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Implementation of energy management and demand side management of a solar microgrid using a hybrid platform

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Abstract: This paper presents the implementation of the advanced distributed energy management and demand side management of a solar microgrid by a multiagent system (MAS) coordination approach. The proposed approach is built upon a hybrid platform in which a solar microgrid, modelled in MATLAB/Simulink, is controlled by a MAS implemented in Java Agent Development Framework (JADE), bringing the MAS closer to the real-time application. Novel control strategies are designed to implement all the smart grid features in the microgrid. The Simulink model is controlled by strategic action of agents in JADE, a multithreaded computing platform, through a middleware, multiagent control using Simulink with JADE extension (MACSimJX). Environment values are fed to JADE through Simulink and the decisions are given back to the Simulink model for validation and also for real-time deployment. JADE leverages the advantages of the MAS and autonomously manages all the environmental dynamics and challenges introduced by the penetration of intermittent renewable energy resources in a short time, improving the stability, reliability, and fault tolerance of the solar microgrid.

Key words: Solar microgrid, energy management, demand side management, multiagent control, Java Agent Development Environment

1. Introduction

The electric industry landscape is changing due to the proliferation of renewable resources and active demand. The power grid is moving towards a more decentralized, more sustainable, and smarter power system. A microgrid is an interconnection of low voltage distributed resources with loads and batteries [1]. It is the building block for a smart grid and poised to play a major role in enabling the widespread adoption of renewable energy. However, their integration into the main grid entails new challenges for control as the power generated is intermittent in nature, which impacts the reliability and stability of the grid. To meet these challenges microgrid monitoring should incorporate communication and control to react quickly to changes and to achieve an optimal balance between generation, energy storage, and load demand. Traditional supervisory control and data acquisition (SCADA) has a central controller that gathers all system knowledge and makes the decision. SCADA is inadequate to cope with the high penetration of intermittent renewable energy resources and complex control decisions due to the lack of flexibility and extensibility. Dynamic management of a large number of resources leads to computational complexity and communication overhead. Maintaining a reliable and stable grid will require that the dynamics be balanced in real time. Dynamic energy management is a key enabler

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for the integration of renewable energy into the electrical grid [2]. Microgrid energy management and various trends in microgrids are discussed in [3,4]. The computational intelligence methods and classical algorithms for energy management of microgrids are discussed in [5]. A centralized approach is used in most of the existing research on microgrid operation problems. In order to reduce communication overhead and improve robustness, a decentralized control approach can be used for energy management of microgrids. The distributed nature and potential for modelling autonomous decision-making entities in solving complex problems motivates the use of a multiagent system (MAS) for the control of a microgrid [6]. MASs are used for controlling microgrid operations and exchange of energy with the grid is discussed in [7]. Here the capabilities of MAS to improve the operational efficiency are analyzed considering a fully decentralized approach of MAS. To be fully autonomous each agent should have complete knowledge about the environment and capacity to make decisions. Therefore, it is not economical to be fully autonomous. Moreover, we want to leverage the asynchronous agent communication for coordinated action. Hence, some level of centralized control is necessary for coordinated operation. The design and implementation details of a MAS in microgrid energy management along with seamless transition from grid connected to island mode are discussed in [8]. Here a hierarchical MAS approach for microgrid operation is considered where the agents take autonomous decisions locally and coordinate with other agents for global decisions. Only MAS simulations in Java Agent Development Framework (JADE) are discussed and further steps towards real-time control are not explained in detail. Optimization of a microgrid using a MAS is discussed in [9]. Here the MAS approach is used in a dynamic environment to improve performance and stability. MASs are simulated in JADE but linking agents to real-time operation is not discussed here. A MAS for operation of an integrated microgrid is discussed in [10]. Here the MAS was implemented in JADE platform and was interfaced with a real-time data simulator (RTDS). The sensing of environment dynamics and control strategies are not discussed here. Multiagent-based distributed energy management for an intelligent microgrid is discussed in [11]. Here the market operation of a microgrid is simulated in JADE. Practical realization of the MAS for market operation is not discussed. A complete review of microgrids in MAS perspectives is discussed in [12]. Multiagent-based microgrid control is discussed in [13]. Control strategies to optimize power exchange between microgrid and main grid are discussed here, but facilitating the MAS for practical application is not addressed. Comprehensive power management in a microgrid with distributed agents is discussed in [14]. Various control strategies to improve the stability of the microgrid along with case studies are discussed here. Distributed online optimal energy management for a smart grid is discussed in [15]. Here MAS is used for economic dispatch and demand response for maximizing the welfare of the society. A detailed review on agent concepts applied to intelligent energy systems is given in [16]. The latest survey on MASs for microgrid control is given in [17]. Most of the papers in these reviews deal with only simulation of MASs in JADE, which is inadequate for validating and implementing the real-time control of a microgrid. MASs with JADE simulations are only used for theoretical study. MASs have to be linked with MATLAB/Simulink for comprehensive simulation for validation and actual deployment in the field. However, MATLAB does not support multithreading operation, which is an essence of MAS. Therefore, we consider a middleware multiagent-based control and simulation with JADE extension (MACSimJX) to link MAS and MATLAB [18]. Although a very recent paper introduced this approach [19], the sensing strategies in dynamic environment, control strategies, MAS to MATLAB linking strategies, and implementation details are not addressed in detail. Moreover, the features of the smart grid are not implemented for dynamic energy management of a microgrid for making it a smart microgrid. The process of co-simulation, development, validation, and verification for actual deployment of time-critical MAS applications in a microgrid have not been adequately addressed to date. Hence, we propose multiagent control based advanced energy management and demand side management of a solar microgrid by linking a MAS with a solar microgrid, modelled in MATLAB/Simulink, by multiagent control using Simulink with JADE extension (MACSimJX). This opens MATLAB to agent development environments, allowing real-time hardware systems to be modelled alongside and interact with the software model, bringing MAS closer to practical implementation. All the possible environmental dynamics are comprehensively analyzed and autonomously controlled by MAS with its inherent features to improve the reliability, stability, and fault tolerance. Novel control strategies are introduced for autonomously sensing the dynamic environment, and controlling the actuators for implementing smart grid features, taking automation to a new level in the microgrid environment. The rest of the paper is organized as follows. In section 2, a detailed discussion on the MAS approach and multiagent platform is given. Problem formulation is given in section 3. Implementation of energy management of a solar microgrid using MACSimJX is explained in section 4. Experimentation and results are given in section 5. The discussion and conclusion are given in the final section.

