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Microgrid Power System Modeling Using the Multi-Agent Systems Concept and Stabilization by Lyapunov-Based Cooperative Controller During Disturbance and Load Shedding

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ABSTRACT: The microgrid power system has a nonlinear dynamic with many uncertainties, such as changes in wind power and solar irradiation. Sustaining such system requires a robust approach. In this paper, in order to deal with this problem, the properties and concepts of multi-agent systems are used to model the microgrid power system, as this system has seven agents all of which have a common point production-consumption power. Afterwards, the design and implementation of cooperative control of the microgrid agents output power are discussed. Due to the fact that in the multi-agent modeling structure, each agent is related only to its neighbor agent, the designed controller is of decentralized or distributed type. Among the advantages of this distributed structure is the ability to adapt immediately and be resistant to uncertainties in the system. In addition, the advantages of the Lyapunov function in the cooperative control structure have been used in order to overcome the disturbances and uncertainties in the structure of the microgrid, and to ensure the stability of the system. Ultimately, the control law designed for the seven-factor model in MATLAB software is simulated and compared with similar previous methods.

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1- Introduction

Due to the increase in air pollutant gases, the high cost of developing traditional networks, and on the other hand by having wind and solar energy, it is no longer economical to use traditional networks to provide electricity [1-4]. Therefore, in the last three decades, distributed energy generation resources have been used. Although micro-grids have many advantages, they have created new challenges in the field of active power control, voltage, frequency, as well as markets for buying and selling electricity [5, 6]. If the micro-grid is considered as a multi-agent system, its factors (distributed generation resources in the micro-grids) are of indefinite nature and uncertainties, such as changes in wind power, solar radiation, and low inertia of power generation resources, which are the control problems of micro-grids. The planning and topology of micro-grids varies according to environmental and climatic conditions and the amount of invested budget [7, 8]. Cooperative and coordinated behavior is a very useful tool for controlling artificial sets of machines, sensors, and micro-grids [9]. This important feature has become one of the most important and active branches of research, known as cooperative systems [10, 11]. Control algorithms of cooperative systems is known as "cooperative control". In fact, cooperative control is controlling a set of agents that form a group to demonstrate the considered and desired collective behavior [4, 12]. Controlling multi-agent systems is one of the issues related to cooperative control that has been considered in the last decade. The purpose of using multi-agent systems is to create optimal cooperation between agents to increase team performance compared to when agents act individually [4]. In [13], a two level "coordinated control" approach is modeled for optimizing the energy management in multi agent distribution systems. The control proposed model is used for upper level and the capacity of each microgrid is applied as fixity variable. In [14] a cooperative control strategy is proposed for DC microgird. According to this paper, distributed generation units are modeled as dissimilar multi agent DC system, first. Afterwards, a cooperative control approach is proposed to model DC microgrid. Finally, the findings are obtained in terms of current sharing in DC microgrid.

One of the most authoritative works in the field of modeling power systems as a multi-agent system, is the research conducted by Kelson and Nahrir in 2011. The modeled micro-grid is a six-agent system including wind turbine, solar cell, Diesel Generator, Fuel Cell, as well as energy-saving resources, namely battery (BESS) and rotating-wheel (FESS). Since it is possible to inject/absorb power into energy-saving resources in shorter periods of time than other distributed generation sources, therefore, the use of BESS and FESS ensures system stability when instantaneous changes of load increase and decrease. Distributed generation resources are connected to the AC-bass using power electronics instruments [15]. Considering that solar cells and wind turbines consume electricity without cost, the control design is based on always using their maximum output power. Since the en-

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ergy produced by wind turbines and solar cells varies under climatic conditions, and considering the high cost of energy-saving resources, Diesel Generator is responsible for the task of load balance in the secondary loop. Therefore, when the load is decreased, the Diesel Generator reduces its power (or BESS and FESS are charged), and when the load increases in the system the Diesel Generator increases its output power (or BESS and FESS are discharged). After the study conducted by [15], several control works have been performed to stabilize the six-agent micro-grid. In a study conducted by Kahrobaei et. al. (2013), the Diesel Generator was responsible for secondary control of frequency in the micro-grid. To demonstrate the performance of the proposed controller, several tests were performed on the micro-grid and the results were compared to a simple PI controller [16]. It is suggested in [17] that voltage control of microgrid is based on the collaborative control of MAS. Hence, controller utilized a game theory model based on leader-following dynamic model.

