH, GRD, and DSL). In the department solar unit Simulink model, the department solar power is given to the department load then the remaining power is given to the hostel load. The further remaining power is given to the department battery, and then to the hostel battery for charging and if anything remaining is finally given to the grid. The hostel solar unit also designed in the similar way. Simulink model of the department solar unit is given in Figure 1. Similarly the hostel solar unit is modelled. In the department load model, the department load first receive power from the department solar unit and then from hostel solar unit. Further requirement of power is taken from department battery, then from hostel battery. If power is still required, it is received from diesel unit and grid unit based on unit price at that point of time. The loads are divided into critical and Non Critical Loads (NCL) so that NCL load shedding can be done before going to the external power resources like diesel or grid. The department load Simulink model is shown in Figure 2. The hostel load is modelled in the similar way. The Simulink model of the department battery is shown in Figure 3. In this model, three types of State Of Charge (SOC) are considered in the battery. Fully charged, SOC is in between fully charged (100\%) and fully drained (40\%), and SOC is fully drained. In the battery, if 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 a long time. The hostel battery is modelled in similar way.

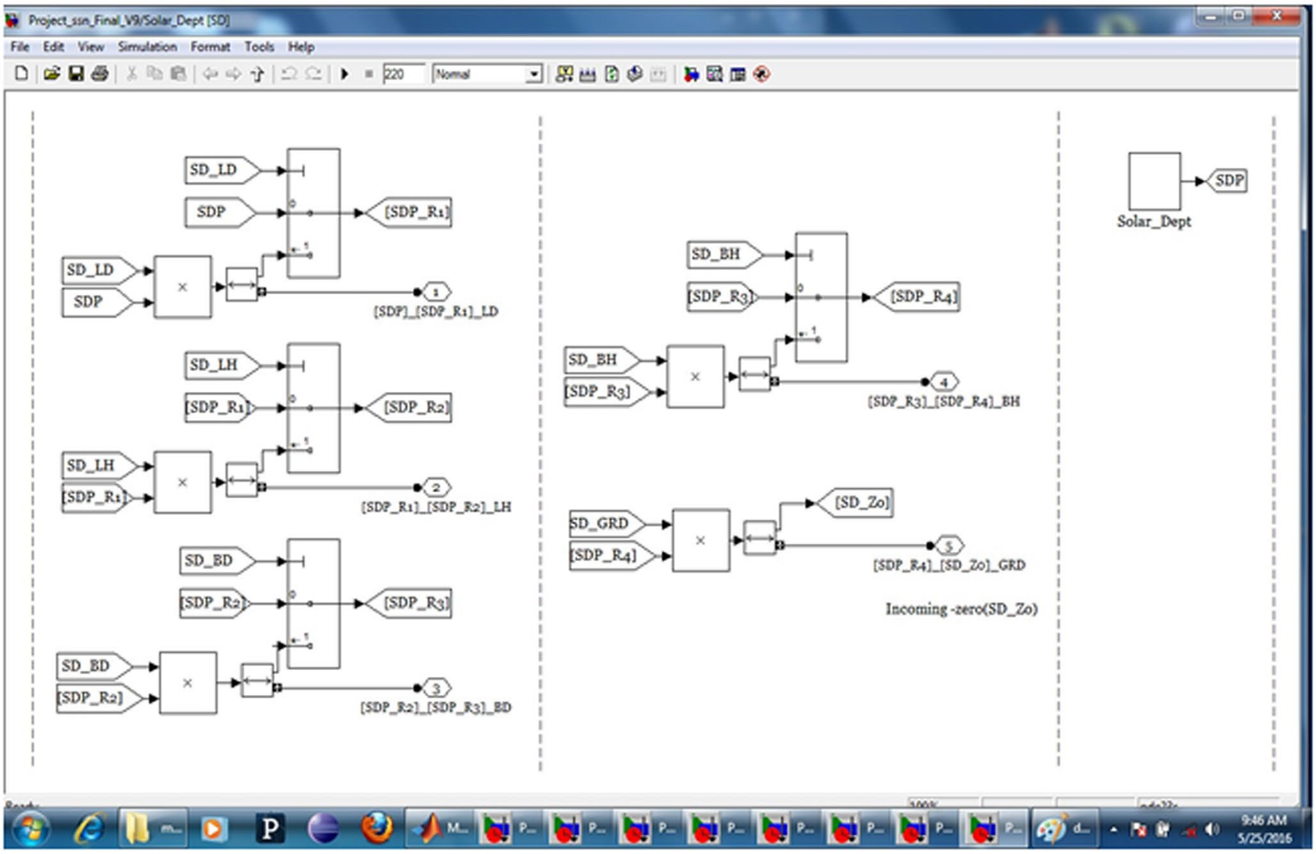

Figure 1. MATLAB/Simulink Model of Department Solar Unit.

