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Multi-agent Energy-Saving Design for the Micro-grid Demonstration Project

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ABSTRACT

A micro-grid is an energy community having various Distributed Energy Resources (DERs) such as diesel engines, micro turbines, solar power, wind power, fuel cells and energy storage devices. The multi-agent architecture offers a hierarchical structure is very suitable for managing multi-individual and heterogeneous DERs in the micro-grid environment. This paper proposes a multi-agent architecture with energy-saving mechanism which merges with the existing micro-grid Energy Management System (EMS). The energy-saving mechanism adopts the embedding of sensors that can provide environmental information to EMS. Moreover, the EMS also exchanges energy information with the other elements of micro-grid to determine the best optimal controls on power flow, load dispatch and scheduling.

1. INTRODUCTION

Micro-Grid (MG) is an energy community having various Distributed Energy Resources (DERs) such as diesel engines, micro turbines, solar power, wind power, fuel cells and energy storage devices. The well developing renewable energy systems in modern world, ether in individual house or in small communities, belong to small-scale dispersed generation system. The overall MG has two operation modes, which are grid-connected mode and isolated mode. The grid connected mode will only be used when the local renewable generation is far less than the load demands (Wang 2011). In the islanded mode, the MG is isolated from the main grid and remains operational and functional as an autonomous entity.

From the system point of view, a MG can freely route the energy among the utility grid, local renewable energy generators, controllable loads, and DES devices, opening up a new paradigm of ‘‘Internet for Energy’’ (Huang 2011). The MG Energy Management System (EMS) is expected to monitor the operational conditions and optimally dispatch power from DERs and Distributed Energy Storages (DESs) nodes to supply the controllable and critical loads. In general, a sophisticated MG EMS has to operate and coordinate a variety of Distributed Generators (DGs), DES, and loads in order to provide high-quality, reliable, sustainable, and environmentally friendly energy in a cost-effective way.

In 2010, a MG demonstration project with total capacity of hundred-kW scale including wind power and high concentration photo voltaic generations has been firstly constructed in Taiwan by Institute Nuclear Energy Research (INER). The MG demonstration project provides an integrated platform that is not only for academic research purpose, but also for industry testing and implementation. Based on these facilities, INER is moving forward to developing an autonomous MG technology including reactive power control, low voltage ride through, frequency droop control, protection coordination, and energy management.

On the other hand, there are great progresses have been made in energy-saving researches and effort in the past decades. In fact, energy-saving mechanism usually takes advantage of smart environment for achieving energy saving purpose. The term smart environment refers to the embedding of sensors and actuators within a environment that react automatically to the users within that environment. The sensors are hidden from the user and become part of the environment (Eric 2012). They usually should not require the user to explicitly interact with the devices. These sensors could be in the form of thermometers, microphones, cameras, motion sensors, or any device that can provide information to an automated control system regarding the state of the environment. The control system can then use actuators to alter the conditions in the environment. Therefore, the integration of energy-saving mechanism with the existing MG architecture becomes an important demonstrate item in INER's demonstration project.

A multi-agent architecture is a combination of several agents working in collaboration pursuing assigned tasks to achieve the overall goal of system (Pipatta. 2009). Moreover, proposed multi-agent architecture inherent benefits of flexibility and extensibility. On the other hand, the major elements of MG, such as DERs, storage units and loads will have different owners. Each owner would like to make their own decision locally. Therefore, the agent-based decomposition structure of multi-agent architecture is most appropriate for modeling and managing elements relationships within the MG environment.

Before going any further, the potential benefits of applying agent-based energy-saving mechanism into multi-agent MG architecture is explained briefly as below:

1) The typical energy-saving mechanism usually employs environmental sensors to actuate controllers and reduce energy consumption. The ability of the environment to perceive and react to changes gives electricity power a sort of energy-saving. Moreover, the agent-based structure provides the capability of rapidly change. Therefore, agent-based structure is suitable for the architecture of energy-saving mechanism design. On the other hand, multi-agent architecture provides a better alternative architecture as agents are loosely coupled and can be integrated anytime any place. Therefore, multi-agent architecture is adopted to deal with the dependencies and interactions between agent-based energy-saving mechanism and the existing MG. Besides, multi-agent decompositions also can enhance the capability of exchange information within heterogeneous DERs.