2. Multiagent systems

2.1. Advantages of a multiagent system

Autonomous components and coordinative actions are the basic ingredients of any distributed system. The limitations of distributed systems that involve many heterogeneous entities are as follows:

i) They lack run-time adaptive behavior as the interactions are fixed while coding instructions.

ii) A distributed system with many on-going interactions is almost infeasible since maintaining parallel communication is expensive. These considerations have motivated us to go for a distributed system based on the agents providing ways for adaptation and on-going interactions.

A MAS is a distributed system consisting of multiple software agents that form ‘a loosely coupled network’ to work together to solve problems that are beyond their individual capabilities. MASs are an emerging subfield of distributed artificial intelligence (DAI) and are decentralized, emergent, and concurrent. MASs have inherent benefits such as flexibility, scalability, autonomy, and reduction in problem complexity. An agent receives information about a state of its environment, takes necessary actions, which may alter that state, and expresses preferences among the various possible states. Agents have their own control over their behavior and internal states in any possible environment. Every agent has four behavioral attributes: autonomy, social, proactive, and reactive. One agent can cooperate with other agents for coordinated action and so has the ability to interact with other agents through an asynchronous communication language called Agent Communication Language (ACL). Reasoning, optimizing, controlling, and learning are the characteristics of an agent. Agents satisfy certain objectives using their resources, skills, and services. The way that the agent uses its resources, skills, and services defines its behavior and the behavior is formed by its goals.

2.2. Multiagent systems in microgrids

Centralized SCADA, which was designed for traditional passive networks, may be inadequate to cope with the high penetration of DERs and complex control decisions due to its centralized approach, lack of flexibility, and extensibility. In the microgrid, uncertainty in SCADA systems arises when inferred knowledge cannot be judged accurate due to the intermittent nature of DERs. Moreover, SCADA has problems dealing with uncertainty, incompleteness, and inconsistent or conflicting data from multiple, heterogeneous sources. Humans supervised such problems to reason and resolve issues. A multiagent energy management system (EMS) can cope with heterogeneity and give a better, faster solution than SCADA, taking the automation of the microgrid to the next level [20].

The energy management system in a microgrid is tightly associated with the communications between stakeholders and entities (agents) to exchange information. Plug and play adaptability for renewable energy is seamless in MASs. MASs can be scaled up by adding other agents or by dispersing them in new environments with new resources and capacities on the fly. In MASs, economic and control mechanisms are used for dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter. MASs have begun to emerge as an integrated solution approach to distributed computing, communication, and data integration needs for deregulated power systems.

2.3. Multiagent platform

JADE provides a convenient distributed platform for users to focus on developing agents for control and monitoring of microgrid operation. JADE is an open system that supports plug and play capabilities and is also scalable without much modification to the control scheme. In this paper, a JADE framework that conforms to the FIPA (Foundation of Intelligent and Physical Agent) standard for intelligent agents is used. The agent platform is a software environment, where software agents run. The agent lives in a container, and a collection of containers makes up a platform. Agent management service (AMS) is responsible for managing the agent platform, which maintains a directory of agent identifiers (AIDs) and agent states. Each agent must register with an AMS in order to get a valid agent ID. A directory facilitator (DF) provides the default yellow page services in the platform, which allows the agents to discover the other agents in the network based on the services they need.