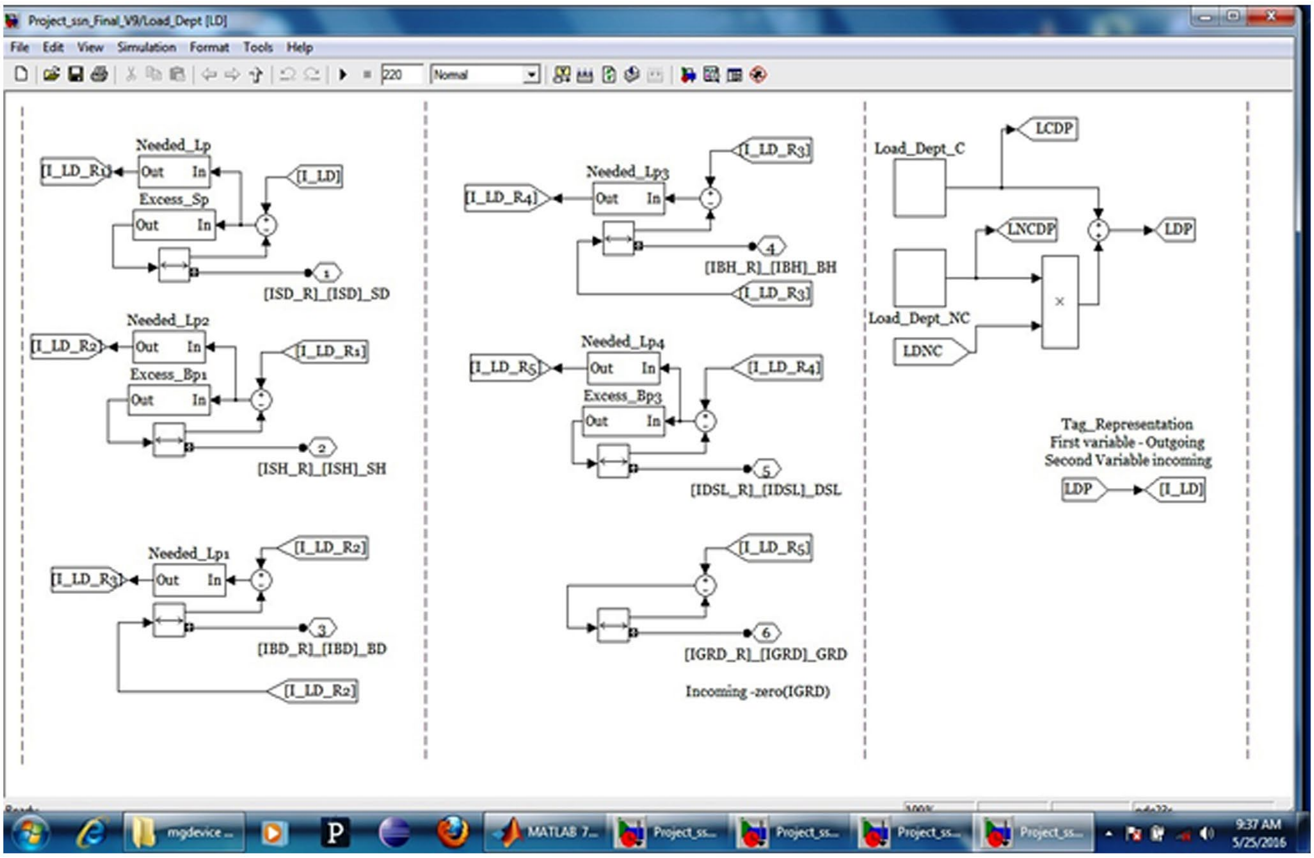

Figure 2. MATLAB/Simulink Model of Department Load Unit.