2) While the need of EMS function to provide supervision and suggest near-optimal operation of the controllers, DER equipments and loads. This multi-agent architecture provides interoperability of diverse devices and would allow for individual devices to veto suggestions from the EMS that the device perceives as unacceptable or dangerous.

3) The philosophy behind multi-agent architecture is that a huge and complex task

can be divided into several smaller tasks assigned to several entities. This reduces the need for maintenance and processing of large data.

The organization of this paper is as follows. Section 2 introduces background information of MG EMS, major components, smart environment with sensors as well as agent technology. A three-layer Energy-saving Demand and Supply Control Framework (ESD-SCF) is proposed in Section 3. Next, the integration ESD-SCF with the existing multi-agent MG EMS and optimization Model with energy-saving agents support are explained in Section 4. Two optimization algorithms used for grid-connected mode and islanded mode are presented in Section 5.1 and Section 5.2 respectively. Finally, some conclusions and future work are given in Section 6.

2. RELATED BACKGROUND

2.1 Overview of Micro-Grid Energy Management System (MG EMS)

Although there is not a universal definition of MG EMS, it can be generally stated that MG EMS is a kind of control software that can optimally operate and coordinate a variety of MG components in order to provide high-quality, reliable, sustainable, and environmentally friendly energy in a cost-effective way (Hunag 2008). The major components associated with MG EMS and their functionalities are explained as below.

1) Distributed Generator (DG): DG is usually defined as a small scale (e.g., kilowatts) electric power generator which is directly connected to the distribution system at or near the load feeder. In contrast, conventional power plants supply electricity through high-voltage transmission lines with a capacity of hundreds of megawatts.

2) Distributed Energy Storage (DES): DES can make MGs more cost-effective by storing energy when energy from the main grid is cheap or there is excessive generation from the local DGs. DES can also be operated as an additional generator during peak demand periods. The detailed operations on DES are performed by the embedded local regulators within DES while the MG- level EMS will control when to dispatch the stored energy and how much. The overall energy management objective for DES varies depending on the MG operational modes. In an islanded MG mode, DES can return electric energy to minimize the disturbance on end-users and maintain the system reliability. In an interconnected mode, DES is mainly responsible for maintaining the stable power output of DGs and storing low-cost.

3) Electricity Load (ETL): In general, ETL might be divided into three categories: Critical Load (CL), Curtail-able Load (CTL) and Re-schedulable Load (RSL). Firstly, CL describes loads that must be met at all times, such as servers and loads. Secondly, CTL demands have a preferred level, but the demand level can be lowered if a certain cost is associated with the load reduction. The magnitude of CTL might be flexible. Thirdly, RSL demands may be flexible in their scheduling. Rescheduling could also involve shifting the execution of some energy intensive activities to later in the day, or further into the future. In the normal operational mode, the DG and DES nodes can be utilized to support as many CL as possible. Once a MG is disconnected from the main utility grid, not all of the load within a MG can be supplied. In order to improve the availability and reliability of power supply for CL, some of CTL and RSL may have to be disconnected or shed accordingly.

4) Point of Common Coupling (PCC): PCC is the point at which the power production, distribution network, and customer interface meet. In the most common configuration, DGs, DESs, and loads are tied together on their own feeders, which are then linked to the utility grid at a single PCC.

5) MG Central Control (MGCC): MGCC serves as a gateway between the distribution network operator and market operator and local controllers within the MG. Ideally, MG EMS is an information and control center embedded in a MGCC. Therefore, MGCC performs the same function as MGCC/EMS in this paper.

2.2 Smart Environment with Sensor for Energy-Saving

The main goal of the smart environment is used to improve the efficiency of energy usage. In the smart environment, usually equipped a few embedded of environment sensors and actuators. Therefore, it may be reacted the environment change automatically. The sensors are hidden from the user so they become part of the environment and should not require the user to explicitly interact with the devices. These sensors could be in the form of motion detectors, thermometers, microphones, cameras, or any device that can provide information to an automated control system regarding the state of the environment. For example, motion detectors that can turn on lights when they detect the inhabitant's presence. The rule-based control system can then use actuators to alter the conditions in the environment. These actuators could be a furnace or air conditioner to control the temperature, the lights or curtains within a room to control the lighting, etc.

