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The Design of Multi-agent based Distributed Energy System

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***Abstract*—Considering the environmental, limited traditional natural resources and power demand pressure, there is a great need to involve the distributed energy resources (DER) to the existing central power plant. So this paper proposes the multi-agent based distributed energy system, which incorporates traditional central power plant and different DER by using Multi-agent system (MAS) technology. A new three layered MAS architecture with good generality is designed, which can be used in small, medium and large scale multi-agent based distributed energy system (MAS-DES). The cluster and super cluster are defined to work as virtual power plants in the medium and large scale case. It also presents the novel architecture for single agent system with learning ability. Moreover, the reliability of Multi-agent system is assessed by Bayesian Statistics. The proposed MAS-DES uses the traditional and renewable resources in a more reasonable way and provides a better solution for the power supply considering the cost, pollution index and reliability.**

***Keywords*—multi-agent system, distributed energy system, machine learning, renewable energy, reliability assessment**

I. INTRODUCTION

Nowadays growing customer needs for electric power, increasing concern for the environment protection and reducing available traditional natural resources (such as coal, oil and gas) greatly challenges the existing large-scale, centralized power plant using fossil fuels and nuclear power. There are obvious drawbacks to such systems: high dependence on un-renewable energy resources, sustaining environmental pollutions, great amount of transmission losses, and extensive expense for system maintenance. In order to solve this problem, the distributed energy resources (DER) should be considered. DER is based on a variety of different alternative and renewable energy resources with different technical and economic characteristics. There are abundant different kinds of DER, such as wind power, solar power, hydro power, wave power, geo-thermal power, biomass power and fuel cells etc. By using these resources, there will be a lot of distributed power generation systems, i.e. wind generation, solar generation, hydro generation and so on. The design, control, management, optimization and integration into existing power plant of these resources are very important and significant.

Several works have already been done about DER. Lasseter et al presented the Consortium for Electric Reliability Technology Solutions (CERTS) Microgrid concept [1] and gave out the definition of a microgrid [2]; Pudjianto et al [3] used the concept of microgrids and virtual power plants to support the integration of distributed energy resources. There also have been some applications of multi-agent systems in power systems [4, 5]. MAS technology was used in Microgrids control in [6]. The operation of MAS for the control of a Microgrid was presented in [7]. A framework of agent based control for Microgrids was proposed in order to control DER in [8]. These contributions more concentrated on the control of Microgrid by using MAS. However, these methods didn't view all the existing power generation systems as a whole to investigate how they cooperate and coordinate each other to supply the electric power.

Considering all the existing power generation systems as a complex open system, this paper proposes multi-agent based distributed energy system (MAS-DES), which incorporates traditional central power plant and different DER by using MAS technology. This leads the complex distributed energy system to smaller manageable components that can interact, communicate and cooperate. The organization of the paper is as follows: section II presents the physical distributed energy system and introduces MAS briefly. Section III proposes Multi-agent based distributed energy system, which provides the general MAS architecture for small, medium, large-scale distributed energy system. Section IV provides the basic control of MAS-DES. The reliability assessment is presented in section V. Finally, section VI concludes.

II. DISTRIBUTED ENERGY SYSTEM AND MAS

A. Distributed Energy System

The technology improvement enables different kinds of power generating method, so different kinds of power generation systems. This paper involves the traditional central power plant and integrates all kinds of DER, which views all of them as a whole, called hybrid distributed energy system (DES). The structure of DES is shown in Figure 1.

1) Traditional central power plant (TCPP): TCPP is usually driven by fuel-fired generators or nuclear power energy. The environmental pollution is the major problem. Lots of renewable energy depends on the weather condition and fluctuating with time, so TCPP plays an important role in DES due to it is more reliable Therefore, there will be a tradeoff among cost, reliability and pollution index.