The proposed approach considers a two layer framework; comprising and functional layer and the agent layer. The physical infrastructure of micro-grid is simulated in MATLAB-Simulink in the functional layer and the behaviour parts of the

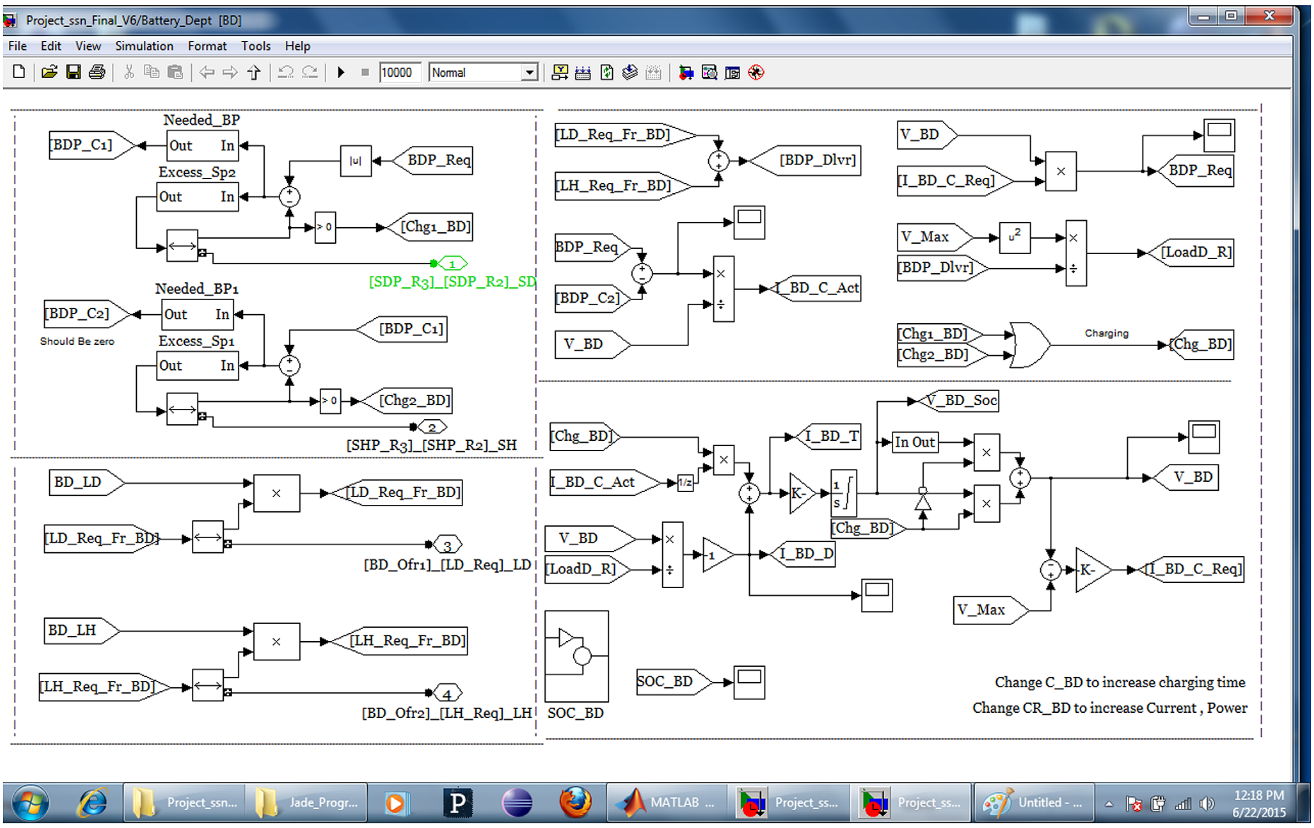

Figure 3. MATLAB/Simulink Model of Department Battery Unit.