An intelligent building is able to manage its smart environment via computer techniques to optimize energy efficiency. There have been many research projects that show the potential for using smart environment to reduce energy consumption. The different approaches use fuzzy logic (Doctor 2005) artificial neural networks (Mozer 1998, Davidsson 2000) and software agent (Z. 2010, Booy 2008) architectures to allow the smart environment to sense and react to the users. However, the software agent approach seems to be the most popular perhaps because its architecture is well understood and can be clearly defined (Eric 2012).

2.3 Agent Technology and Multi-agent Architecture

An agent is an encapsulated computer system that is situated in some environment and can act flexibly and autonomously in that environment to meet its design objectives (Jennings 2000). An agent might be working alone in an environment or it may communicate, coordinate and share with other agents to achieve its assigned goals. In agent oriented software engineering intentions are modeled as behaviors. A behavior of an agent may consists of a single or multiple actions and lead to a achievement of a goal or a sub goal.

A multi-agent architecture consists of several coordinating and computing entities called “agents”. These agents share common or distinct goals, react to the information received from their environment and other agents, perform computations and assist other agents in achieving their tasks in pursuit of achieving the overall goal of the multi-agent system. Moreover, a multi-agent architecture provides a natural way of decomposing a software system into subsystems and to model interactions between these subsystems and individual agents within the subsystems.

3. Energy-saving Demand and Supply Control Framework

In MG EMS, the potential benefits of integrated energy supply side and demand side control to achieve the goal of economic savings and improved energy efficiency. However, few studies have been done to integrate with the energy-saving mechanism. Figure 1 illustrates a three-layer Energy-saving Demand and Supply Control Framework (ESD-SCF) which represents a sensor-based control framework for integrating energy supply and demand side. ESD-SCF consists of Equipment Monitoring Layer (EML), Reconfigure and Control Layer (RCL) and Information Management Layer (IML). The functions of three layers are explained as below:

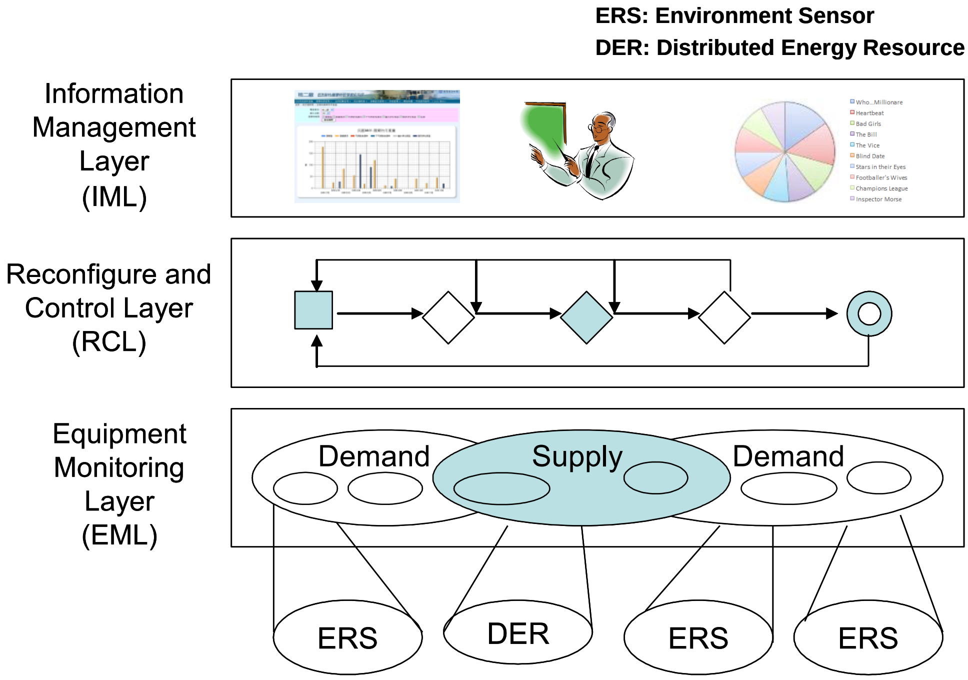

Fig. 1 Energy-saving Demand and Supply Control Framework (ESD-SCF)

1) Equipment Monitoring Layer (EML): The EML is classified into supply side and demand side based on their different control functions. In the demand side, there are various Environment Sensors (ERS) are adopted to monitor environment change, such as infrared sensors, pressure sensors, humidity, and light sensors, etc. Those environmental monitoring data are very useful for energy demand prediction. In the supply side, DERs equipments are responsible for reporting their operating status and performance information. The information of DERs equipment is the essential resource for the energy supply assessment.