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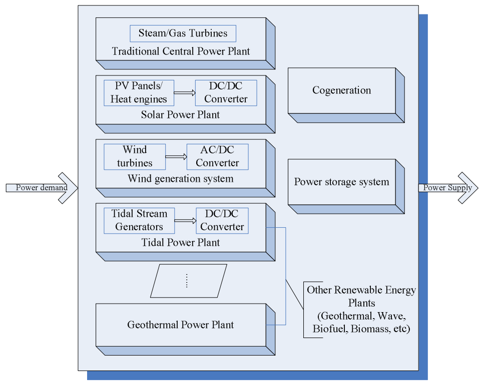

Figure 1. The structure of hybrid distributed energy system

2) Solar power plant(SPP): SPP converts the solar energy into electric power by heat engine or photovoltaic panels. Solar power is clean, renewable and the system is simple to install and maintain. The cost and maintenance of SPP is low and the solar energy is abundant, which make SPP a very important component of DES. However, SPP has the unstable problem because of the sunlight change during the year or even day.

3) Wind generation system(WGS) : WGS uses wind turbine generators to convert the wind energy into electricity in areas with strong and steady winds. Wind power is renewable, widely distributed, clean and produce low pollutant emissions. So more and more wind farms, which is a group of wind turbines in the same location used for electric power production, appear in mountains, offshore and onshore of the coast. But the fluctuations of power supply ability caused by the changing weather conditions make WGS unstable. Both WGS and SPP have very short start-up and shut down time, which make them easy to operate.

4) Other kinds of renewable energy plants: Geothermal power plant (GPP) generates the electricity from heat stored in the underground of earth. Tidal power captures energy from the tides, both in vertical direction and horizontal direction. The tidal stream generators will generate power in tidal power plant (TPP). And wave power takes energy from waves, which is continuous available. Hydro power plant (HPP) impounds a reservoir of water and releases it to drive water turbines to generate electricity, which is a reliable system. There are also many bio-chemical renewable resources such as biofuels, biomass etc.

All renewable energy sources such as PV panels, fuel cells and wind turbines have unstable output voltage. The power DC/DC and DC/AC converters are needed to obtain stable output AC voltage and frequency and then link to the utility network. Cogeneration makes good use of waste heat from industrial processes, which can also be a useful component of the system.

5) Power storage system(PSS) : The challenge of variable power supply caused by fluctuation of weather condition can be readily alleviated by PSS. The energy storage system can reduce the unstable influence of some renewable energy plants and improve the load availability of DES [10]. Available storage technologies include pumped-storage hydro systems, batteries, hydrogen fuel cells, thermal mass and compressed air. When DES generates more power than the load demand, the surplus power will be stored in PSS. Conversely when there is deficiency in DES, PSS will provide the stored power to supply the load to improve the system reliability.

B. Brief Introduction of MAS

A MAS is a loosely coupled network of agents, which interact to solve problems that beyond the capabilities or knowledge of each individual agent [11]. It is composes of the following elements [12]: environment, objects, agents, relations, operations and operators. An agent is merely "a software or hardware entity that is situated in some environment and is able to autonomously react to changes in the environment" according to Wooldridge [13]. Both the agent and environment can be physical or virtual, and the agent may alter the environment by taking actions physically or virtually. Woodridge extends an agent to an intelligent agent, which is autonomous, social, reactive and pro-active [14]. Autonomy means agents are independent and can operate in an unsupervised mode; Social ability enables intelligent agents cooperate and communicate with each other. It is more than simply passing the information; Reactivity connotes that an agent is able to react to changes in the environment in a timely fashion; Pro-activeness means that agents dynamically change its behavior to achieve their goals [15]. Social ability, reactivity and pro-activeness lead the agents different from the traditional software and hardware systems.

III. DESIGN OF MULTI-AGENT BASED DISTIRBUTED ENERGY SYSTEM

DES described in section II is a complex system consisting of many subsystems, so the traditional centralized control or loosely decentralized control schemes is no longer the best system control solution. A MAS has a great potential to deal with the complexity and distributed problems in industry [15]. Thus, this section designs MAS to control DES at a higher level. Each agent in MAS-DES has special function to solve the distributed problem in power systems. Whenever a power demand signal comes, all agents cooperate and coordinate each other to supply the electric power regarding cost, reliability and pollutant emissions.

