Anticipatory Response Model for Multi-Agent Based Energy Management System in a Standalone Microgrid

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***Abstract*—In this paper, multi-agent architecture was used to provide control for standalone microgrid with distributed generations. Therefore, to achieve a faster control compared to the centralized controller, each agent incorporated with a local prediction or forecasting model to provide anticipatory responses. To accomplish their common goals successfully, the agents cooperated based on facilitator architecture with game-theory. Initially, the agents estimate its own parameters and dynamically adjust them by playing non-cooperative game with other agents. The predictive algorithm is based on autoregressive model where each agent will predict the load demand alongside renewable energy resources in order to dynamically regulate the control parameters. This will provide a faster response where the agents will anticipate future load demand and available renewable resources and adjust their parameters beforehand. Hence, this will minimize the fluctuations of voltage and frequency in the microgrid leading to more efficient power dispatch and lower power losses.**

Keywords—microgrid; anticipatory response; multi-agent; distributed generation; renewable energy

I. Introduction

Generally, an energy management system (EMS) is based on a centralized controller [1-3]. Through centralized EMS, the microgrid central controller is capable of maximizing the power production by optimizing the power generation from each distributed energy resources. For instance, a centralized EMS was used to control the power converters in a microgrid that comprises of photovoltaic and wind systems [1]. Meanwhile in [3], centralized EMS was utilized in order to maximize the output power of the hybrid renewable energy systems while minimizing the energy cost and carbon dioxide emissions. Moreover, to minimize fuel consumption, a centralized controller was used for optimizing the energy supply and demand in a microgrid [4].

Although the centralized control method has shown to provide universal successes in microgrid control, this system has several drawbacks from its 'top-down' approach. For example, it has to be planned properly with built in redundancy, since it represents a 'single point of failure'[1, 5]. Despite has been used for finding optimal control solutions, the centralized EMS needs a powerful computing capability as the system becomes bigger and complex in order to handle the vast amount of data [6]. It also requires a highly distributed communication capabilities and control strategy [7]. In contrast, the decentralized EMS with 'bottom-up' approach is less complex and more robust compared to the centralized EMS [8, 9]. The distributed control components has some intelligence that enables them to perform computation, planning action and making decision independently. Hence, not only it can reduce the computation and communication capability, but it also taking into consideration the performance and requirement of various parts in the microgrid in decision making [7]. Therefore, a self-adaptive system that are dynamic, intelligent and open is crucial for the microgrid that comprises of hybrid renewable energy system to operate optimally under renewable resource intermittency and dynamic load variations.

The aim of a decentralized EMS is to offer maximum autonomy for DER units and loads in a microgrid. The autonomous local controllers are intelligent and able to communicate among each other to establish a larger intelligent unit. The primary control task of each local controller is to maximize its power production in the most efficient and economical method, while also improving the overall performance of the microgrid [10]. In this paper, a multi-agent system (MAS) based EMS has been implemented in a microgrid model that deploys intelligence agents to several parts of the power system such as generators, loads, and grid, for monitoring and control. Each agent can cooperate and exchange information with other agents in different nodes. Through utilizing intelligent agents, the complex problem of EMS in microgrids can be decomposed and allocated to local agents. In this case, the MAS based EMS has been developed and multi-agent coordination methods (e.g. game theory) can be used to solve the power dispatch and load balancing.

This paper will discuss the implementation of anticipatory response for agents in a MAS based EMS. This will offer a faster response where the agents will anticipate future load demand and available renewable resources and adjust their parameters beforehand.

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II. Standalone Microgrid Model

A. Microgrid Architecture

Fig.1 shows the overview of the microgrid architecture utilizing MAS based EMS. The microgird consists of diesel generators, mini-hydropower systems, wind turbines, photovoltaic systems, and battery storage systems. The distributed control through agents optimizes the output power of each power generators based on the available renewable energy sources and load demand. Therefore, it able to provide a stable and optimal microgrid operations.

B. Simulink Model of the Standalone Microgrid System

Simulink SimPowerSystems was used to develop, simulate and test the microgrid system comprises of distributed generation systems. The system level microgrid comprises of six primary components: mini-hydropower systems, PV, battery storage systems, wind farms, diesel generators and load demand. The peak power for the microgrid provided by the diesel generator systems. Meanwhile, the renewable energy systems such as PV, wind and mini-hydropower system that are connected to the grid will provide the base power for the microgrid. Due to complex microgrid network, the model developed and simulated in SimPowerSystems's phasor mode to achieve a faster simulation time. The standalone microgrid model in Simulink SimpowerSystems is illustrated in Fig. 2.