In practice, due to uncertainties in the micro-grid, the dynamic parameters of the micro-grid components are constantly changing, which causes the normal performance of the micro-grid to be disrupted. Therefore, another study conducted on the mentioned six-agent micro-grid power system is the resistance of the designed controller against the dynamic changes of micro-grid. In a study conducted by Kazentsova et. al. (2014), the resistance degree of the proposed control method against the parameter changes of the micro-grid equipment was investigated. In this study, to test the micro-grid frequency resistance in presence of the designed controller, the fluctuations of the main parameters of the frequency response model, such as adjustment coefficient (D), inertia constant (M), drop constant (R), generator time constant (Tg), turbine time constant (Tt), battery time constant (TBESS), and turntable rotating-wheel time constant (TFESS) are controlled [18] . Another challenge related to micro-grids is the presence or absence of an agent called "Fuel Cell' in the structure of a multi-agent power system, which is the subject of the study conducted by Kazentsova et. al. (2015). The Fuel Cell has a high efficiency and a low time constant up to 0.26 seconds. On the other hand, the generator time constant is up to 0.4 seconds. Therefore, it seems that the cooperation between the Fuel Cell and Diesel Generator as generating resources in the secondary loop, in addition to improving the performance of the system in the secondary control of micro-grid frequency, can also reduce the fuel consumption of Diesel Generators and consequently reduce the pollution arising from fossil fuel consumption [19]. In the study conducted by [20], the Diesel Generator was the only unit involved in the secondary control of the frequency, but in the study conducted by [21], the simultaneous cooperation between the Diesel Generator and Fuel Cell for the secondary control of the micro-grid frequency was investigated. In a study conducted by Radakrishnan et. al. (2016), a type of special island micro-grid was modeled [22]. More precisely, by using mathematical calculations related to fuzzy knowledge and probability laws in this study, a distribution system based on multi-agent systems is presented to evaluate the stability of each of the micro-grid agents. In fact, the multi-agent system fuzzily calculates the importance and impact of each of the agents constituting the micro-grid through fuzzy computations. Agents influencing on the micro-grid system are divided into two High and Low membership functions. The biggest challenge related to this system is the extremely high dynamics and openness of the designed fuzzy system. This means that the nonlinear and unpredictable behavior of the modeled micro-grid may add other agents to the micro-grid that are overlooked by experts. Additionally, complexity and agents have been introduced as factors involved in the distrust of the results from fuzzy control in this study. A review paper is provided in [6] to introduce the recent studied applications for "cooperative control" for microgrid. In addition, open gaps in the field of microgrid is discussed in [6]. In a study conducted by Raju et. al. (2016), the micro-grid frequency in island working mode (disconnected from the main network) was controlled using robust controllers. The above-mentioned micro-grid is a seven-agent system that includes wind turbine (WTG), solar arrays (PV), Micro Turbines (MT), Diesel Generator (DEG), Fuel Cells (FC), energy-saving resources, such as batteries (BESS) and rotating wheels (FESS) [23]. One of the main problems in implementing the robust control methods is the method of extracting and modeling uncertainty, which was presented in a study conducted by Marzband et. al. (2016) [24]. In various references such as [25, 26], uncertainties definitions and categories have been provided. However, in general, uncertainties can be classified into two general categories: disturbance signals and dynamic uncertainties [27, 28]. Dynamic uncertainties are divided into two categories: modeling errors, which actually represent inaccurate dynamics of system model (especially at high frequencies), and non-modeled dynamics, which ignore some system dynamics (such as nonlinear system linearization). Dynamic uncertainties are in fact the difference between real system models and the modeled system. In reference [24], dynamic uncertainties are modeled as a block Δ (s) and multiplied by the output. An important matter that has been pointed out in this study is that the proper selection of weight functions is very important and necessary in obtaining a controller. In reference [3], the secondary control of the frequency in a micro-grid is investigated by designing different control methods. In reference [29], the secondary control of frequency is performed by the Diesel Generator agent and the coordination between this agent and the Fuel Cell. In reference [30], in addition to coordination between the Fuel Cell and Diesel Generator, the micro-turbine agent is also used. However, since the time constant of the agents involved in the secondary control are large and have a slower response than the battery factor, energy-saving agents which have a faster response are used in the initial moments of the error. A broad overview is provided in [2] for control methods in power management of DC microgrid. Furthermore, consensus of multi agent system as a concern in cooperative control is discussed in [2].

In most studies conducted in this field, such as [31, 32], energy-saving agents (i.e. batteries and rotating wheels), have always been present in the system and it has been assumed that energy-saving agents are able to always inject the necessary energy into the system. In other words, it is assumed in these studies that the battery State of Charge (SOC) is in the appropriate range (between 20% to 100%). Hoever, in practice, it is not always correct to consider such an assumption, since it tries to install a small number of energy-saving agents due to the high cost compared to other power generation agents and be used only when necessary. Therefore, their battery charging status should also be considered when using energy-saving resources. In a study conducted by Morstyn et. al. (2016), a simple method for controlling SOC was presented that is to consider this parameter as an agent in the micro-grid multi-agent system and its control independently. In this method, the battery charge status agent is fed back to the battery by a PI controller. However, the problem of this method is that a bias value is added to the battery output. This method does not charge the battery and cannot compensate the amount of power taken from the battery. This matter decreases the power quality of exchange lines [12]. Voltage control of microgrid based on the collaborative control of MAS is suggested in [17]. In this study, the controller utilized a game theory model based on leader-following dynamic model.

In a study conducted by T Ma et. al. (2016), a cooperative control method (simultaneous and coordinated) between the battery agent and the Diesel Generator agent has been proposed to enhance the independent control capability of the SOC agent. In this method, the SOC of the battery is collected with the input reference signal to the Diesel Generator agent, and the amount of power taken from the battery agent for compensating the disturbances when an error occurs in the system is compensated by the Diesel Generator agent. After removing the disturbances and controlling the micro-grid frequency and passing from the transient state to the stable state of the micro-grid, the Diesel Generator agent generates an additional amount of power to charge the battery [33]. In reference [9], electric vehicles are introduced as an energy storage in the event that the power supply network is cut off. To achieve this purpose, a collaborative control methodology based on the MAS is proposed in [9].

1- 1- Paper Contribution

Considering the importance of micro-grid power systems and their application in power generation, many articles and books have so far been published to address the challenges of micro-grids. However, there are still problems in the control, planning and exploiting of micro-grids, so that past works cannot explain and justify them. Therefore, in order to stabilize the frequency and voltage in a micro-grid, cooperative control (simultaneous and coordinated control of all factors) is proposed in this paper, which it is hoped that by precisely controlling the micro-grid, while using all the factors, it will also improve the efficiency of the micro-grid. The idea of the present study for addressing these challenges is to consider the micro-grid as a multi-agent power system, in which each source plays the role of an agent in the power system that is the simultaneous and coordinated control (cooperative control) of these agents. The novelties of this article can be briefed as follows:

1. Modeling the Micro-grid power system with the help of Multi-agent System Concepts.
2. Stabilizing the Micro-grid power system with Cooperative Controller based on Lyapunov
3. Modeling the Micro-grid by considering the disturbances as well as load shedding

This article is organized into five sections. In the second part, the dynamic model of micro-grid power system is presented using the concepts of multi-agent systems. In the third section, a cooperative control strategy based on Lyapunov's function is formulated. In the fourth section, the results of the simulation are presented, and finally the fifth section is dedicated to the conclusion.