A. The Closed-loop MAS-DES

It is worth noticing that some of the renewable energy systems (such as SPP, WGS, TPP.) are unstable due to they are sensitive to the fluctuations of weather condition. To make MAS-DES stable, the whole system is designed as a closed-loop system, where the system loads status as the feedback controller. Normally MAS-DES will supply demanded amount of power, but in emergency the system load will be reduced to avoid the system damage seriously. The block diagram of the closed-loop MAS-DES is given in Figure 2.

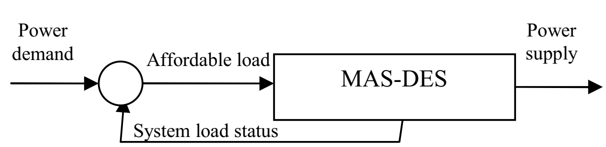

Figure 2. The closed-loop MAS-DES block diagram.

B. The MAS Architecture for Small-scale DES

Each component in DES is embedded with an agent, which is a virtual entity (software system). Each agent controls a physical entity. The physical entity can be any component of DES in figure 1. Agent is the basic unit of the MAS-DES, i.e. each physical entity appears to be an agent in control level. DES with different scales normally requires different control methods. In order to enhance the system reliability, this paper proposes a system-level scheme: a new three layered MAS architecture. A MAS architecture for small-scale DES is shown in figure 3. As shown in Figure 3, the bottom layer is called physical layer, which contains TCPP agent, SPP agent, and other physical entity agents. The middle layer is named application layer, which is composed of coordinator agent, fault diagnosis agent, and recover agent etc, which provides service to the physical layer. All agents in this layer are virtual entities and each of them has its own responsibility as its name implies. The top layer is the user interface layer, which enables the interaction between human and MAS. It is normally used for monitor the running status of MAS-DES, but in emergency, user can make decisions for agents in physical and application layers to avoid the whole system out of control. The functions of the agents in physical layer are used to control those physical entities described in section II.

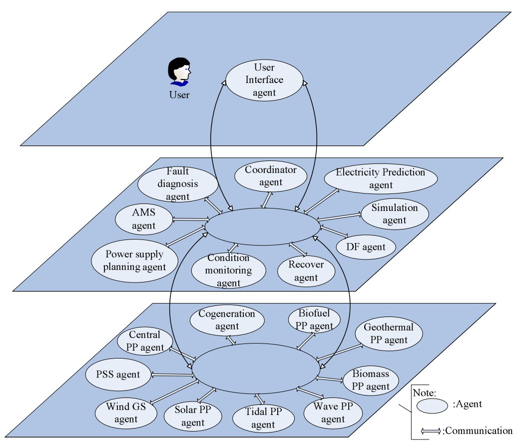

Figure 3. MAS architecture for small-scale DES

The functions of agents in application layer are presented as follows:

1) Coordinator agent: it works as a coordinator. Normally, when the power demand signal comes to MAS-DES, the agents will negotiate with each other to decision the power supply solution, i.e. which agents will supply the power and how much will they provide depending on the power demand and the capability of agents. If they have conflict in negotiation and can not solve in a specific time, then coordinator agent will help to solve the conflict.
2) Fault diagnosis agent: MAS-DES is a complex system, whenever some part of the system is down, this agent diagnoses the fault. Different classification methods such as NN, SVM, and decision tree can be stored in this agent to enable its learning.
3) Recover agent: It stores the information of each agent in MAS-DES. When some of them are down, it can recover the agent, which improves the system reliability.
4) Condition monitoring agent: it collects the information and monitors the status of each agent in physical layer. It also records the current system load status, this agent works as the feedback controller in figure 2.
5) Electricity prediction agent: It predicts the consumption of the electricity and provides this information to the agents in physical layer. This information helps the generations to adjust their status in advance and avoid blackout.
6) Power supply planning agent: several algorithms such as particle swarm optimization, genetic algorithms and other heuristic algorithms are stored in this agent. It helps to implement self-organization of agents in physical layer, i.e. plan the amount of power that each agent supplies considering the cost, pollutant index and capability.
7) Simulation agent: for a complicated system, it is better to do simulation before take the real action. So simulation agent is necessary and the efficiency requirement for this agent is very high. This agent provides the results and analysis of "what-if" scenarios.
8) AMS agent: maintains a directory of agents registered within the MAS-DES. When each agent starts up, it registers with the AMS agent.
9) DF agent: requests the agent address from AMS agent and queries the service each can offer. For a specific task, an agent use DF to search for other agents that provide services it needs.