C. Microgrid Distribution Network and Components

The total capacity of the standalone microgrid system in Fig. 2 is 6 MW. A total of 2 MW from the total energy capacity contributed by the hybrid renewable energy system. The microgrid system consists of four diesel generators with one 2.5 MW diesel generator and three 500 kW diesel generators. Whereas, the mini-hydropower system has two 250 kW turbines and the wind farm comprises of two 250 kW wind turbines. The PV system comprises of two PV arrays with a rated capacity of 500 kWp each, and the battery storage system has 10800Ah capacity that it utilized to minimize the fuel consumption of the diesel generators.

The mini-hydropower system, wind and PV system will directly provide power to meet the load demand in day time. Meanwhile, the battery storage system will be charged by the surplus energy from the renewable energy systems. Load following dispatch strategy has been used for charging the battery system. If the renewable energy system cannot meet the load demand during day time, the diesel generator systems will be turned on to provide energy for the loads. Battery storage system will be utilized to meet the energy demand if the hybrid renewable energy system cannot provide enough energy for the load. Diesel generators will be turned on when the battery storage system is fully discharged or when the energy demand exceeds the battery capacity. The electricity of the standalone microgrid distributed through 11 kV, 50 Hz distribution network. The hybrid power generation systems such as mini-hydro, wind, PV and diesel systems are AC coupled to the microgrid. The PV and diesel generator system are connected directly to the 11 kV bus. Whereas, the mini-hydropower and wind system are connected to the grid via 575 bus that is stepped up later to 11 kV for distribution. The 11 kV bus is

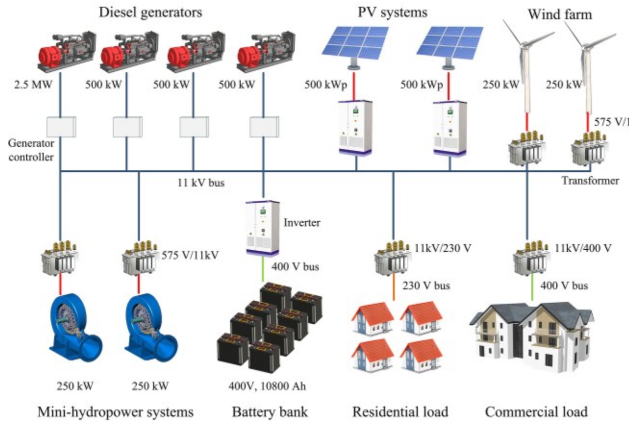

Fig. 1. Schematic of the microgrid.

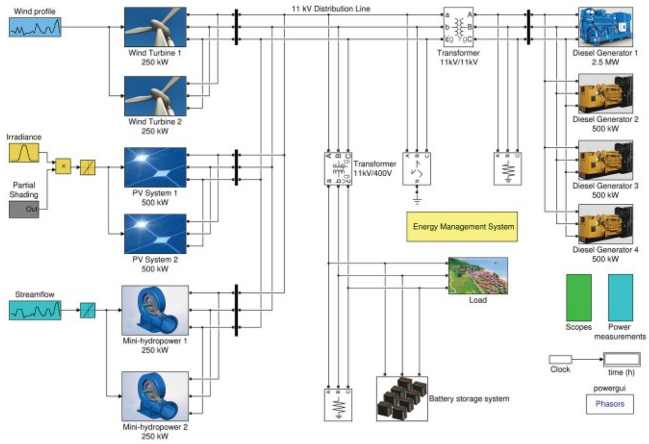

Fig. 2. Microgrid model in Simulink SimPowerSystems.

stepped down to 400 V and 230 V for commercial and residential load respectively.

III. MAS Architecture for EMS

To fulfill the openness, adaptability, fault tolerance and autonomous of the standalone microgrid system, the distributed agents were design and modeled based on bottom-to-top approach. The Simulink block of the EMS employed in the microgrid system is shown in Fig. 2. The primary goal of the EMS is to reconfigure and optimize the energy management based on system and environmental parameters in order to satisfy the energy demand. The EMS objective is also to optimize the microgrid benefits and efficiency. Moreover, it also evaluate the system performance based on the output power of hybrid power generation system.