2- Modeling the Micro-Grid Power System Based on the Concepts of Multi-Agent Systems

The dynamic of the agents constituting the micro-grid power system is presented by Feizi et. al. (2016) [34]. The power system consists of seven agents which include: wind turbine (WTG), solar arrays (PV), Micro Turbine (MT), Diesel Generator (DEG), Fuel Cells (FC), battery (BESS), and rotating wheel (FESS).

Fig. 1. shows a simple diagram of this power system with its components. The sum of the output power to supply the micro-grid load includes the power of all its components and is expressed as Equation (1).

$$P_{Load} = P_{DEG} + P_{MT} + P_{WTG} + P_{PV} + P_{FC} \pm P_{BESS} \pm P_{FESS} \quad (1)$$

Considering that the power of all components is effective on the overall power of the micro-grid, the micro-grid can therefore be considered as a multi-agent system in which each component plays the role of an agent of this system. Thus, each component of the micro-grid is considered as an agent. In the field of multi-agent systems, these components will be related to each other as seven agents with a regular hexagonal topology, shown in Fig. 2.

Considering that the purpose of modeling the microgrid power system in this research is the simultaneous control of frequency and voltage, the proposed model should therefore include these two variables as output. The details of the proposed controller are shown in Fig. 3 and Fig. 4.

By properly defining the state space variables, the realization of the system state space can be represented according to Equation (2).

$$\dot{x}_i = A\,x_i + B_1\,w_i + B_2\,u_i,\ y_i = C\,x_i \text{،} \quad i = 1\text{،} 2\text{،} \cdots\text{،} 7 \quad (2)$$

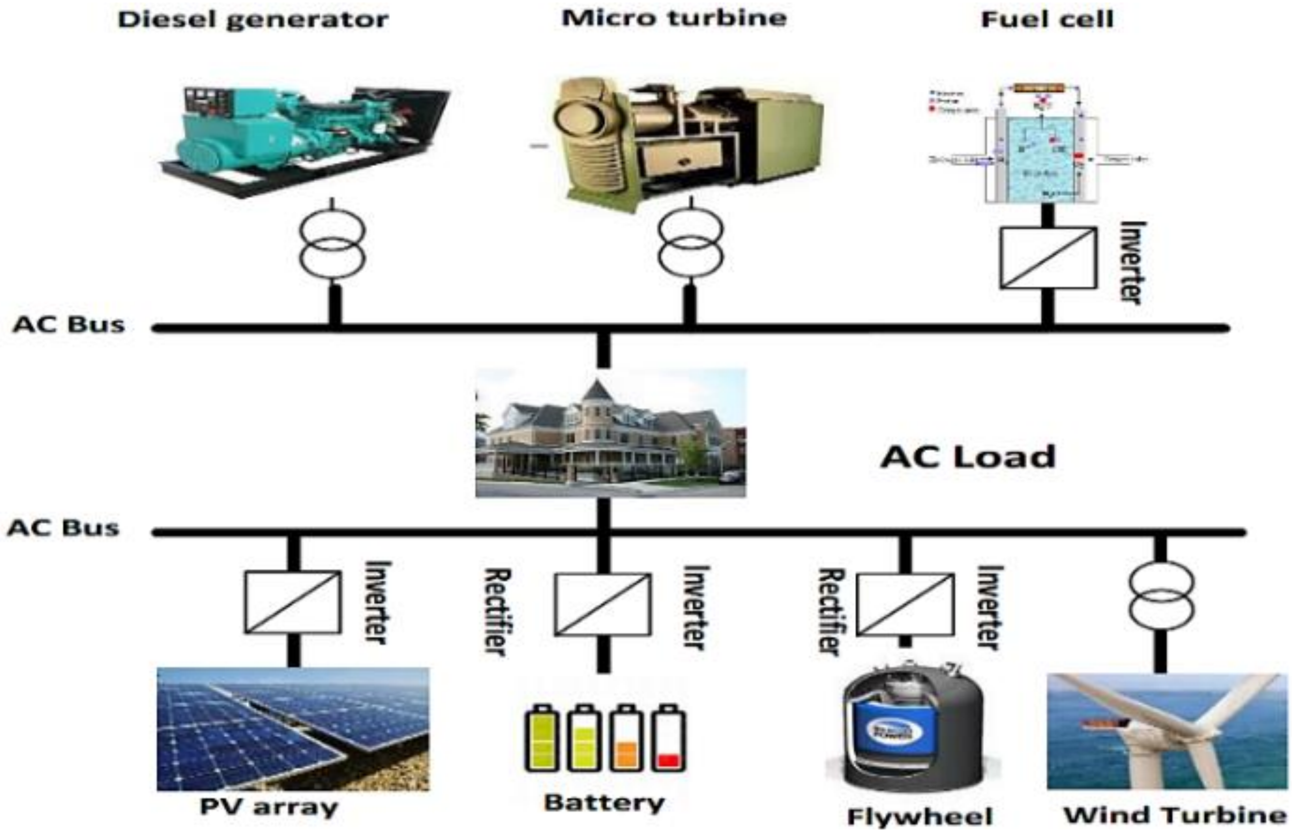

Fig. 1. Micro-grid power system [23]