Because agents are independent on the control from other agents, this makes MAS-DES an open system, i.e. agent can be removed or added from the MAS without affecting the ability of the remaining agents. They have social ability, which supports communication and negotiation of agents. The core technology of MAS [7] is to control complicated system with minimum data exchange and minimum computational demands. All the agents are pro-active and active, which leads MAS-DES a robust system because they can react to the changes of their environment and alter their behavior as required. One scenario: the power supply is deficient, due to the react and proactive property the PSS agent controls PSS to supply power instead of store power. The parallel architecture in the bottom layer of MAS improves the reliability of MAS-DES, because they can supply power simultaneously.

C. MAS Architecture for Medium-scale and Large-scaleDES

With the increase of the number of agents in physical layer, the communication load and the control complexity of the MAS increase accordingly. The proposed three layer MAS architecture in section B is with good generality, which is still applicable. To improve the efficiency of the medium-scale MAS-DES, agents in physical layer only needs to change to larger units. The agents in physical layer are grouped into different clusters according to their energy recourses types. When a cluster agent contains too many agents the control becomes very hard, thus there is a number limit for each cluster agent. There can be many cluster agents that belong to the same type. The remaining agents except those within cluster agents form a microgrid agent, which incorporates different kinds of energy recourses. Physically the power plant cluster or microgrid is connected to the distributed network through a single point of common coupling (PCC) and appears to the power network as a single unit. Here the cluster and microgrid can be considered as virtual power plants. Virtually, the agents within one cluster agent or microgrid agent are controlled by this cluster agent or microgrid agent. The reasons why involves cluster agents are as follows. Geographically the same types of power generations are located near, because of clime and natural condition. For example, some place with great wind energy, there are probably many wind farms. Moreover, it is easier to control a cluster agent than a microgrid agent because the same factors and control patterns are considered for the same type of agents, e.g. WGS agents all consider the wind velocity and direction. The MAS architecture for medium-scale DES is to replace the physical layer of figure 3. The application and user interface layer remain the same.

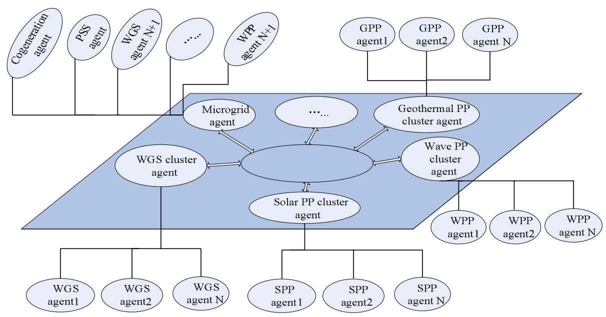

Figure 4. Physical layer of MAS architecture for medium-scale DES

For large-scale DES, the physical layer of MAS becomes super cluster agent, which combines similar kinds of cluster agents and microgrid agents. Each of them can be considered as a virtual power plant and have certain numbers of cluster or microgird agents. The MAS architecture for large-scale DES as shown in Figure 5 is obtained by replacing the physical layer of figure 3. In all, when the proposed MAS architecture is implemented in real world, one of the specific architectures is applied according to different scales of the real system.