The structure of the agents is modeled in Simulink SimPowerSystems. Meanwhile, the agent's behavior modeled via Simulink Stateflow. This paper demonstrate the utilization of multi-agent for managing and optimizing the energy for a standalone microgrid in a simulation environment. The layered architecture has been used in constructing the intelligent agents, where the control subsystem of the agents are hierarchically arranged. At higher level of agent layers, the abstraction of information interpretation is increased. The agent architecture follows InteRRaP structure by having a vertical layering structure with two pass controls [11]. The InteRRaP agent architecture is commonly used in the robotics area [12]. In order to deal with microgrid EMS, the InteRRaP structure has been modified accordingly. Fig. 3 shows the agent architecture that has been modified to suit the application for EMS. Initially, facilitator incorporation in MAS was proposed in [13], where similar agents were grouped and facilitators act as medium of information exchange between agents. In this study, facilitators utilized for battery and power generators agents. The primary objective of facilitator is to coordinate the multi-agent controls, provide reliable communication between agents, and reduce communication burden of the agents. The multi-agent architecture of the standalone microgrid EMS is illustrated in Fig. 4.

IV. ANTICIPATORY RESPONSE MODEL FOR MAS

The logic behind the anticipatory response model is fairly simple. For instance, assuming the load demand increases rapidly in a typical microgid. The increment in load would results in frequency drop of the system. Thus, diesel generator will increase its power generation in order to stabilize the frequency. This action for regulating the frequency causes power losses leading to lower system's efficiency due to slow time taken to recover the frequency. However, with the implementation of anticipatory response for agents in the MAS based EMS will provides faster response of frequency regulation. By forecasting the future load demand based on previous observations, the diesel generator agent will receive command to increase power generation in order to minimize the frequency fluctuations.

The load demand for the standalone microgrid modeled as discrete time intervals. In this thesis, the load forecasting problem approached using autoregressive model where the load demand, Y and one step ahead prediction, $\hat{Y}(K+1)$ at time, K can be found through observations of past data such as Y(1), Y(2),…Y(K-1) and Y(K). The flowchart of the anticipatory response model is illustrated in Fig 5.

The power demand observations can be expressed as in (1) and (2):

$$Y(K) = a_1(K)Y(K-1) + a_2(K)Y(K-2) + \\ ...a_n(K)Y(K-n) + W(K) \tag{1}$$

$$Y(K) = \sum_{j=1}^{n} a_j(K)Y(K-j) + W(K) \tag{2}$$

where these equations are known as autoregressive process of order n represented by *AR(n)*. In this work, *AR* of order ten has been used for load and RE sources prediction. For example, the linear weighted sum of previous load data called the autoregression coefficients, a_j are used to make prediction for future load and W is the noise term that is treated as Gaussian white noise.

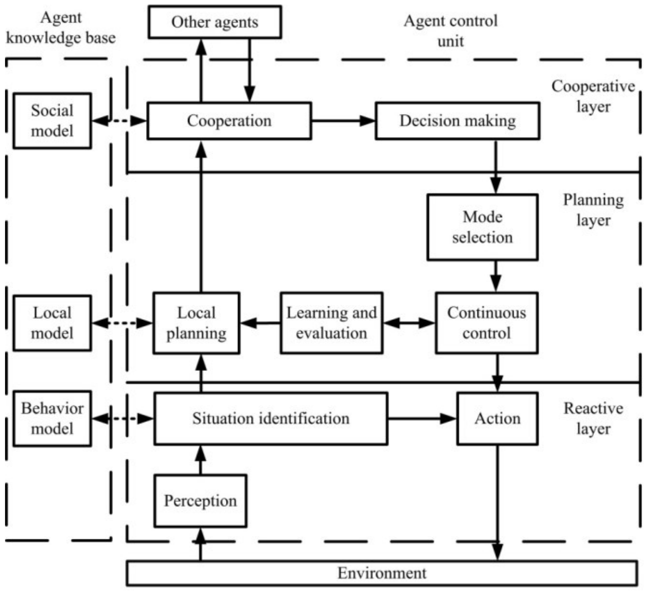

Fig. 3. Agent architecture.