3. Problem formulation

i) To implement advanced distributed energy management and demand side management of a solar microgrid with a hybrid platform in which a solar microgrid, modelled in MATLAB/Simulink, is controlled by a MAS implemented in JADE.

ii) To improve the stability, reliability and fault tolerance of the solar microgrid under the dynamic environment using multiagent control, increasing operational efficiency, and reducing the carbon emission, leading to economic and environmental optimization.

iii) To validate the MAS control operations through comprehensive and accurate simulations using MATLAB/Simulink for real-time implementation in the field.

iv) To implement smart grid features in the microgrid for making it a smart microgrid.

4. Implementation of energy management of solar microgrids using MACSimJX

4.1. Simulink model of solar microgrids

We consider two solar microgrids, one in the department and other in the hostel on our campus. The Simulink model is developed for the solar microgrid components such as solar power generator, load, and battery for the department and hostel units, diesel generator, and grid (SDP, LDP, BD, SHP, LHP, BH, GRD, and DSL). Each device is modelled in such a way to carry out their operations. The waveform across all the devices can be seen through scope. In the Simulink model of the department solar power unit, the power is given to the department load and 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 the remaining power is given to the grid. The hostel solar unit is also designed in a similar way. In the Simulink model of the department load, the load receives power from the department solar unit and then from the hostel solar unit. The further requirement of power is taken from the department battery and then from the hostel battery. If power is still required, it is received from a diesel unit or grid unit based on unit price at that point of time. Load is divided into critical load (CL) and noncritical load (NCL) so that NCL shedding can be done before going to the external power resources like diesel or a grid. The load in the hostel is also modelled in a similar fashion. In the Simulink model of the department battery, three types of state of charge (SOC) are considered. Fully charged, SOC is in between fully charged (100%) and fully drained (40%) and SOC is at fully drained (40%). The less 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 a very short time and if less power is drawn, it discharges for a long time. Simulink models of grid and diesel are designed in such a way that both the department load and hostel load can take power from the diesel or grid based on the unit price at that point of time. The cheapest power is taken every hour for economic optimization. It is designed in such a way that when the diesel power is exhausted, grid power is taken without price comparison. The input ports, output ports, and switching operations relevant to these Simulink models are shown in Figure 1. Here SD_LD represents the switch connecting the department solar unit and its load. SH_LH represents the switch of the hostel solar unit and its load. Similarly, other switches are identified. Twelve input ports and 25 output ports are considered. The environmental variables are given to Simulink through the 12 input ports. The 25 output ports are connected to the actuators for physical switching action, which is reflected in the simulation output.

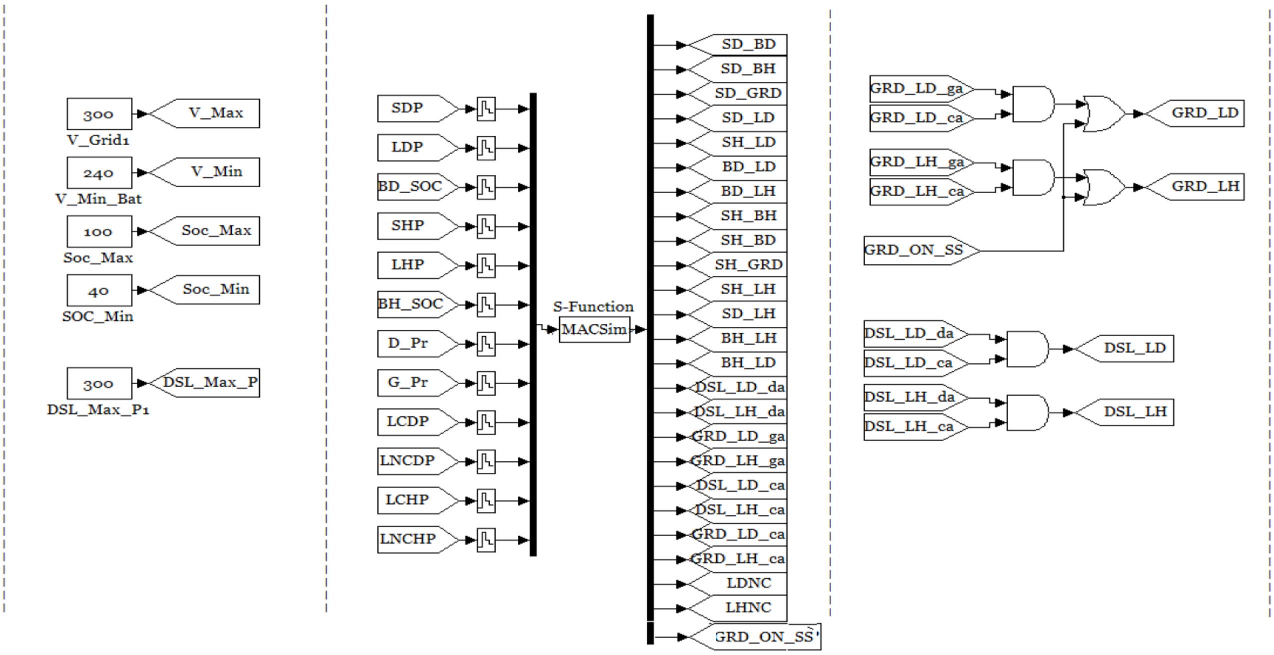

Figure 1. Solar microgrid switching operation in Simulink.