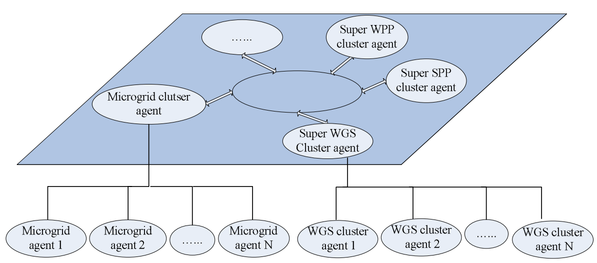

Figure 5. Physical layer of MAS architecture for large-scale DES

D. The Design of Single Agent System

The single agent system is the basic unit to control MAS-DES and situated in different distributed environments, so its design is significant. The proposed architecture for each agent is drawn as figure 6, which is embedded with intelligence and learning ability. Each agent is composed of four units interacting with each other in a synchronized manner. They are perception unit, decision making unit, communication unit and action implementation unit. The perception unit is responsible for the raw data collection; the communication unit ensures the coordination between agents, sending and receiving the data or negotiation message; the action implementation unit is to take action that made by decision making unit into the environment. The decision making unit works as a human brain, which makes decisions or plans according to the objective.

The decision making unit is designed as a MAS, which is composed of knowledge base agent, inference engine agent and learning agent. The knowledge is stored in the form of rules in the knowledge base. When there is an input or scenario comes in, the inference engine agent selects which rules are fired (used) and then use these rules to give out the output-decision or plan. The knowledge base can be updated from time to time by learning agent. The architecture for each agent is the same, but the contents in the knowledge base are different depending on the function of the agent. The learning agent can learn the preference from the agent behavior history, which leads to preference model driven multi-agent based system. The learning agent can also be a multi-agent system, where different kinds of machine learning methods are applied. One scenario of learning agent is shown in figure 7. The major advantage of proposed design is the ability of learning. Each agent only knows part of the environment and makes its own decision according to the information it knows. They need to negotiate with each other in order to cooperate to finish the task considering the cost, reliability and pollutant index.

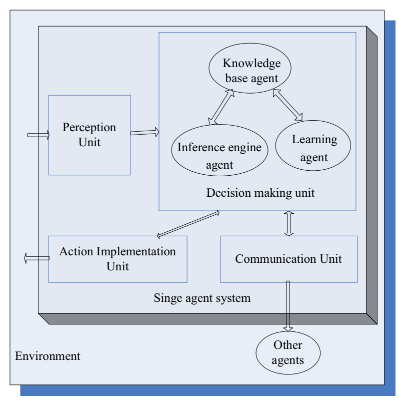

Figure 6. The architecture of single agent system

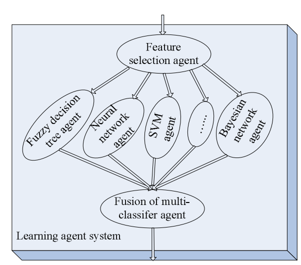

Figure 7. The architecture of learning agent for fault diagnosis

IV. CONTROL OF MAS-DES

The notion control in MAS involves operations such as coordination and negotiation among agents. The communication languages enable the social ability of the agents, which define how agents exchange information, communicate, and negotiate. The protocols and content languages compose and interpret the meaningful messages. In order to cooperate, all agents within the community must agree on the adoption of appropriate agent communication language standards and the same ontology. ACL proposed by FIPA [9] is used for the negotiation and communication of MAS-DES. The content language uses the FIPA-SL content language because it a stable standard. The JADE platform [17], which supports FIPA standards and robustness of the agents, is used to implement MAS. The ontology contains concepts, predicates and agent actions, which is the same structure with JADE. Concepts are model domain concepts; predicates illustrate concept relationships, which always need to be evaluated as true or false [15]. An example predicate in MAS-DES ontology is *Generation (SPP, power)*, which can be used to determine SPP agent will generate power or not. Action is a special type of concept for communicative acts. An example action is *StorePower(PSS)*, which can be used to discuss the storage of power to PSS.