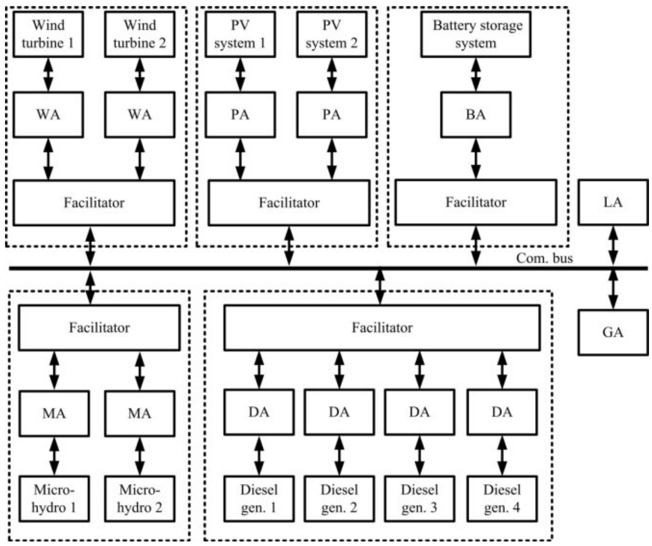

Fig. 4. MAS architecture for EMS.

The one-step-ahead prediction can be found as follows:

$$\hat{Y}(K+1) = \hat{a}_j(K)Y(K) + \hat{a}_2(K)Y(K-1) + \\ \hat{a}_3(K)Y(K-2)... \tag{3}$$

$$\hat{Y}(K) = \sum_{j=1}^{n} a_j(K)Y(K-j+1) \tag{4}$$

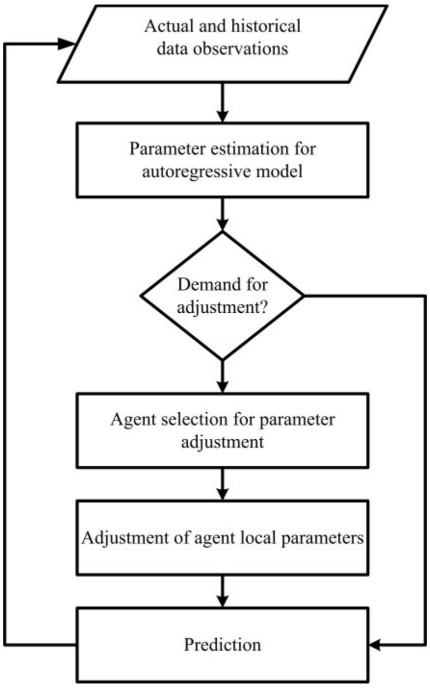

Fig. 5. Flowchart for anticipatory response model.

The overall flow of MAS based EMS combining global optimization, game-theory and anticipatory response is summarized in Fig 6. The threshold for prediction time characterized by *n*, where the anticipatory response in agents will make next data prediction each 10 minutes based on previous data.

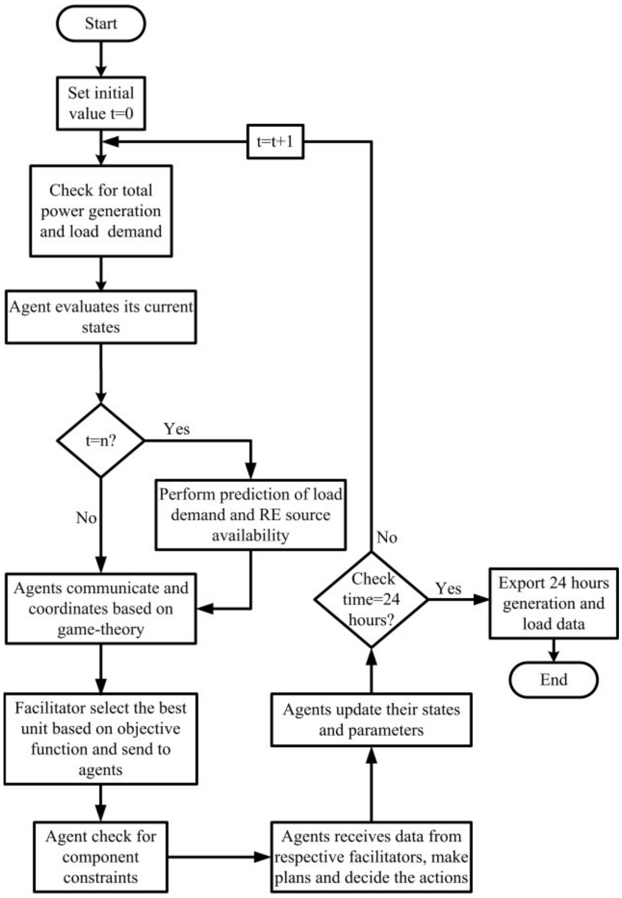

Fig. 6. MAS based EMS flowchart.