4.2. Multiagent control using Simulink with JADE extension (MACSimJX)

In Simulink, the S-functions are unable to handle multiple threads of execution, which is an essential characteristic of MAS: they become unstable if several processes run concurrently inside Simulink. To overcome this problem, we use a middleware MACSimJX, to act as interface between Simulink models and the agents, bringing MAS closer to the practical applications. MACSimJX has client-server architecture, separating the MAS from Simulink as shown in Figure 2. Distributed energy resources (DERs) use a decentralized approach of MAS for simultaneous operation to improve the operational efficiency of the microgrid. The S function in Simulink allows programs written in other languages like C++ and Java to run on MATLAB. Therefore, the agents can be created in Java and run on Simulink. However, in JADE agents run in parallel with multithreading and S functions do not support parallel operation, which is the essence of MASs. S functions become unstable if several process run concurrently inside the Simulink. Thus, multiagent control for Simulink (MACSim) is developed as a medium for JADE agents to pass data to and from Simulink. MACSim utilizes the S function ability of Simulink but only as a gateway to pass data to JADE with parallel processing capacity. In the client-server architecture of MACSim, the client part is embedded in Simulink through an S function and the server code is incorporated in the separate program. Communication between the client and server is then performed through the use of named pipes in Windows operating systems. Two pipes are used, one for passing configuration information and the other for passing simulation information. This allows these two processes to be run asynchronously. All communication across these pipes is passed in a fixed size message format. Queries are sent by the client and responded to by the server. The MACSim server manages the parallel operations of JADE and passes data to and from the MACSim client, which is embedded in Simulink through an S function. Thus MACSim circumvents the multithreading issues of Simulink to manage the simultaneous operations of DERs to improve runtime efficiency. JADE leverages the advantage of MAS and comprehensive simulation is done in Simulink for validation of time critical applications.

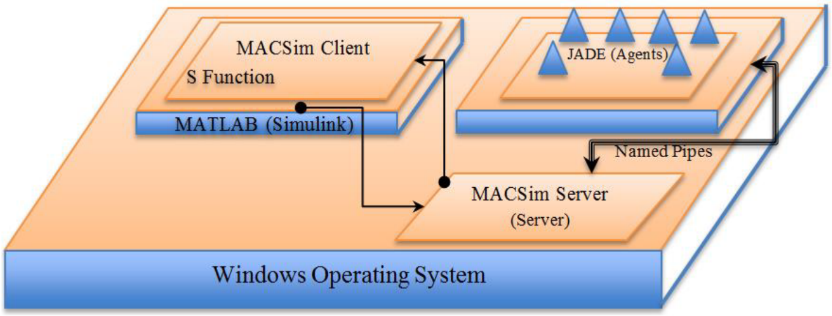

Figure 2. Architecture of MACSimJX.

The complete model of MACSimJX is shown in Figure 3, which shows how the signals are given from MACSim client to the MACSim server. Once simulation signals arrive at 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 the 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, namely solar department agent (SDA), solar hostel solar agent (SHA), load department agent (LDA), load hostel agent (LHA), grid agent (GA), diesel agent (DA), and control agent (CA). These agents are programmed in Java in JADE environment jointly operating on the data arriving from Simulink in order to accomplish the goal of optimizing the energy management of a solar microgrid. 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 Simulink simulation cycle so that the resulting actions are reflected in the Simulink model and further they can be sent as to intelligent electronic devices (IEDs), program logic controllers (PLCs), and remote terminal units (RTUs) for switching operation of circuit breakers and relays in the field.

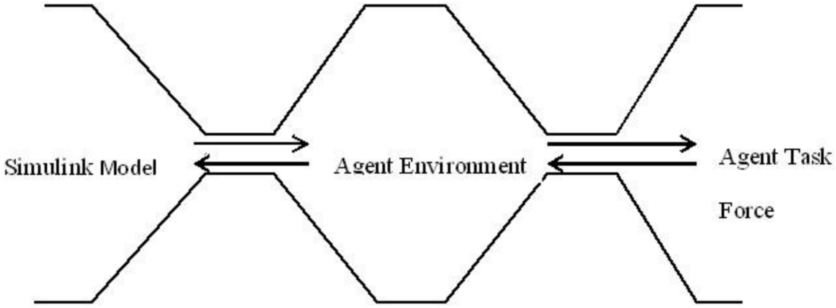

Figure 3. A complete model of MACSimJX.

4.3. A novel control strategy

Based on all possible environmental dynamics, an eight-bit number is formed as shown in Figure 4. The various combinations of load and solar power values in the 8-bit number give 256 possible states, from 0 to 255; 108 of these states are active and the remaining states are null states, i.e. they do not occur. The states are analyzed and relevant output port switch operations of these ports are identified. The switching operations corresponding to all the agents in the ATF are identified. Then for these output port switching operations the relevant state numbers are consolidated. The state number is broadcasted to all the agents, and, by observing it, an agent decides on the subset of switching operations it is expected to do. Each agent does the switching operation based on the environmental scenario reflected in the 8-bit number. The dynamic control operations of agents are reflected in the Simulink model for actual deployment.