2) Reconfigure and Control Layer (RCL): In ESD-SCF, RCL is the middle layer and is in charge of controlling the relevant actuators and assigning the set point of

equipment to achieve energy saving goals. In the electricity demand side, RCL ranks the heterogeneous demand, identified by applying energy-saving policies without violating existing constraints. In the electricity supply side, RCL interact with the EIL to perform their control tasks. Besides, it also is in charge of transforming relevant information to the above IML.

3) Information Management Layer (IML): IML is the top layer in ESD-SCF. IML is responsible for analyzing the load demand and electricity supply as well as make the optimal energy-saving decision. Furthermore, it has the responsibility to negotiate with outside electricity grid after an optimal reconfiguration decision. While a final optimal decision is made, the reconfigure and control command will be issued by RCL. Finally a set of energy-saving actions on the EML will be deployed.

4. Applying ESD-SCF TO MULTI-AGENT MICRO-GRID EMS ARCHITECTURE

4.1 Multi-agent Micro-grid EMS with Energy-saving Agents Support

A multi-agent architecture which applies ESD-SCF into the existing MG EMS structure is proposed as shown in Fig.2. In the novel architecture, there are two agents are designed in EML: Generator Agent (DGA) and Smart Environment Agent (SMA); DER Agent (DEA) and Energy-Saving Agent (ESA) are defined in RCL. However, DGA and DEA are adopted to support electricity supply side control; SMA and ESA are used for controlling demand side. The tasks of IML will be achieved by optimization model which is presented in Section 4.3.

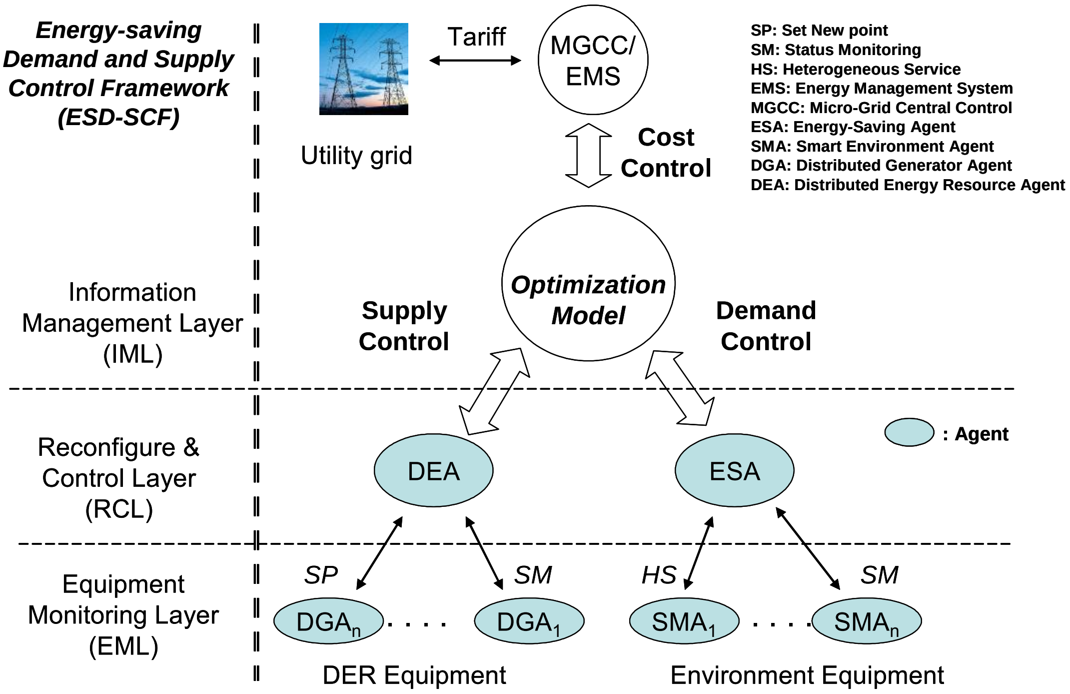

Fig. 2 Structure of the MG multi-agent architecture with energy-saving agents support

4.2 Energy-saving Agents Design

Based on the above ESD-SCF descriptions, this paper proposed four agents: Distributed Generator Agent (DGA), DER Agent (DEA), Smart Environment Agent (SMA) and Energy-Saving Agent (ESA). The further detailed descriptions of agents are as follows.