V. Results

In this study, the simulation time for the microgrid model runs for 24 hours simulating daily output power. The input parameters for the model are according to Tioman Island load demand profile and renewable energy sources such as streamflow, wind speed and solar radiation. The detailed information on the input parameters are not enclosed in this paper and available in previous study conducted as in [14, 15]. On the island, 11 kV distribution networks has been used for electricity distribution. The 24 hour primary power supply for the island provided by a diesel plant. Meanwhile, during peak demand, distributed diesel generators are used as a backup power supply when the primary diesel generators output cannot meet the load demand.

As provided in [14], the daily solar radiation follows a typical profile where highest solar radiation falls in noon. Meanwhile, the daily streamflow and wind speed varies during the day with several peaks and lows. The daily load profile has peak and minimum demand at 20:00 and 07:00 respectively. Since Tioman is a resort island, the occupancy and daily activities of the tourist heavily affected the load profile. During the day, the energy demand is low and increased to a peak in the evening and slowly dropped in the night.

Several scenarios such as load demand variations and renewable resource fluctuations that disrupt the microgrid frequency were simulated in order to evaluate the performance of the MAS based EMS. Table I shows the scenarios and disturbances simulated. No disturbances were simulated for scenario one. This scenario particularly assess the microgrid performance in normal operation when there are no disturbances occurred.

TABLE I.
Disturbances Simulated for Evaluating Model Performance

Scenarios	**Time (s)**	**Disturbances**
One	-	Normal operation with no disturbance
Two	10:30 – 11:00	Occurrence of partial shading that compromise the PV system output power.
	12:00 – 13:00	The total renewable energy output power surpasses the load demand.
	22:00 – 23:00	Wind speed exceeds the wind turbine cut-out speed.
Three	15:00	The load demand exceeds 1.8 MW.
	20:00	Commercial load (asynchronous machine) is turned on
Four	-	The battery initial SOC is lower than 80%.

Meanwhile, in scenario two, several disturbances and events were simulated as shown in Table I. This scenario focuses on evaluating the system's ability to deal with renewable resource intermittency throughout the day. The streamflow data has been tuned to simulate high output power of the mini-hydropower system during noon leading to a total renewable energy generation that exceeds the load demand. However, the third scenario concentrates on the system's performance in handling the load side disturbances. In this scenario, the commercial load has been represented by a 0.2 MVA induction motor model that was turned on at 20:00. To simulate the microgrid performance when the load demand cannot be meet by one diesel generator, a daily load profile with 2.8 MW peak has been used for this scenario. Longer simulation runs is essential in order to have a better understanding of the control performance when the battery has been depleted after 24 hours or when having SOC less than 80%. It is also crucial to evaluate the control performance on next day scenario (after 24 hours) when the battery initial SOC is less than 80%. Therefore, in scenario four, the microgrid performance at initial battery SOC at 20% was assessed. The control performance results for all scenarios are listed in Table II. Meanwhile, the power losses of the system for centralized and decentralized EMS are shown in Fig. 7

TABLE II.
CONTROL PERFORMANCE COMPARISON BETWEEN CENTRALIZED EMS AND MULTI-AGENT BASED EMS

	Centralized EMS				Multi-agent based EMS			
	S1	S2	S3	S4	S1	S2	S3	S4
η_{sys}	0.639	0.603	0.54	0.696	0.771	0.753	0.684	0.798
η_{pv}	0.677	0.621	0.517	0.784	0.853	0.772	0.612	0.887
η_{wind}	0.653	0.643	0.533	0.827	0.885	0.813	0.673	0.911
η_{hydro}	0.687	0.668	0.526	0.812	0.856	0.828	0.654	0.897
P_{loss} (%)	2.541	4.037	7.636	2.127	1.211	2.039	3.634	1.033

Based on the control performance results illustrated in Table II, it is clear that the centralized EMS exhibits lower efficiency compared to the multi-agent based EMS. For example, the novel distributed controller demonstrates high efficiency with an additional 21% for overall system efficiency, 27% for mini-hydropower system, 31% for wind system efficiency and 18% for PV system efficiency. It also shows to provide 34.7% lesser power losses compared to the conventional centralized EMS.