4.4. Demand side management

The load is divided into CL and NCL in the department and hostel. Every hour, we define the NCL and resort to grid or diesel, only if there is a shortage of power for CL. Thus demand side management is done for economic operation. Along with the 8 other agents, a control agent is also included in the ATF that specifically controls the NCL. Two layers of agents are formed: the control layer contains a control agent for NCL control and the system layer contains all the other agents for controlling the CL. The necessary parameter communication between these two layers is established for microgrid control switching operations. A 6-bit number is formed for NCL shedding operations. A special state number is formed for the power requirement post NCL shedding in the control agent to bypass the comparison of unit price of grid and diesel when the diesel power is fully exhausted. The control layer agent does the switching operation of LDNC, LHNC, GRD_LD, GRD_LH, DSL_LD, and DSL_LH to control the NCL for demand side management. GRD_LD represents the grid to department load switch. The control layer agent acts in coordination with system layer agents for controlling NCL. After the shedding of NCL, only when the conditions in the two layers are favoring is the grid or diesel connected to the loads.

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 [+] $W_D = 0$ [-] $W_D = 1$	SHP-LHP [+] $W_H = 0$ [-] $W_H = 1$	SDP-LDP + SHP-LHP [+] X=0 [-] X=1	[1] SOC_BD = 100 [2] SOC_BD < 100 & >40 [3] SOC_BD = 40	[1] Y_D=00 [2] Y_D=01 [3] Y_D=10	[1] SOC_BH =100 [2] SOC_BH < 100 & > 40 [3] SOC_BH = 40	[1] Y_H=00 [2] Y_H=01 [3] Y_H=10	DSL_Pr > GRD_Pr [>] Z = 0 [<] Z=1
SSN	WD	WH	X	Y_{D1}	Y_{D0}	Y_{H1}	Y_{H0}	Z
245	1	1	1	1	0	1	0	1

Figure 4. System state number formation.

5. Experimentation and results

5.1. Agent operation

In the solar microgrid every hour the solar power, load and the battery level, NCL, and dynamic pricing are monitored continuously and based on the randomness of load and intermittency of solar power the agent considers all possible logical options and chooses the best possible action for optimal energy management of an advanced, dynamic solar microgrid, leading to economic and environmental optimization. Two grid-connected solar microgrid systems that contain a local consumer, a solar PV system, and a battery are considered. The first solar unit is in the department with capacity of 1000 kW and the other solar unit is in the hostel with capacity of 1000 kW. The load patterns are calculated and the generated solar power of the department and the hostel are observed with the help of the National Renewable Laboratory (NREL). Eight inputs are considered: 1) solar department and hostel power (SDP, SHP), 2) diesel generator power (DP), 3) department and hostel load (LDP, LHP), 4) state of charge of the department and hostel batteries (SOC), and 5) grid power (GP). All the operations are considered and Java programming is done for all the agents in JADE framework and executed in Eclipse integrated development environment. The JADE sniffer output diagrams, showing interaction of the agents and transaction details, are shown in Figure 5. The flowchart is shown in Figure 6. The overall procedure is as follows.

i) Initially the department load agent (LDA) communicates the power demand through an ACL message with the available solar power in the department solar agent (SDA) of the department at that specific hour. If the power is not sufficient to cover the load, it checks with the availability of solar power in the hostel solar agent (SHA) through a control agent (CA). If required power is not sufficient in SHA, it looks into the battery of the department (BDA). The battery supplies the full requirement until it gets drained. If more energy is required, it gets drained in less time and if less energy is required, it takes more time to get drained. Then it checks the hostel battery agent (BHA) and gets full power from it, until it gets drained. These strategic actions are taken through the control agent.

ii) Even after taking from the solar unit and battery, if power is still required, then the control agent checks