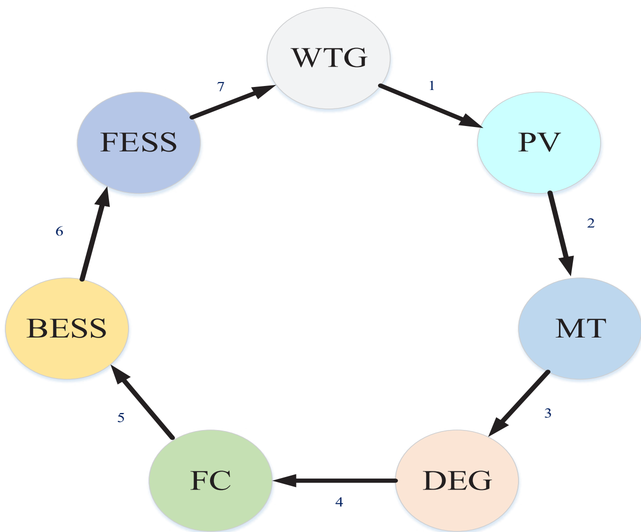

Fig. 2. Topology of micro-grid power system with seven agents

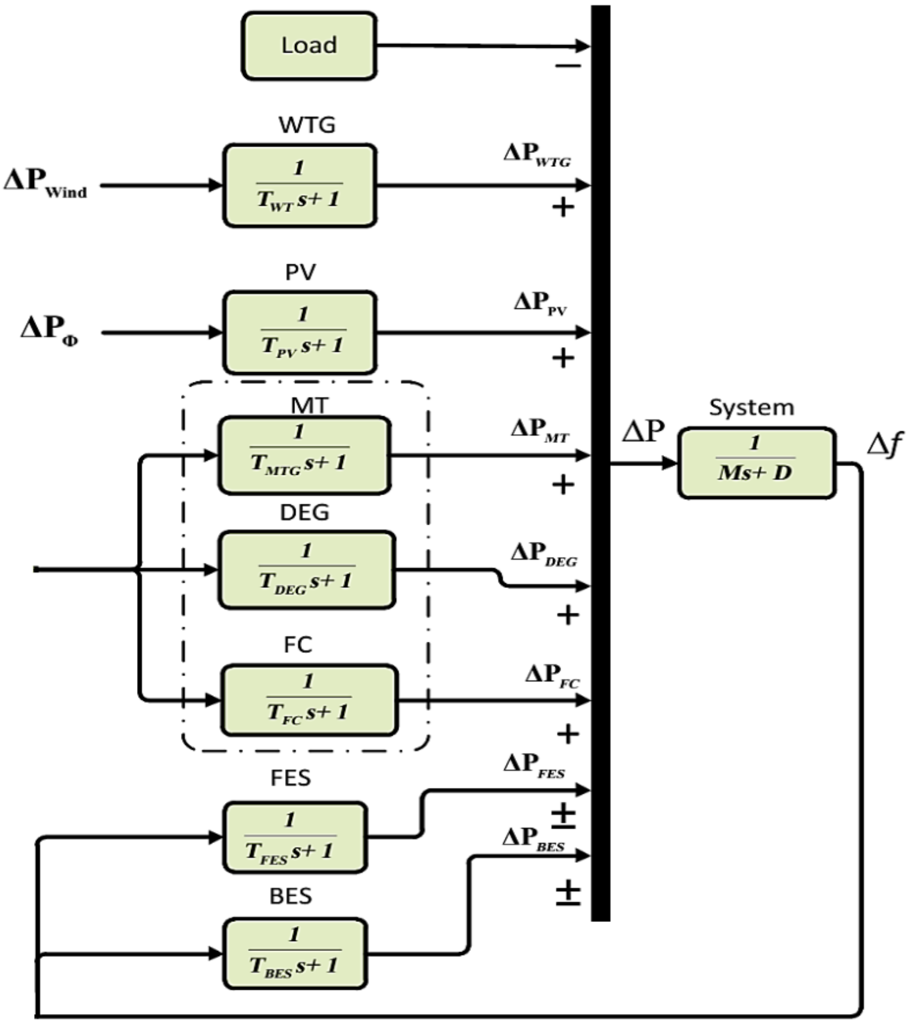

Fig. 3. Microgrid frequency output based on active power

where x_i is the state variable, w_i is the disturbance signal and u_i is the control input signal of the system and is defined as follows:

$$x_i = \begin{bmatrix} \Delta P_{WTG} \\ \Delta P_{PV} \\ \Delta P_{DEG} \\ \Delta P_{FC} \\ \Delta P_{MT} \\ \Delta P_{BESS} \\ \Delta P_{FESS} \\ \Delta f \end{bmatrix}, w_i = \begin{bmatrix} \Delta P_{Wind} \\ \Delta P_{\varphi} \\ \Delta P_{Load} \end{bmatrix}, y = \Delta f \qquad (3)$$

According to the reference [34], a first-order dynamic model is considered for each of the septet agents of the system, which is sufficient to investigate the distributed cooperative control in the micro-grid. The state space model of the i_{th} agent of the seven-agent micro-grid system is as Equation (4). The numerical values of the dynamic model parameters (4) are extracted from research [34], and are presented in Table 1. .

$$x_i = \begin{bmatrix} -1/T_{WTG} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1/T_{PV} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1/T_{DEG} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1/T_{FC} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1/T_{MT} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1/T_{BESS} & 0 & 1/T_{BESS} \\ 0 & 0 & 0 & 0 & 0 & 0 & -1/T_{FESS} & 1/T_{FESS} \\ -1/H & -1/H & -1/H & -1/H & -1/H & -1/H & -1/H & -D/H \end{bmatrix} x_i + \begin{bmatrix} 1/T_{WTG} & 0 & 0 \\ 0 & 1/T_{PV} & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1/H \end{bmatrix} w_i + \begin{bmatrix} 0 \\ 0 \\ 1/T_{DEG} \\ 1/T_{FC} \\ 1/T_{MT} \\ 0 \\ 0 \\ 0 \end{bmatrix} u_i, \; y_i = [0 \; 0 \; 0 \; 0 \; 0 \; 0 \; 0 \; 1]\, x_i \qquad (4)$$