The full set of FIPA-ACL message contains 13 fields and they are type of communicative acts, participant in communication, content of message, description of content and control of conversation according to the category of parameters [9]. The 'performative' filed in the message defines the type of communicative act of the ACL message. FIPA specifies lots of performatives and the main performatives employed by MAS-DES are "subscribe", "inform", "query-ref" and "confirm" [4]. One scenario for agent negotiation is as follows. The system generates more power than demanded but TCPP always provides power because it has long start-up and shut down time. Thus TCPP agent negotiates with PSS agent to store power. The agent negotiation diagram is shown in figure 8.

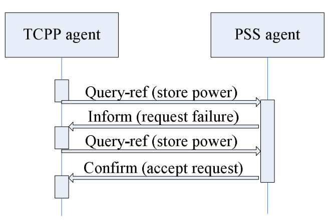

Figure 8. Agent negotiation diagram for one scenario

V. RELIABILITY ASSESSMENT OF MULTI-AGENT SYSTEM

For the system design, one of the important engineering tasks is the reliably assessment. The reliability is defined as the probability that an item will operate without failure for a stated period of time under specified conditions [17].

A. Reliability diagram of MAS

Here are some assumptions in this reliability assessment: each component can only be in two disjoint states up and down; the elementary events E_i denote the failures which change component C_i from state up to state down; all control and communication devices are independent from each other; only first order failures are considered; the system is homogeneous and no repairs are considered. Without loss of generality, we assume there are four components in physical layer ($C_1 - C_4$), six components in application layer ($C_5 - C_{10}$) and one in user interface layer (C_{11}). The parallel structure in physical layer guarantee the power supply, the function of components $C_5 - C_{11}$ is to improve the system reliability, which are try to avoid or recover the failure of the system. If one of them is down, the system can still run normally. The reliability diagram derived from figure 3 is shown in figure 9.

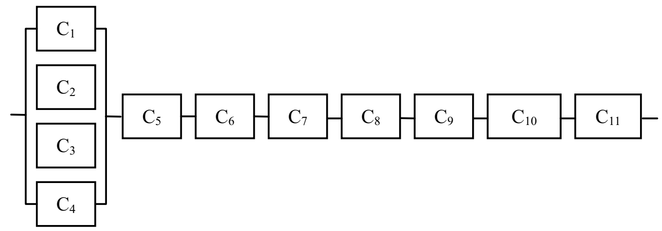

Figure 9. An illustrative Reliability diagram of MAS-DES

B. Reliability assessment of MAS by Bayesian Statistics

The reliability of the system shown in Figure 9 can be written in the following equation:

$$R_s(t) = \max(R_1(t), R_2(t), R_3(t), R_4(t)) \times R_5(t) \times R_6(t) \times R_7(t) \times R_8(t) \times R_9(t) \times R_{10}(t) \times R_{11}(t) \quad (1)$$

where $R_s(t)$ is the reliability of the whole system and $R_i(t)$ is the reliability of the i-th component. Without loss of generality, we assume numerical values for failure rates of each component is $\lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = 10^{-5}\,\mathrm{h}^{-1}$, $\lambda_i = 10^{-6}\,\mathrm{h}^{-1}$ for i=5,6,…,11, and consider the mission time $T_F = 200\mathrm{h}$,then $R_j(T_F) = e^{-\lambda t} = e^{-0.002} = 0.998,\ for\ j=1,2,3,4.$ $R_i(T_F) = 0.998,\ \ for\ i=5,6,...,11.$ Applying Eq. (1), we obtain the exact value of the system reliability $R_s(T_F) = 0.9966$.