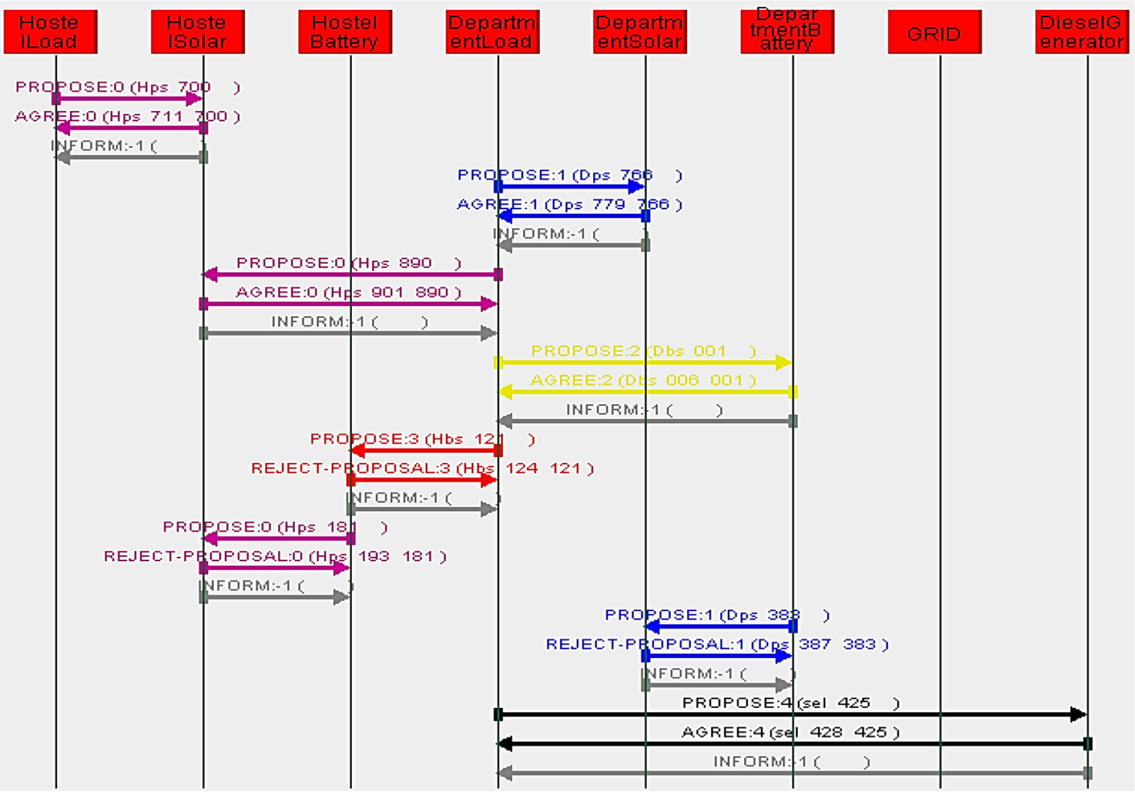

Figure 5. JADE Sniffer output.

for NCL shedding at that particular hour and follows demand side management strategies. Load response strategies include both load shedding as well as load shifting. Load shedding involves curtailing equipment that is not critical and load shifting is the rescheduling of energy-intensive operations to a different time period. NCL is specified for every hour and can have many priorities based on the requirement. Even after NCL shedding, if load requires power, it checks with the unit pricing of the grid and diesel at that hour and chooses the lower priced one. The diesel power is limited and so if diesel unit price is less it chooses diesel and when diesel power is fully exhausted, grid is chosen irrespective of price. This leads to economic optimization.

iii) If surplus energy is available in SDA after supplying to its load (LDA), it checks its battery agent (BDA) to charge it fully and it checks the hostel battery agent (BHA) to charge fully. Then the surplus power is given to the grid through the control agent.

iv) Each agent is programmed with relevant switching operation for taking reflexive action. The directory facilitator facilitates coordination of agents for the switching actions at appropriate times based on different scenarios. Based on the dynamics of environment variables, an 8-bit number is formulated as mentioned in section 4.3 and this number is broadcasted to all the agents. By looking at the number that reflects the particular environment scenario, the agents do the relevant switching operation. These switching commands are given to Simulink by MACSimJX for dynamic simulation. These action commands are further given for physical action of switches in the solar microgrid.

v) Post NCL operation, if the grid or diesel power is not required then the control agent switches off the grid even when the other agent switches on the grid, by its priority. Moreover, when the diesel power