- Distributed Generator Agent (DGA) : Each piece of DER equipment has a specified range of operating levels, and a particular level of performance at each operating level. This performance will depend on equipment capabilities as well as on external factors such as ambient temperature, humidity, and pressure. Therefore, the DGA is designed to monitor the current status of DER equipments. In addition, weather conditions will affect the performance of DER equipment itself. Thus, the real-time environment monitoring data from SMA might be useful for the performance predict of DER equipment.
- DER Agent (DEA): DEA is responsible for storing associated DER equipment information, as well as monitoring and controlling power levels and its connect/disconnect status. DER equipment information includes DER identification number, type (solar cells, micro-turbines, fuel cells, etc), power rating (kW), local fuel availability, cost function or price at which users agree to sell, as well as DER schedule.
- Smart Environment Agent (SMA): SMA is designed to perceives the surroundings by collecting the information from environment sensors via wired or wireless communication network. Therefore, there are various SMA s are correspond to and control environment sensors, such as temperature SMA, illumination SMA, and air quality SMA and so on. For example, temperature SMA monitors the room temperature and receives data from the temperature sensors. The temperature SMA might set the heating system of heating up the room automatically or send relevant environment information to the agent of the upper layer (RCL).
- Energy-Saving Agent (ESA): ESA is in charge of executing the tasks of IML. ESA works on behalf of the decide-making of IML which demand control message to SMAs. On the other hand, the internal actual electricity needs and the monitoring message from SMA could be transmitted to IML. For instance, ESA receives CO_2 concentration information from air quality SMA. Next, ESA may control the opening and closing of valve actuator for ventilation system based on the making-decision from IML.

4.3 Optimization Model

The purpose of optimization model is to determine the proper dispatch of different kinds of DER equipments and provide optimal Heterogeneous Service (HS) for electricity loads with the final goal of minimizing the energy cost.

In Firestone study (Firestone 2005), the proper dispatch involves evaluating the reliability and performance of DER equipments. Moreover, the DER equipment reliability is related to DER dynamic properties such as the age of equipment, operating level and the time since the last maintenance. Load control is a key function of the MS EMS. Owing to some of the end-user load are assigned to higher (CL) or lower priority (CTL or RSL) on limited resources. HS can be thought of as the executer of load control. Therefore, this paper adopted three main input resources for the optimization model: the price comparison, DER equipment information and load information. The price comparison represents the result of comparing the price of self-generation and utility grid. DER equipment information comes from the DEA; load information is provided by ESA. In other words, DEA and ESA are in charge of reporting the monitoring status of DER equipments and end-user loads.

After receiving the above three resources, an optimization algorithm is employed to find the suitable solution. Once the optimal decision is made, purchase utility electricity, generation dispatch and the execution of HS are conducted. The day-ahead scheme based on hourly bids is assume to be adopted in this paper. Therefore, the above closed loop is executed hour by hour. The optimization model's inputs and outputs are depicted graphically in Fig.3.