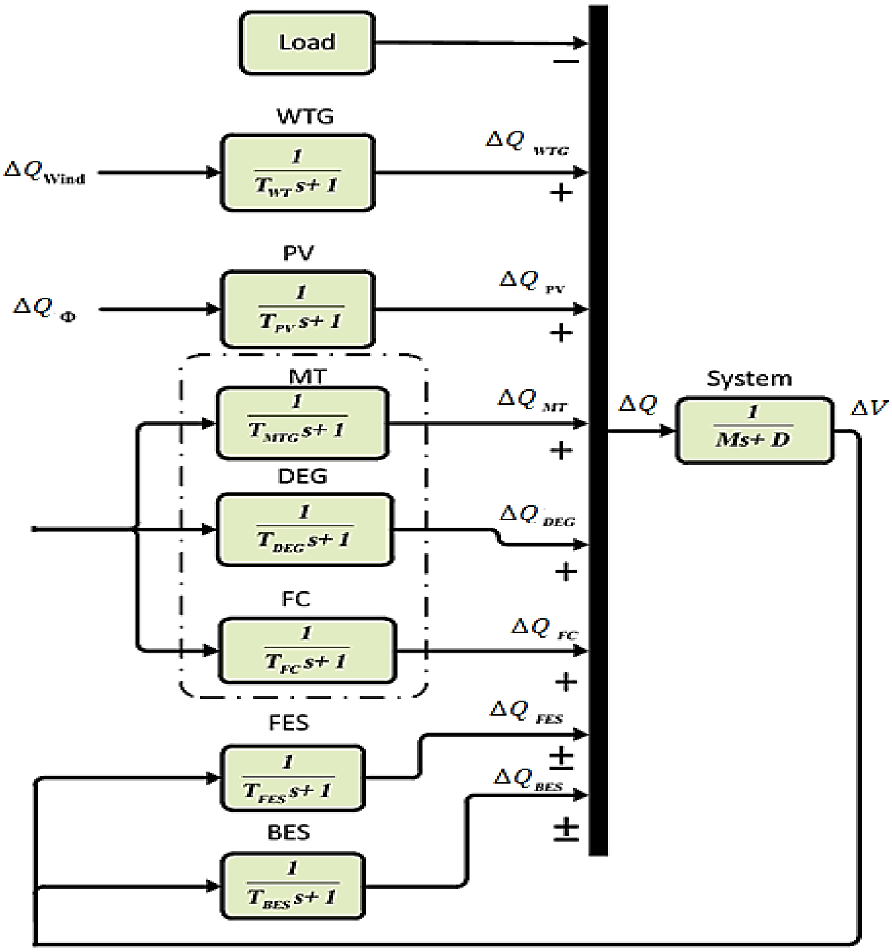

Fig. 4. Microgrid voltage output based on reactive power

2- 1- Model Stability

In order to evaluate the stability, it is necessary to calculate the eigenvalues of the system matrix. These values were obtained using MATLAB software and are shown in Table 2.All these values are imaginary on the left side of the axis and the system is generally stable. Therefore, a controller should be chosen for this system that, first improves the stability of the system, and second can meet the purpose of tracking the desired value of the designer.

2- 2- Model Controllability

The controllability matrix is formed by placing the model matrices (4) in the equation (5):

$$U = [B \quad AB \quad A^2B \quad A^3B \quad A^4B \quad A^5B \quad A^6B \quad A^7B] \quad (5)$$

The matrix U is the system controllability matrix, which is ranked by MATLAB software:

$$U = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.5 & -0.25 & 0.125 & -0.0625 & 0.0313 & -0.0156 & 0.0078 & -0.0039 \\ 0.25 & -0.0625 & 0.0156 & -0.0039 & 0.001 & -0.00025 & 0.00006 & -0.000015 \\ 0.5 & -0.25 & 0.125 & -0.0625 & 0.0313 & -0.0156 & 0.0078 & -0.0039 \\ 0 & 0 & -62.5 & 656.875 & -333.9437 & -62716 & 664510 & -375780 \\ 0 & 0 & -62.5 & 656.875 & -333.9437 & -62716 & 664510 & -375780 \\ 0 & -6.25 & 3.1875 & 623.4806 & -6605.5 & 3735.5 & 626930 & -668270 \end{bmatrix} \quad (6)$$

$$Rank(U) = 4$$

Table 2. Eigenvalues of the micro-grid multi-agent power system model

Eigen Values	Numerical Values	Stability
λ_1	-10	√
λ_2	-5.03+j8.6775	√
λ_3	-5.03-j8.6775	√
λ_4	-0.6667	√
λ_5	-0.56	√
λ_6	-0.5	√
λ_7	-0.25	√
λ_8	-0.5	√

Table 1. Dynamic model parameters of micro-grid multi-agent power system

Parameters	Numerical Values	Unit of Measurement
$\boldsymbol{D}$	0.012	pu/Hz
$\boldsymbol{M}$	0.02	pu/sec
$\boldsymbol{T_{FC}}$	0.4	sec
$\boldsymbol{T_{FESS}}$	0.1	sec
$\boldsymbol{T_{BESS}}$	0.1	sec
$\boldsymbol{T_{DEG}}$	2	sec
$\boldsymbol{T_{MT}}$	2	sec
$\boldsymbol{T_{WTG}}$	1.5	sec
$\boldsymbol{T_{PV}}$	1.8	sec

Therefore, the controllability matrix of the multi-agent power system modeled in this paper is incomplete, and it is concluded that the controllable system is not complete. In practice, this result means that a control rule can be found for the system that can improve system stability.

2- 3- . Model Time Response

For multi-agent micro-grids modeled in this paper, ΔP_{Wind} , ΔP_{φ} and ΔP_{Load} are considered as disturbance signals in the micro-grid, as well as parameters D and M are considered for dynamic uncertainties. In this study, uncertainties are multiplied by the output. In the first step, the simplest disturbance input, the single step, is applied to the open-loop system, and the result obtained from the septet agents is given in Fig. 5. The septet agents of the micro-grid power system have not been able to exhibit coordinated behavior due to the application of the input signal of a single step disturbance in the open loop mode (without the application of a controller), and are changed unstably form over time.