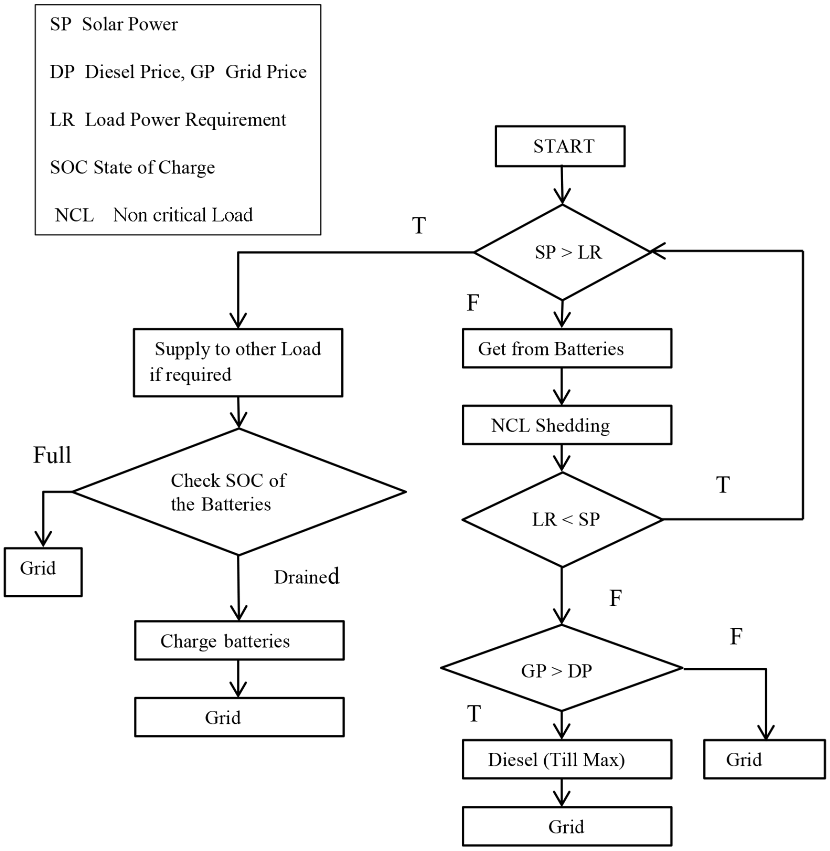

Figure 6. Flow chart.

is exhausted, the required power is received from the grid irrespective of the price. These logics are implemented by giving a special status to the control agent. Every hour based on the load requirement and availability of solar power, the agent takes the best possible decision for economic operations in a distributed environment. Similar steps are followed for the hostel agent.

Every hour the power is traded with the grid or diesel generator due to the intermittent nature of the solar power and randomness of load. After negotiation is completed, the final result is reported by the CA, which tells other agents how much power is to be traded with the grid or diesel generator based on the per unit price at that time. Every hour various possible scenarios are considered and the agent chooses the best possible action for economic and environmental optimization of the solar microgrid. Economic optimization is in the sense that it chooses the least cost resources, which is the best possible option every hour. Environmental optimization is in the sense that it chooses the renewable energy resource (solar) as much as possible whenever there is a demand.

Thus every hour the environment variables of the solar microgrid are sensed and given to the agents through the MATLAB/Simulink model. Programming is done for every agent in JADE. Agents coordinate and take strategic decision and the control commands are given to MATLAB/Simulink for validation and also for real-time physical action. Thus energy management is done dynamically for the solar microgrid by using the hybrid platform. Due to the multithreading operation of JADE and inherent features of the MAS, faster response is achieved to improve the responsiveness, reliability, and stability of the solar microgrid.

5.2. Case study

The experimental values for the solar microgrid environmental variations in every hour are shown in the Table. Here LCDP and LNCDP represent CL and NCL of the department. Similarly LCHP and LNCHP represent CL and NCL of the hostel. GPR and DPR represent grid and diesel price. After the strategic action of the agents the resulting actions are reflected in MATLAB/Simulink output as shown in Figure 7. In this simulation output, initially from hour 0 to 1, the department and hostel solar powers (SDP and SHP) are 200 kW more than the corresponding load demand and so the department and hostel batteries are fully charged with the total excess power of 400 kW and then this power is given to the grid. As shown in the simulation output,

Table. Experimental values of solar microgrid (kW).