agents are done in the agent layer aiming to optimize micro-grid operation. These two layers are linked with MACsimJX, which acts as a gateway to translate semantics from agent world to services world. The functional layer feeds the environmental values and requests services and the agent layer take necessary actions for optimizing the solar micro-grid under dynamic environment. The agent layer interacts with the function layer to test and validate the control strategies. Every component in the solar micro-grid is considered as an agent. All the agents are programmed in Java and made to run in JADE platform in Eclipse background. The multi-threading feature of Java and multiple behaviours per agent leads to heterogeneous concurrency, which is the essence of Multi Agent Systems. All of the smart grid features are implemented by coordinated actions of agents. The agent paradigm of computing has flexibilities, than the object oriented paradigm as they cannot access other agent's methods without its permission. The agents can say no and can negotiate for optimal action. These agents dynamically interact in the run time using the directory facilitator to manage the uncertainties of solar power supply and randomness of the load. They take strategic decision for demand side management, self-healing, dynamic pricing and plug and play. The characteristics of agent based computing such as autonomy, proactive and social are incorporated using inherent features of JADE and its various simple and composite behaviours. The semantic, Agent Communication Language (ACL) is used to communicate and coordinate among agents.

4.1. Agent Relationship

Agents sense the environment and make simple decisions, which are within its capacity. They are called, reflective action. For complex decisions and deliberative actions, it

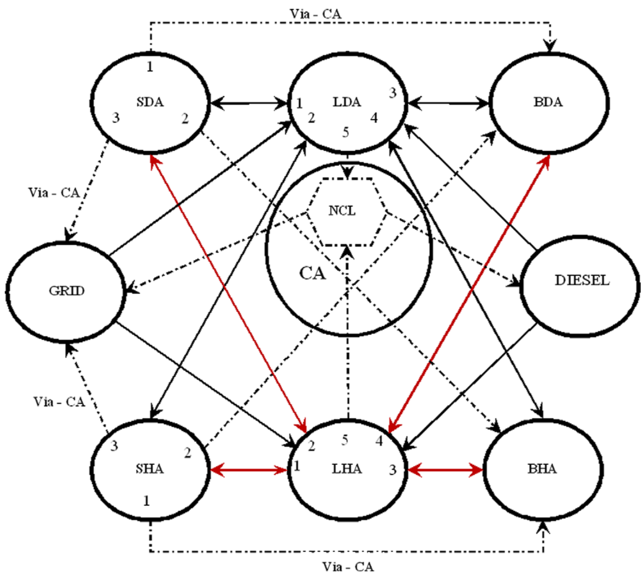

Figure 4. Agent Relationship Diagram.

communicates with the control agent and informs the requirements. For example, the department solar agent gives power to the department load requirement if it is having enough power. If there is a shortage of power, it informs the control agent about the power requirements. The control agent gets the status of all the agents from Directory Facilitator (DF), where all the agents are registered with their status and services. It coordinates with other agents and validates the request made by other agents and informs other agents about the best place to get the requirement for optimal energy management in the solar micro-grid. The agent's relationship diagram is shown in Figure 4.

Here, the load agents participate in the system as buyers of energy, while the solar generator agent as sellers of energy. Here the hierarchical approach, which combines centralized and decentralized approach, is used. Every agent autonomously takes local decision, and then through control agent it communicates to other agents for strategic decision. We consider Solar Department Agent (SDA), Load Department Agent (LDA), Battery Department Agent (BDA), Solar Hostel Agent (SHA), Load Hostel Agent (LHA), Battery Hostel Agent (BHA), Grid Agent (GA), Diesel Agent (DA) and Control Agent (CA). Every hour based on the net power availability and the load requirement, the transaction with the grid is made by the CA. When LDA request power from SDA, SDA gives power to LDA autonomously. If surplus power is available, it is given to BDA. Further excess power is given to BHA and finally to the Grid agent (GA). The validation is done through the control agent. The priority of the operation is mentioned as 1, 2, and 3 in the diagram. If there is not enough power available in SDA, then LDA contacts SHA and receives the available power. If the power is still required, it contacts the BDA and then BHA and finally it communicates with the control agent to do the NCL shedding and finally the post NCL shedding power is received from grid or diesel agent based on the unit price at that point of time. Similarly the LHA contacts SHA for power. SHA makes the autonomous decision to give the power to LHA. If surplus power is available after supplying to LHA, SHA checks the BHA and BDA for charging and further excess power is given to grid. If SHA does not have enough power required by LHA, LHA contacts SDA and gets the power available there. If power is still required, LHA contacts BHA and BDA to get the power available in the battery. The further required power is managed by contacting the control agent, which does the NCL shedding and finally the post NCL shedding power is received from grid or diesel agent after comparing their unit prices. The priority of operation is mentioned as 1, 2, 3, 4, and 5 in the diagram.