In the second step, the disturbance signal entered the open loop system as a time-varying input in fig.6. The result of applying this input is shown in fig.7. By applying time-varying disturbance input, the septet agents of micro-grid behave very uncoordinatedly that they will not be able to meet the designer's demands. The proposed solution is to design a controller that, while eliminating the fluctuation of agents, can create a coordinated and simultaneous behavior in them.

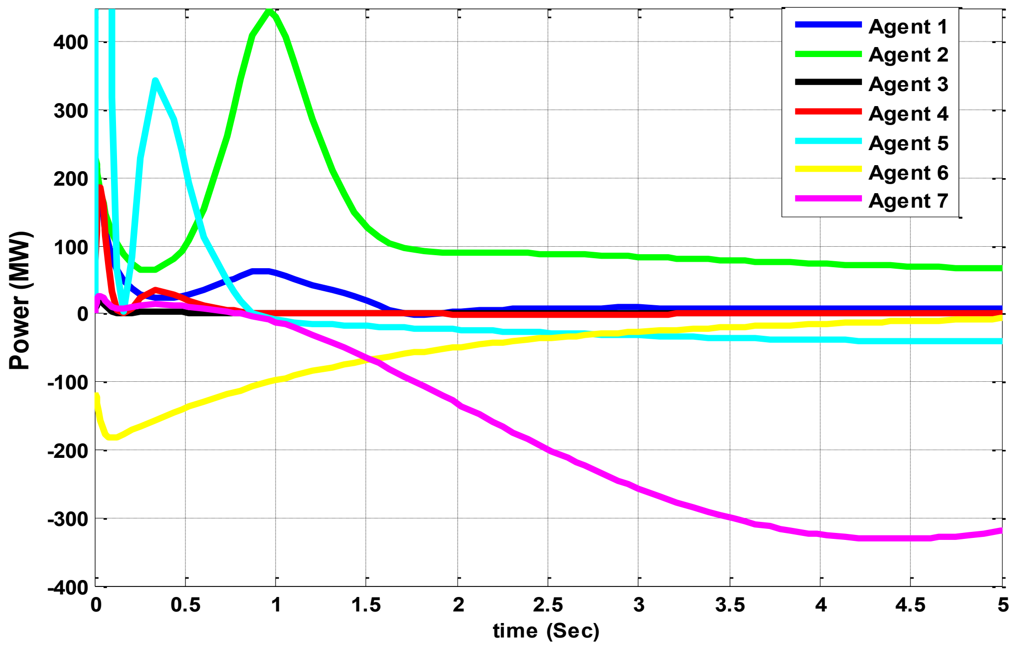

Fig.5. behavior of the septet agent of micro-grid power system model for single step disturbance input