From section B, we notice that the parameter $\lambda_i,\ for\ i=1,2,...,11$ must be estimated in order to estimate the reliability of MAS. Thus the Bayesian statistics [18] is applied to the parameters estimation, which is mainly based on the Bayes' rule, yields the posterior density:

$$\pi(\theta|X) = \frac{p(\theta, X)}{p(X)} = \frac{\pi(X|\theta)\cdot\pi(\theta)}{p(X)} \quad (2)$$

where θ is the unknown parameter, $\pi(\theta)$ is the prior distribution of parameter θ , X is the observed data, $\pi(X|\theta)$ is the likelihood function, $p(X)$ is the marginal distribution where $p(X) = \sum_\theta \pi(\theta)\pi(X|\theta)$ or $p(X) = \int \pi(\theta)\pi(X|\theta)d\theta$, and $\pi(\theta|X)$ is the posterior distribution for unknown parameter θ based on the observations. For each component C_i the failure rate maybe different, thus we need to estimate $\lambda_i,\ for\ i=1,2,...,11$ respectively. After we get all the failure rates, then the system reliability is calculated by Eq. (1). Here we take λ_1 for example to do the case study.

Prior distribution is one of the most important elements in the Bayesian methodology. Due to the difficulty to elicit a subjective and informative prior for the MAS-DES reliability assessment problem, the noninformative prior is used for this application. Noninformative priors work quite well in many circumstances. Assume the prior distribution for λ_l follows the uniform prior, i.e. $\lambda_1 \sim uniform(0,1)$. A natural idea of choosing the uniform prior is we do not have any information about the prior knowledge. Denote X_{i1},for i=1,...,n. is the time interval for i-th failure of component C_l . Assume X_{i1},for i=1,...,n. is i.i.d. (independent and identically distributed) and follows an exponential distribution with mean $1/\lambda_1$. The exponential distribution is commonly used for the random variables such as time interval. Thus, we obtain the likelihood function is $\pi(X_1|\lambda_1) \sim Exp(1/\lambda_1)$. With the running of MAS-DES, the observations of X_{i1},for i=1,...,n. can surely be obtained. Assume the data observed for X_{i1},for i=1,...,10. are: 2700h, 3600h, 3145h, 4766h, 2918h, 4200h, 3590h, 3798h, 3984h, and 3425h. Therefore, we can find out the posterior distribution $\pi(\lambda_1|X_1)$ by using Bayesian theorem. The WinBugs [19] is used for the simulation, which is a software for the Bayesian analysis for complex statistical models using Markov Chain Monte Carlo methods. The posterior density function and the history plot for the parameter λ_l are shown in figure 10 and 11 respectively. The statistical summary for parameter λ_l is shown in Table I.

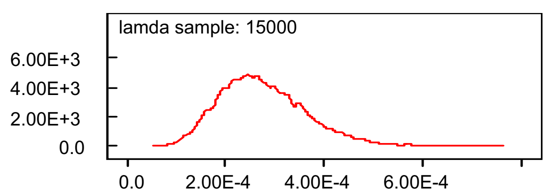

Figure 10. The posterior density function for parameter λ_l

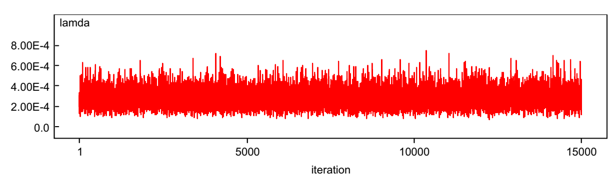

Figure 11. The history plot for parameter λ_l

TABLE I. STATISTICAL SUMMARY PARAMETER λ_l

Statistical name	value
Posterior mean	2.768E-4
Posterior standard deviation	8.818E-5
MC error	7.283E-7
95% HPD credible set	[1.324E-4, 4.748E-4]
median	2.669E-4
Number of samples	15000

VI. CONCLUSION

This paper proposes MAS-DES which applies MAS technology to distributed energy system by integrating traditional power plant and DER. It designs a new three layered MAS architecture with good generality, which is open, robust and reliable. This paper presents the novel architecture for each single agent system with learning ability. The control and implementation platform of MAS-DES are also provided. Furthermore, it proposes to estimate MAS reliability by Bayesian statistics. The proposed MAS-DES gives a better solution for power supply considering the cost, pollution index and reliability. But to enable MAS-DES work more intelligently, further investigation to improve the learning agent is needed.

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