4.2. Control Strategies for Autonomous Energy Management of a Solar Micro-grid

In the solar micro-grid model, 12 input ports and 25 output ports are considered. Environment variables are given to the input port and the output ports are connected to the switches. All possible conditions are considered for optimal energy management. Based on values of these parameters, an 8 bit number is formed. The first bit is formed by comparing the solar power values of department (SDP) and hostel load (LDP). If the difference (SDP-LDP) is positive, then the first bit value is 1, if negative the bit value is 0. Similarly the second bit is found by comparing the value of department solar power (SHP) and load (LHP). The third bit is formed by comparing (SDP-LDP) and (SHP-LHP). If the difference is positive, the value is 1 and if negative, the value is 0. The fourth and fifth bits are found by knowing the department battery charging value. If it is fully charged the value is 00 and intermediately charged, the value is 01. If the charge reaches the cut of value then the value is 10. Similarly the sixth and seventh bits are found for the hostel battery. The eight bit is found by looking at grid and diesel unit price. If the diesel price is greater, the value is one and if grid price is greater, the value is 0. Thus the 8 bit number is formed. This number is broadcasted to all the agents and by looking at it each agent comes to know the switching operations it is expected to do. JADE does the switching operations in parallel due to multi-threading and reduces the time of operations considerably. The load in department and hostel is divided into critical and non-critical load (CL and NCL). NCL is defined for every hour, which can be shed before going to grid. Along with the 8 agents already mentioned; control agent is also included, 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. Communication between these two layers is established for micro-grid control switching operations. 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. Coordination between control agent and system layer agents is formed for controlling NCL. If the power requirement is managed in post NCL shedding, the control agent does not favour the grid even though the system layer agent favouring it. For control agent actions, separate state model is worked out and a 6 bit number is generated based on the conditions as shown in Figure 5.

CSN	Control State Number (CSN) Calculation		
W	[SDP-LCDP]+ [SHP-LCHP] > [LNCDP + LNCHP]	[Yes] W = 0	[No] W = 1
X_2	[SDP-LCDP] > [SHP-LCHP]	[Yes] X_2 = 0	[No] X_2 = 1
X_1	[SHP-CLCHP] >0	[Yes] X_1 = 0	[No] X_1 = 1
X_0	[SDP-LCDP] > 0	[Yes] X_0 = 0	[No] X_0 = 1
Y	[SDP-LCDP]+[SHP-LCHP] > LNCDP	[Yes] Y = 0	[No] Y = 1
Z	[SDP-LCDP]+[SHP-LCHP] > LNCHP	[Yes] Z = 0	[No] Z = 1

Figure 5. Control State Number (CSN).

Special State Issued by Control Agent	
[(LCDP + LNCDP*NCLD_SW)-SDP + [(LCHP + LNCHP*NCLH_SW] - SHP > DSL_MAX_P	
[Yes] - GRD_ON_SS = 1	[No] - GRD_ON_SS = 0

Figure 6. Special State (SS) of Control Agent.

The 6 bit number generates 64 states, out of which 50 states are active and the remaining are null states. For all the active states the switching operations are identified. Then for every switching action the state numbers are consolidated. The control agent is programmed with consolidated state numbers for each switching operations. The control agent is given a special state to bypass the logic for switching action of external power resources and go for grid irrespective of the unit price, when the diesel power is exhausted. The special status is formed as shown in Figure 6. If the NCL switches of department and hostel are switched on and if the total load power requirements is greater than the generated solar power, the Special State (SS) of Control Agent checks whether the required load power, after exhausting the department and hostel solar power, is greater than the available diesel power. If it is greater, SS of CA is made to 1 and the grid is connected to the loads irrespective of prices of diesel and grid.