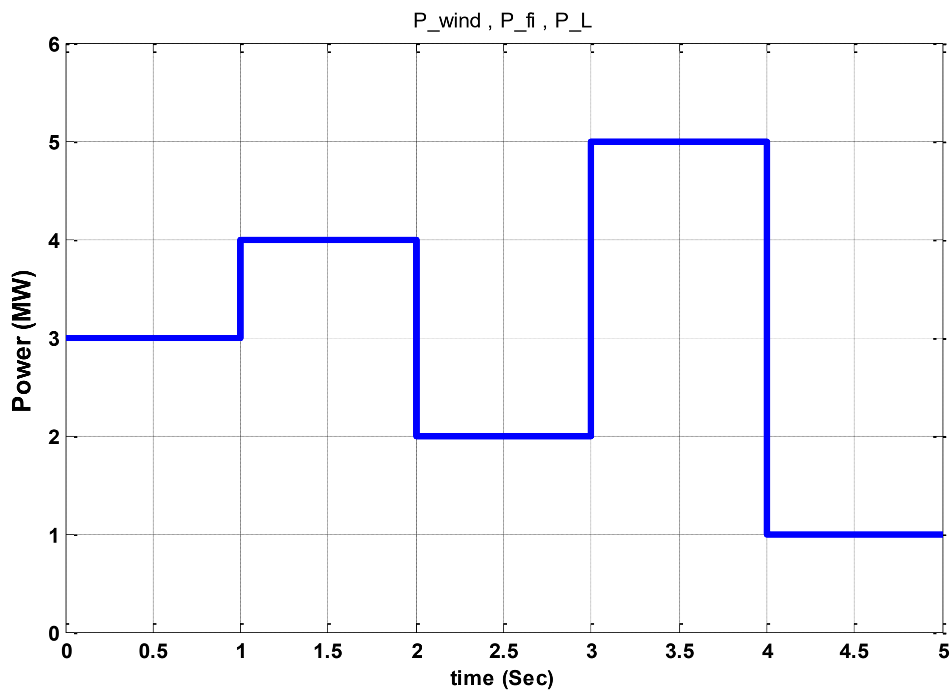

Fig.6. Time-varying disturbance signal

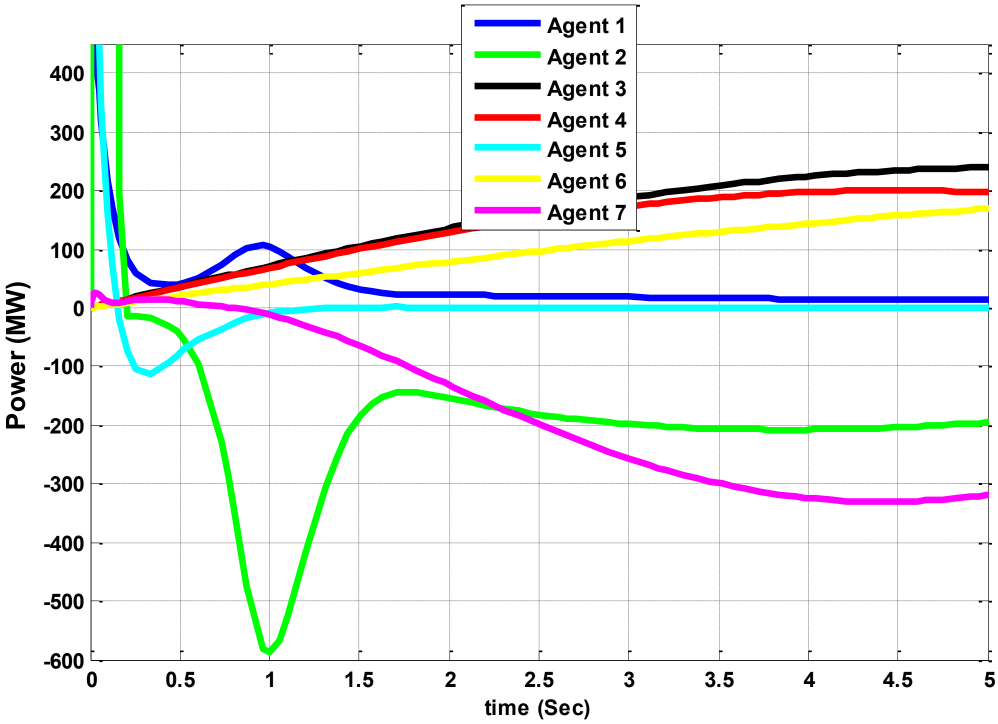

Fig.7. behavior of the septet agent of micro-grid power system model for time-varying disturbance input

3- Examining the Structure of the Proposed Control Strategy

The first step to design a stabilizer controller is to determine how the agents relate to each other in the form of a matrix called "Laplacian matrix". This matrix is obtained according to the topology of septet agents in Fig 2, as follows:

$$L = \begin{bmatrix} 1 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & -1 \\ -1 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (7)$$

According to the constituent components of the Laplacian matrix in (7), it is clear that each agent receives only the output information of its neighbors, therefore, the controller design will be distributive (decentralized). Since the ultimate purpose in power systems is to achieve stability, unwanted inputs to the micro-grid multifunction system will be confronted based on the Lyapunov function in the controller design, while ensuring system stability. The proposed cooperative controller is a controlling method based on the concepts of receding horizon and Lyapunov function. In the following, the steps of designing a Lyapunov-based cooperative controller are presented.

3- 1- Problem Definition

The first step is to select the appropriate cost function. According to the dynamic of the modeled multi-agent power system, the cost function presented in [35] was selected. The structure of this function is as follows:

$$J = \int_{t_k}^{t_k+N} [\tilde{x}(\tau)^T \, Q_c \, \tilde{x}(\tau) + \, u_k(\tau)^T \, R_c \, u_k(\tau)] d\tau \quad (8)$$

where $\tilde{x}(\tau)$ are the predicted state variables of the system and Q_c and R_c are the weighted matrices determining the cost. The purpose of the control strategy in this research is defined as follows:

$$u_k^*(t) = \min_{u_k \epsilon \, S(\Delta)} J \quad (9)$$

According to Equation (9), the purpose is to find a control rule in form of $u_k^*(t)$ that can minimize the cost function defined in (8). In this relation, S is a family of continuous piecewise fixed functions with sampling period of Δ.

3- 2- Predicting the Future State Variables of the System Using the Micro-Grid Multi-Agent Power System Model

After determining the cost function, the first step to minimize it is to provide an initial prediction of the system state variables using the multi-agent power system model. The predicted model of the system is as follows:

$$\dot{\tilde{x}}(t) = f\left(\tilde{x}(t), u_k(t)\right) \tag{10}$$

3- 3- Presentation of Lyapunov Function to Ensure System Stability

In order to ensure the system stability, the properties of Lyapunov function will be used in the cooperative control structure. For this purpose, after reviewing various references, the Lyapanov function introduced in study [5] was selected. This is a square function and its structure is as follows:

$$V(x) = X^T\, P\, X \tag{11}$$

Vector X in the structure of Lyapunov function is the result of difference between the system state variables, and the steady state value and is defined as follows:

$$X = \begin{bmatrix} \Delta P_{WTG} - \Delta P_{WTG}{}^{s} \\ \Delta P_{PV} - \Delta P_{PV}{}^{s} \\ \Delta P_{DEG} - \Delta P_{DEG}{}^{s} \\ \Delta P_{FC} - \Delta P_{FC}{}^{s} \\ \Delta P_{MT} - \Delta P_{MT}{}^{s} \\ \Delta P_{BESS} - \Delta P_{BESS}{}^{s} \\ \Delta P_{FESS} - \Delta P_{FESS}{}^{s} \\ \Delta f - \Delta f^{s} \end{bmatrix} \tag{12}$$

Additionally, the matrix P in the structure of Lyapunov function is a definite positive matrix that can be obtained by solving the following Riccati equation:

$$A^T P\, A - P - A^T P\, B\, (B^T P\, B + R)^{-1} B^T P\, A + QL = 0 \tag{13}$$

where A and B are the system matrices of the multi-agent micro-grid model, L is the Laplacian matrix, and Q and R are the weight matrices in the cost function structure.

3- 4- System Closed-Loop Function Constitution with Help of the Lyapunov-Based Cooperative Controller

As a final step, the multi-agent micro-grid closed-loop system in the presence of Lyapunov-based cooperative control signal is formed as follows:

$$\dot{\hat{x}}(t) = f\left(\hat{x}(t), h\left(\hat{x}(t)\right)\right) \tag{14}$$

Where $\hat{x}(t)$ is the system state variables, and $u = h\left(\hat{x}(t)\right)$ is also a Lyapunov-based cooperative control signal, defined as:

$$h(x) = \begin{cases} -\dfrac{L_f V + \sqrt{\left(L_f V\right)^2 + \left(L_g V\right)^4}}{L_g V} & if\ L_g V \neq 0 \\ 0 & if\ L_g V = 0 \end{cases} \tag{15}$$

where f and g are the functions of the micro-grid multi-agent power system, and the operator L is defined as follows:

$$\begin{aligned} L_f V &= \frac{\partial V(x)}{\partial x} f \\ L_g V &= \frac{\partial V(x)}{\partial x} g \end{aligned} \tag{16}$$

In the following, the results of the simulation of Lyapunov-based cooperative control algorithm conducted on multi-agent micro-grid system are discussed.