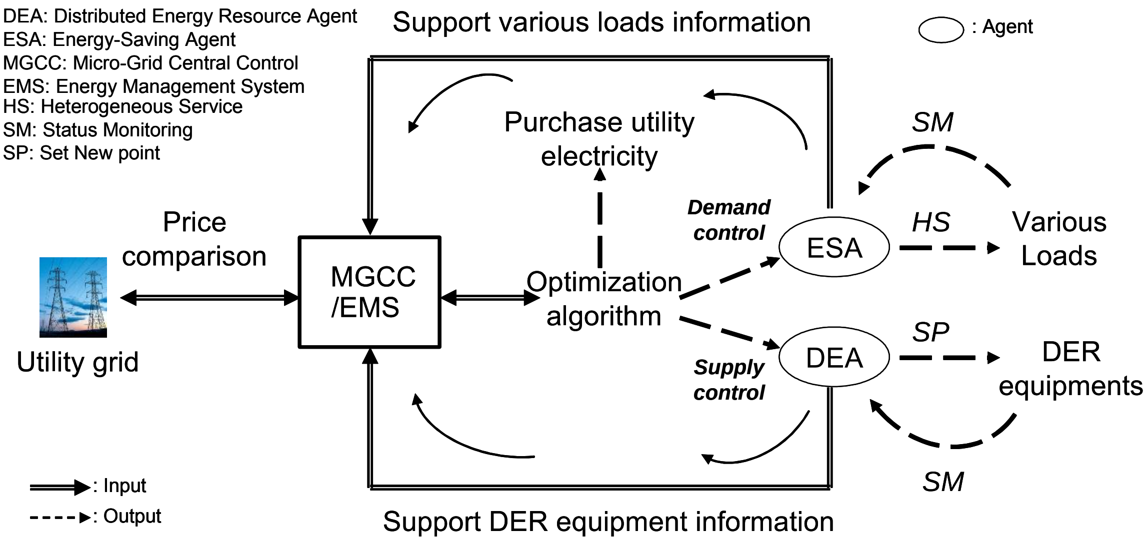

Fig. 3 Optimization model with energy-saving agents support

5. OPTIMIZATION ALGORITHM

5.1 Assumption Statements

Firstly, a day-ahead scheme based on hourly bids is adopted in this paper. Assume that a set of electricity loads **L**. Each electricity load $L_i \in \mathbf{L}$ is characterized with number of quality of service such as critical load, curtail-able load and re-schedulable load (L_i_**CL** *or* L_i_**CTL** *or* L_i_**RSL**). Each L_i is assumed quite stable and its values do not change through time.

In addition, assume that a set of DER equipments **R**. Each DER equipment $R_i \in \mathbf{R}$ is characterized with equipment information such as operating levels, ambient temperature, operating humidity, operating pressure and the age of the equipment as well as the time since the last maintenance. (R_i***_GEN***, R_i***_OPL***, R_i***_TEMP,*** R_i***_HUM,*** R_i***_PRE***, R_i***_AGE,*** R_i***_TIME,*** R_i***_COST***). The electricity generation cost of DER equipment (R_i***_COST***) is known, such as cost of electricity, natural gas, propane, heating oil, and any other fuels. The utility electricity price is assume $Price_{(hour)}$***_DAY-AH*** based on the day-ahead scheme hour by hour.

The optimal approach also needs to consider the requirement of regulatory constraints. Regulatory constraints may restrict the acceptable range of DER operations, and include restrictions on emissions and system efficiency (R_i***_CONST*).**

5.2 Optimization Algorithm in Grid-connected Mode (OA-GCM)

In grid-connected mode, there are two electricity suppliers and one end-user load should be considered. Therefore, the electricity price comparison between self-generation and utility grid should be made. When a new a new demand request comes from end-user, OA-GCM algorithm will perform the price comparison firstly, load information (L_i***_CL*** *or* L_i***_CTL*** *or* L_i***_RSL***) and DER equipments (R_i***_OPL***, R_i***_TEMP,*** R_i***_HUM,*** R_i***_PRE***, R_i***_AGE,*** R_i***_TIME***) are provided to find the minimal electricity purchase cost and optimal demand-supply management control. The above information is provided by energy-saving agents (ESA or DEA).

Step 0: MGCC/EMS checks all DER equipments after receiving the DER equipments information (R_i***_OPL***, R_i***_TEMP***, *Ri****_HUM***, R_i***_PRE***, R_i***_AGE***, R_i***_TIME***) from DEA. If meet the constraint requirement (R_i***_CONST)***, store the electricity production and cost of DER equipment in array ***A*** (R_i***_GEN***, R_i***_COST***). The generation cost is obtained by summing the generation cost for each DER unit ($\sum_{r=1}^{n} R_i\text{\_cost}$)

Step 1: MGCC/EMS performs load prediction after receiving the current load information (L_i***_CL*** *or* L_i***_CTL*** *or* L_i***_RSL***) from ESA.

Step 2: MGCC/EMS performs the DER reliability and performance assessment based on the DER equipments information (R_i***_OPL***, R_i***_TEMP,*** R_i***_HUM,*** R_i***_PRE***, R_i***_AGE,*** R_i***_TIME***)

Step 3: When the electricity prices of utility grid are high, the MG satisfies the total demand of the loads by exploiting as much as possible its local production. Then stop the algorithm and the solution is found.