4.3. Power Transfer Strategy

The power transfer strategies are shown in Figure 7. Here there are two layers namely system and control layers. Various

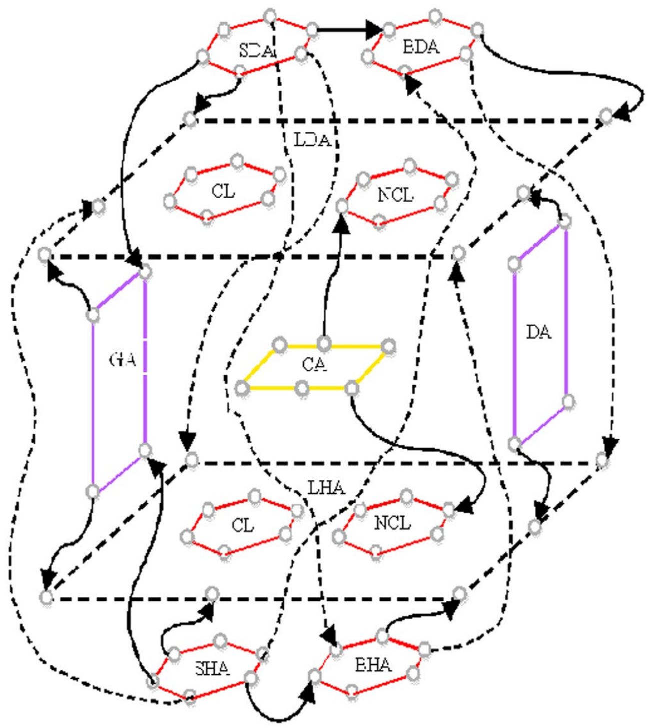

Figure 7. Power Transfer Strategy of Agents.

components of the solar micro-grid agents function in the system layer. The Control agent functions are in the control layer. Here the interaction of the agents for energy management and demand side management is clearly indicated. Solar Hostel Agent (SHA) has the possibility to link with Load Hostel Agent LHA, LDA, BDA, BHA, and GA based on hourly status of the solar power and load. It gives power first to local load and if excess power is available, then it gives to department load. Further excess power is given to its own battery and then to the department battery and finally to the grid. If there is deficiency for LHA, then LHA receives power from SDA, then from BHA and BDA and the further power requirement is received from Grid or Diesel agents. This way it is connected to all these agents. Similarly Department solar agent (SDA) has the possibility to link with LDA, LHA, BDA, BHA and GA. In the figure, department agents are mentioned in the upper part and hostel agents are represented in the lower part. All the possible connections between agents are given in detail. Non critical load shedding is coordinated by control agent before going for power transactions with the grid. 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 projected in the 8 bit number, and the output from agent's operations is sent to activate these switches through Simulink. Thus the interaction among agents takes place to consider all possible options for dynamic energy management under intermittent supply of solar power and varying load.

4.4. Example for Switching Strategies for System State and Control State Number

We consider a case for which the value of SDP = 200 kW, LCDP = 300 kW, LNCDP = 200 kW, SHP = 100 kW, LCHP = 400 kW, LNCHP = 100 kW, DPR = 8, GPR = 10. An eight bit system state number, 111101010 is formed as explained in Section 4.2. This gives the state number as 245. The relevant switch operations for this state are identified as SD_LD, SH_LH, DSL_LD and DSL_LH. There are 8 agents in ATF and the state number 245 is broad-casted for all the agents. The agents look at it and execute the required switching operations. Solar department agent executes the switching operation of SD_LD. Solar hostel agent does the switching operations of SH_LH. Diesel agent does the switching operation of DSL_LH and DSL_LD. For NCL operations, a 6 bit number 101111 is formed based on Figure 2 and it specifies the state as 47. For this state number, the grid agent switches GRD_LD and GRD_LH. The switch control strategy of agents for the system state and also the control state are shown in Figure 8. The special state of control agent is used to switch on the grid after the full diesel power is exhausted. In this case, out of the total load demand of 700 kW, NCL shedding is done for 300 kW and out of the remaining demand of 400 kW, the full capacity of 300 kW is received from DSL and the remaining 100 kW is received from grid through special state of control agent as the special state value is one. Thus the agents corresponding to the switching operations are identified and executed.