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

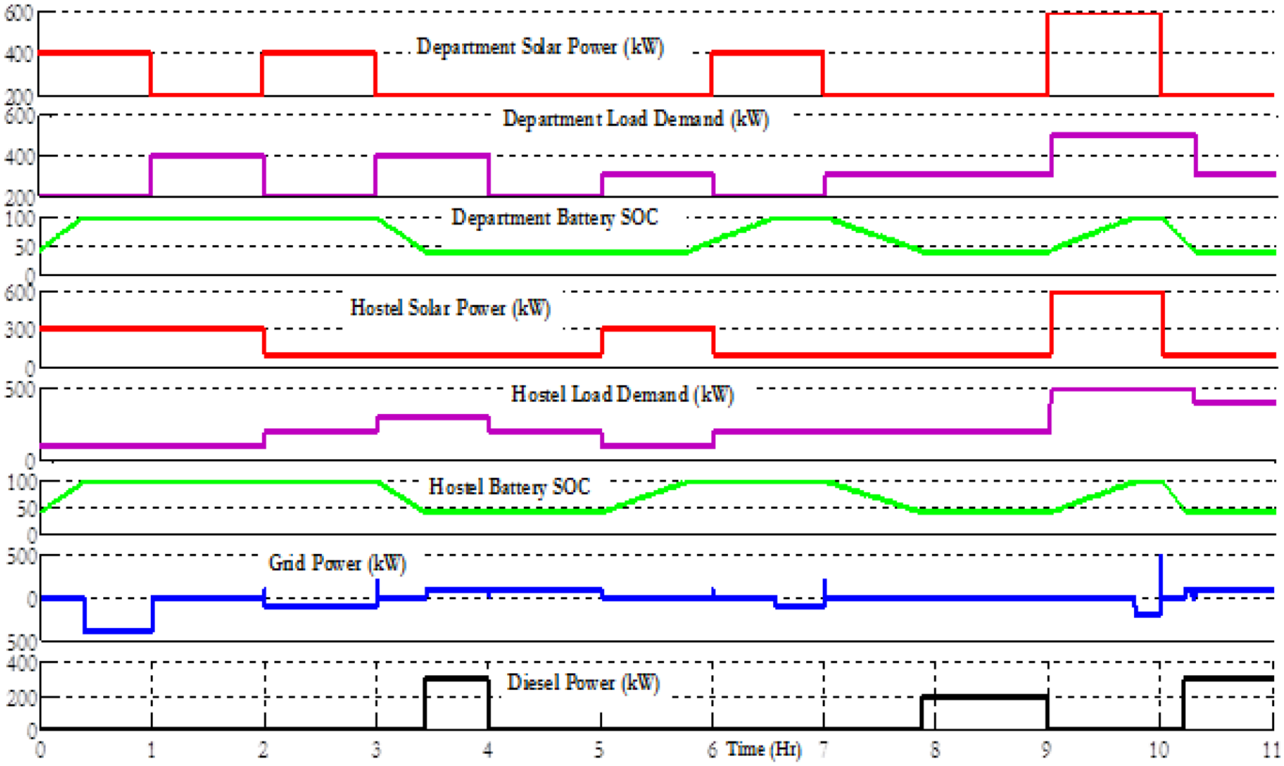

Figure 7. Solar microgrid energy management with NCL.

after the charging of batteries, the grid goes to negative, meaning that power is given to the grid. From hour 1 to 2, the load demand in the department is 200 kW more than the solar power and in the hostel the solar power is 200 kW more than the load. Since the SOC of the battery is continued from the previous state, both are fully charged. Therefore, the excess 200 kW power in the hostel solar is given to the department load. In hour 2 to 3, the department solar has excess power of 200 kW and the hostel solar has 100 kW deficit. Out of the 200 kW excess power, the department solar gives 100 kW to the hostel load and the remaining 100 kW is given to the grid. From hour 3 to 4, there is 200 kW deficit in both the hostel unit and the department unit. Thus, with a total of 400 kW deficit, both the batteries are discharged until they get drained and then the full available power of 300 kW is received from the diesel unit. The remaining 100 kW is received from the grid. From hour 4 to 5, there is 200 kW deficit in both the hostel unit and the department unit. Hence with a total of 400 kW deficit, the NCL of 200 kW in the department and 100 kW in the hostel is shed. The power requirement postshedding is 100 kW. Since the batteries are fully drained in the previous hour, the required 100 kW is received from the grid, as the grid price is less than the diesel price. From hour 5 to 6, department load requires 300 kW but the available solar power is 200 kW. Since there is 200 kW excess in the hostel unit, it gives 100 kW to the department load and the remaining 100 kW is first used to charge the hostel battery and then the department battery. From hour 6 to 7, there is 200 kW excess power in the department unit and 100 kW deficit in the hostel unit. Therefore, department solar gives 100 kW to the hostel load and the remaining 100 kW is used for charging the department battery until it is fully charged, and then the 100 kW is given to the grid as the hostel battery was fully charged in the previous hour. From hour 7 to 8, the department and hostel units have a deficiency of 100 kW each and so both the batteries are discharged until the cut-off and then the required 200 kW is received from the diesel unit as diesel price is less than grid price. From hour 8 to 9, the department and hostel units have deficiency of 100 kW. Thus the required power of 200 kW is received from diesel as the diesel price is less than grid price. From hour 9 to 10, the total excess power is 200 kW (100 kW each in the department and hostel). After both the batteries are charged fully, 200 kW is given back to the grid. In hour 10 to 11, there is 300 kW deficit in the department and 400 kW deficit in the hostel. Here the NCL of 200 kW in the department and 100 kW in the hostel are shed after the batteries of the department and the hostel are fully discharged to meet power requirement for the load. Post-NCL shedding, out of the required 400 kW, 300 kW is received from diesel as it is cheaper and its full capacity is 300 kW. The remaining 100 kW is received from the grid irrespective of the price, by activating the special status action of the control layer agent. The NCL control operations are observed in hours 5 and 11 of operations for effective demand side management. In this simulation all the smart grid features such as dynamic pricing, net metering (giving back to grid, prosumer), modularity, flexibility, fault recovery, demand side management, and demand response are included in the microgrid, thus making it a smart microgrid. Moreover, the agent chooses the best possible option (economic optimization) and uses solar as much as possible (environmental optimization). Validation is done for agent operation through a comprehensive and accurate simulation using MATLAB/Simulink, before practical verification in the solar microgrid field.

6. Conclusion

Practical application of a MAS for distributed energy management and demand side management of a solar microgrid is realized by linking MAS with MATLAB/Simulink. All the options available for the agents in the microgrid are comprehensively analyzed, tested, and validated for optimal, autonomous, distributed energy management of the solar microgrid for economic and environmental optimization under the intermittent nature of the solar microgrid and randomness of load. Smart grid features are implemented in the microgrid. Due to the decentralized approach of MAS and multithreading effects of JADE, it is obvious that in the proposed approach the response time and operational efficiency are increased considerably when compared to the conventional methods like SCADA, improving the reliability, stability, and fault tolerance of the solar microgrid. Future work will focus on scaling the work by integrating multiple diverse renewable generators (solar and wind) with several intelligent agents and interfacing with an Arduino microcontroller for verification of real-time operation.

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