Step 4: When the electricity prices of utility grid are low, the DERs in the MG are switched off and the load demand is satisfied entirely by the network.

Step 5: Compare $Price_{(hour)}$***_DAY-AH*** with ($\sum_{r=1}^{n} R_i\text{\_cost}$).

Step 6: Set index i at the beginning A, Find the number of DERs will be switched off and store in the list ***E*** (i**,** R_i***_COST)***

Step 7: Increase i to the next index of ***A***

Step 8: Determine mini R_i***_COST*** in the ***E***

Step 9: DEA send set new points or switched off command to related DERs. ESA perform HS for various electricity loads.

5.3 Optimization Algorithm in Islanded Mode (OA-IIM)

There is only one electricity supplier in islanded mode. In other words, the electricity supply is limited. Therefore, both the Heterogeneous Service (HS) and economic dispatch might be applied to minimize the electricity cost.

Once the PCC announces islanded mode, MGCC/EMS will decide the expected time of utility power outage (*T*_***DISCONNET***). OA-IIM algorithm will collect load information (L_i***_CL*** or L_i***_CTL*** or L_i***_RSL***) and DER equipments (R_i***_OPL***, R_i***_TEMP***, R_i***_HUM***, R_i***_PRE***, R_i***_AGE***, R_i***_TIME***) information.

Step 0: MGCC/EMS checks all DER equipments (R_i***_OPL***, R_i***_TEMP***, *Ri*_***HUM***, R_i***_PRE***, R_i***_AGE***, R_i***_TIME***). If meet the constraint requirement (R_i***_COST***), store the electricity production and set-point of DER equipment in array A (R_i***_SETPOINT***).

Step 1: MGCC/EMS performs load prediction task based on the current load information (L_i***_CL*** or L_i***_CTL*** or L_i***_RSL***).

Step 2: MGCC/EMS performs the reliability and performance assessment based on the real-time monitoring data of DER equipments information (R_i***_OPL***, R_i***_TEMP***, R_i***_HUM***, R_i***_PRE***, R_i***_AGE***, R_i***_TIME***)

Step 3: To ensure the electricity demand of critical load, electricity capability should be reserved (L_i***_CL*** * *T*_***DISCONNET***).

Step 4: Based on the organizational policy, optimal dispatch decision is made for CTL and RSL. ($\sum_{r=1}^{n} Ri\_GEN - Li\_CL$)

Step 5: ESA performs the HS based on the result of optimal dispatch decision.

Step 6: DEA send the new set-point command for related DER equipment based on the result of optimal dispatch decision.

6. CONCLUSION AND FUTURE WORK

A Micro-Grid (MG) Demonstration Project with total capacity of hundred-kW scale including wind power and high concentration photo voltaic (HCPV) generations was constructed by Institute Nuclear Energy Research (INER) in 2010. In accordance with National Sustainable Energy Policy (NSEP), the energy-saving technology was developed to integrate the existing MG facilities. Multi-agent architecture offers a hierarchical structure to manage multi-individual and heterogeneous environments.

This paper proposes a multi-agent architecture which is intended to merge energy-saving design into the existing MG structure. The contributions of this paper are shown below:

1) The proposed approach is a hybrid process based both on the MG operational cycle as well as energy-saving mechanism to improve the MG energy management. Moreover, it can be used to address energy-saving early in the MG development process, and makes informed choices as far as energy-saving mechanisms are concerned.

2) The proposed ESD-SCF emphasizes platform-independent multi-agent architecture - it is suitable for application to generous intelligent buildings or smart environments. In addition, ESD-SCF provides a three-layer structure with exclusive agents which are easy to merge into the existing intelligent buildings environment.

3) Detailed descriptions between energy-saving agent and MG operational cycle are useful for reader to better understand the procedures of energy-saving operation. They also enhance the communication between energy-saving manufactures and MG developers. Moreover, the proposed negotiation processes are useful for software engineer to develop energy-saving programs. For validating and testing the proposed negotiation processes between ESA and SMA as well as DEA and DGA, related XML schema and web services will be designed to verify data exchange and traceability within the energy management processes.

The future work will reference Particle Swarm Optimizer (PSO) (Wang 2012) to optimize the set points in the energy-saving mechanism integration and MG system. Furthermore, a more comprehensive and versatile energy-saving function may be defined as the overall comfort index used in the optimization process.

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