5. Case Study

For the department and the hostel, LDPC and LHPC represent critical loads, and LDPNC and LHPNC represent non-critical loads, respectively. The input values given to Simulink model are shown in Table 1. After the coordinated operations of the agents, the simulation output for the above input values is shown in Figure 9. In the 5th hour, both the hostel and the department have 200 kW deficits. Here, the non-critical load of 200 kW in the department and 100 kW in the hostel are shed. Then the required 100 kW is received from the grid as the grid price (GPR) is less than the diesel price (DPR). In the 11th hour, both department and the hostel have a deficit of 300 kW and 400 kW respectively. Here the batteries supply to the corresponding load until it is drained and then the non-critical load of 200 kW in the department and 100 kW in the hostel is shed. Then out of required power of 400 kW, 300 kW is received from diesel as it is economical and the remaining 100 kW is received from grid by activating the special state action of control layer agent.

6. Practical Verification of Demand Side Management of Solar Micro-grid using Arduino

JADE agent operations are verified by linking it with Arduino microcontroller. A Java library called RxTx is used to facilitate serial communication with the Arduino. Initially COM serial port is connected to the Arduino board in the device manager of the operating system. Then a connection is established between the Arduino and PC. Arduino software is ran on a PC to read or write the data available at the connection port through a Java code developed in Eclipse. The environment variables are sensed by using potentiometer where the maximum ranges are fixed for the value 0-1023. For example if hostel solar power is 50 kW, then 1023 represents 50 kW. Similarly all the environment variable values, department solar and load, hostel solar and load, department and hostel battery, grid and diesel values are fixed in eight potentiometers. Then, by varying the potentiometer, these values can be changed within the fixed range. These values are given to the

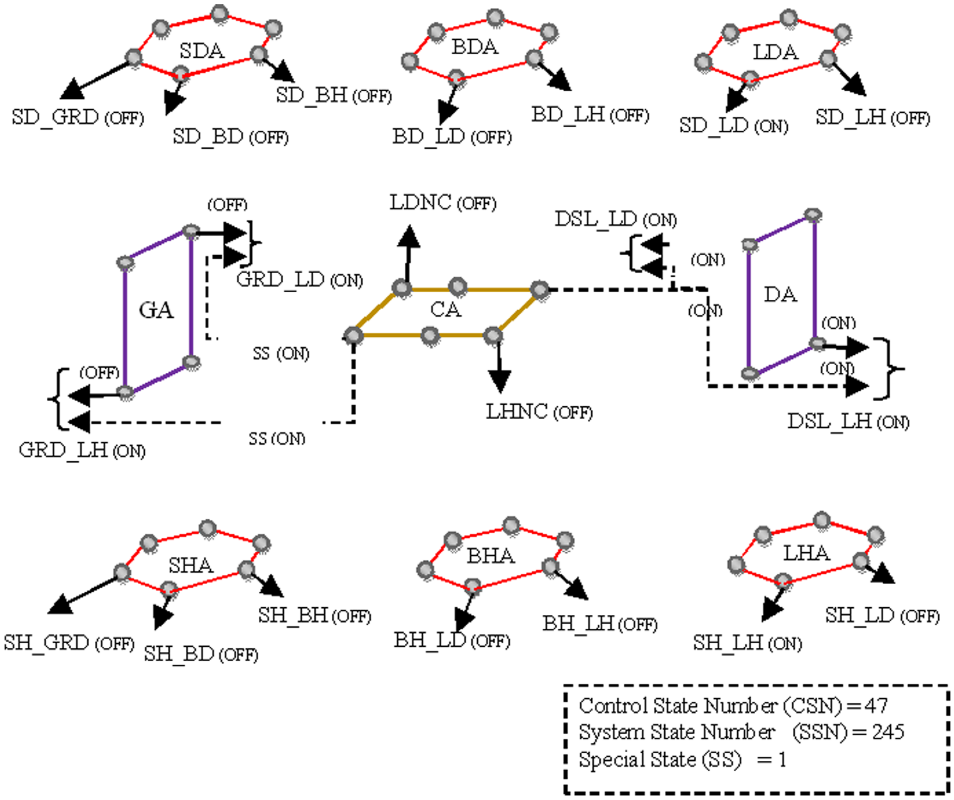

Figure 8. Switching Strategy of Agents for SSN and CSN.