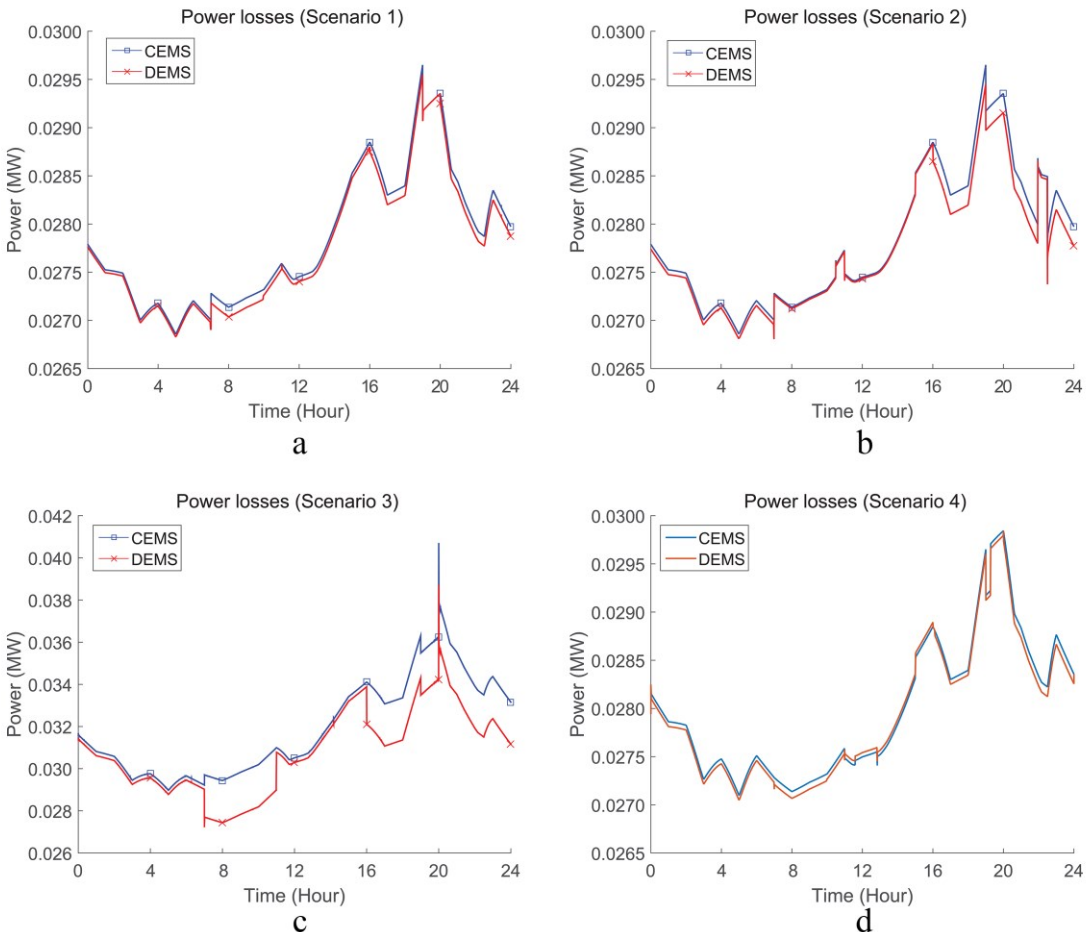

Fig. 7. Power losses for decentralized and centralized EMS a) Scenario one b) Scenario two c) Scenario three d) Scenario four.

The robust and high performance of the MAS based EMS are due to its unique and distinct agents for each type of power sources and also distinct individually based on sizes, capacity and control algorithm. Hence, it is able to achieve faster controls compared to the centralized EMS that is based on corrective approach. The computational burden of the centralized EMS also contributes to its lower performance caused by extensive computation for optimization by the central controller. This causes slow reaction time in dealing with environmental changes and disturbances in the microgrid. Meanwhile, the anticipatory response model in the MAS based EMS provides faster response by anticipating future load demand and renewable sources leading to a faster controls, lesser power losses and higher efficiency. The power losses of both centralized and decentralized EMS in all scenarios are shown in Fig. 7.

VI. CONCLUSION

The result shows that the proposed simple anticipatory response model in the multi-agent based EMS architecture capable to enhance further the control performance by providing faster response time for generation and load side disturbances. On the other hand, the extensive computation for optimization by the central controller causes high computational burden contributing in lower overall control performance. Therefore, the centralized EMS have slow reaction time in dealing with environmental changes and disturbances occurred in the microgrid compared to the MAS based EMS with anticipatory response model. The anticipatory response model in the MAS based EMS offers faster response by anticipating future load demand and renewable sources leads to a faster controls, lesser power losses and higher efficiency.

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