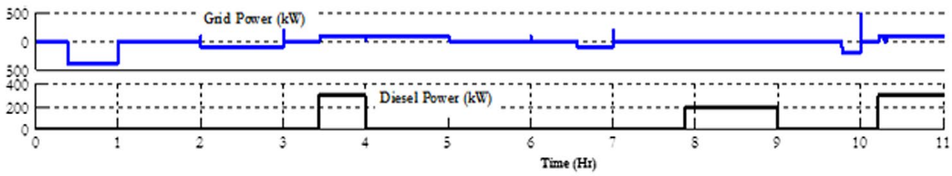

Figure 9. Simulation of Energy Management of Solar Micro-grid with NCL.

Table 1. Case Study Values (kW).

Time	SDP	LCDP	LNCDP	SHP	LCHP	LNCHP	DPR	GPR
0	600	400	0	400	200	0	12	9
1	300	500	0	500	300	0	12	9
2	500	300	0	200	300	0	9	12
3	300	500	0	200	400	0	9	12
4	300	400	100	200	200	200	12	9
5	300	400	0	200	200	0	12	9
6	600	400	0	400	400	0	9	12
7	400	500	0	300	300	0	9	12
8	300	400	0	400	400	0	9	12
9	500	400	0	400	300	0	12	9
10	200	300	200	100	400	100	12	9

control agent through serial communication and from the control agent all other agents get their environmental values. The agents communicate and coordinate with other agents for strategic decision and the resulting command signals are passed to the actuators for physical action. This is observed through the corresponding LEDS, Digital write of high or low is done on the agent when the ACL communication is active. We consider an 8 bit number, each bit represent a micro-grid device action. Bit value 1 represents ON and 0 represents OFF. These 8 bit output is given through Arduino microcontroller to the corresponding LEDS to show the physical action of the corresponding micro-grid devices. Thus the real time operation of MAS for energy management of the micro-grid is practically verified by using the Arduino microcontroller as shown in the Figure 10. Here we consider in the tenth hour of simulation, both the department and hostel have 100 kW excess after supplying their respective loads. This 200 kW excess power is used to charge the batteries. Here all the agents are active except grid and diesel agent. So, in the figure the last two LEDs representing Grid and Diesel are OFF and all other LEDs are ON. Thus the agent operations are verified using Arduino.

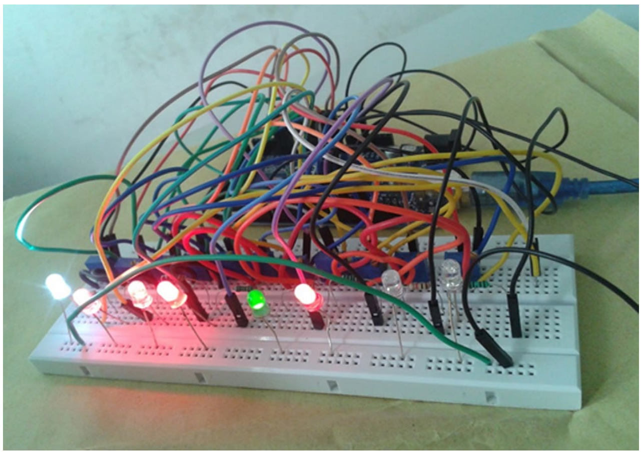

Figure 10. Practical Verification of Agent Operations using Arduino Microcontroller.

7. Conclusion

Since MAS implementation in JADE framework is not capable of performing real-time constrained control operation of micro-grid, it is linked with solar micro-grid model, developed in MATLAB/Simulink, through MACSimJX. This helps to validate the agent operations through hardware in loop simulations bringing MAS closer to practical implementation. Autonomous energy management and demand side management of solar micro-grid is implemented to achieve the lowest possible cost of power generation under intermittent nature of solar power and randomness of load. The proposed framework explores all possible logical sequences of options, understand the stochastic environment, and select the optimal energy management actions to increase operational efficiency autonomously in a distributed environment. MAS in JADE are implemented with Arduino microcontrollers and the agent operations for environment dynamics are practically verified. Future work will focus on extension to multiple agents integrating diverse renewable generators (solar and wind etc.). Furthermore, this autonomous, distributed energy management of micro-grid can be scaled through big data, data analytics and cloud computing principles for smart grid and industry 4.0 applications.

Disclosure statement

No potential conflict of interest was reported by the authors

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