4- Simulation Results

First, the information contained in [5] is used, and the weight functions in cost function structure Error! Reference source not found. are obtained as follows:

$$Q = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 10 \end{bmatrix} \quad R = \begin{bmatrix} 0.1 & 0 \\ 0 & 0.01 \end{bmatrix} \tag{17}$$

By placing the high values in the Riccati equation (13), and by using MATLAB software, the matrix P in the structure of Lyapunov function (11) is obtained as follows:

$$P = \begin{bmatrix} 20.2557 & -0.5698 & 0 & 0.0732 & 2.8401\times10^{-16} & 0 \\ -0.5698 & 1.0524 & 0 & -0.0026 & -1.7751\times10^{-17} & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0.0732 & -0.0026 & 0 & 5464.1 & 163.4 & 0 \\ 2.8401\times10^{-16} & -1.7751\times10^{-17} & 0 & 163.4 & 10.3167 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1669.2 \end{bmatrix}$$

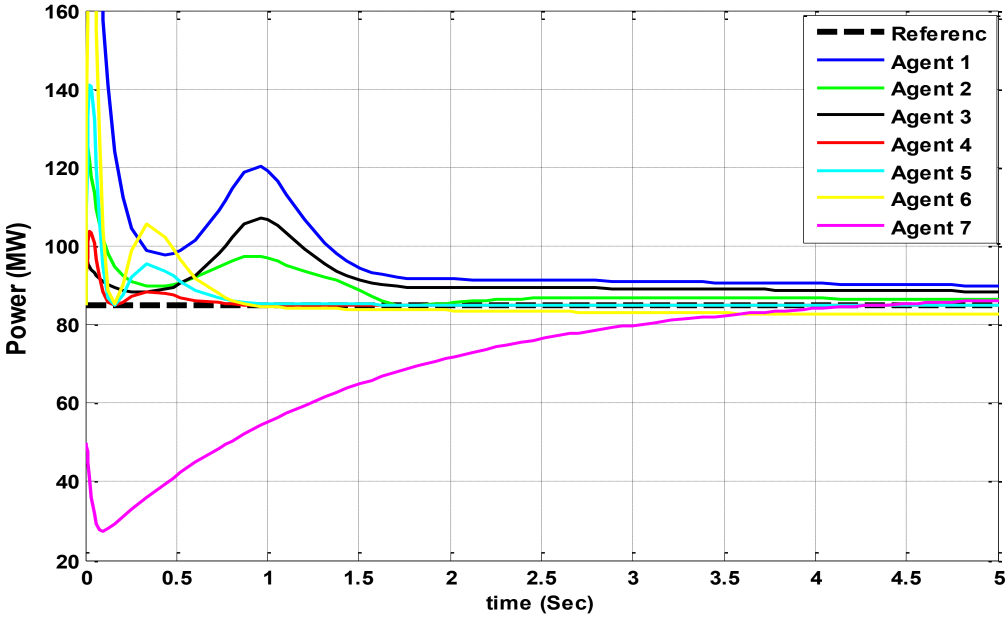

Fig 8. Stabilizing the power of the septet agents of the micro-grid power system in the presence of the distributed cooperative controller

In the following, the results of applying the control algorithm designed on the multi-agent power system modeled in this research are shown.

According to Fig. 8, the purpose of the controller design for the modeled multi-agent system is to create a coordinated and simultaneous behavior in the output variables of these agents. For this purpose, the amount of base power in this system is 85 MW. This means that both power-consuming agents, such as Diesel Generators, and power-generating agents, such as battery, simultaneously and coordinately produce or consume power equal to the base value. As can be seen in the diagram, all agents were able to converge to the base value in an acceptable time of 5 seconds. One of the salient points in the obtained diagrams is the power loss of the seventh agent (the rotating wheel) compared to the overshoot occurred in the power of other agents. Given that the rotating wheel agent is known as a generative agent, it is therefore possible that this power loss leads to the phenomenon of power shortages in the network and, as a result, blackouts in consumers. The following figure shows the cooperative control efforts to stabilize the amount of power generation/consumption of the components of the micro-grid multi-agent system.

In order to ensure the correct performance of the designed cooperative control system, the disturbance input shown in Fig. 6 is applied to the multi-agent model presented in this study. Fig 10 shows the obtained result. The amount of power production/consumption in the components of the micro-grid power system do not go through the same process for stabilization. Specifically, the second agent (solar arrays) and the sixth factor (battery) face severe power loss, and the first agent (wind turbine) faces severe power consumption. Among these three agents, battery is known as power generator and wind turbine and solar arrays are known as power consumers in the micro-grid. Among the considerable things about the graphs obtained for the power of micro-grid agents is the convergence time of these agents. When there is no disturbance input in the system, the convergence time is equal to 5 seconds, and in the presence of disturbance input, this time is increased up to 20 seconds, which is not desirable.

The following figure shows the control efforts applied by the cooperative controller for the state in which the system has a disturbance input.

4- 1- Checking the Stability of the Controller in the Face of Load Removal

In power systems, events such as faults, sudden load changes, and inadequate power generation remove the balance between production and consumption. If the power generation is not sufficient for the total load, the system should eliminate unnecessary and lower-priority loads. To investigate this important event, the following steps are performed:

1. The presence of all constituent agents under Lyapunov-based cooperative control at the beginning of the simulation.
2. Eliminating a number of load consuming agents in the grid at 10 seconds after beginning the simulation. These agents are: Solar Arrays (PV), Micro-turbine (MT), Diesel Generator (DEG), Fuel Cells (FC).
3. Investigating the changes in power consumption of the wind turbine agent (WTG), produced power of battery (BESS), and rotating power (FESS) agents in Fig12.

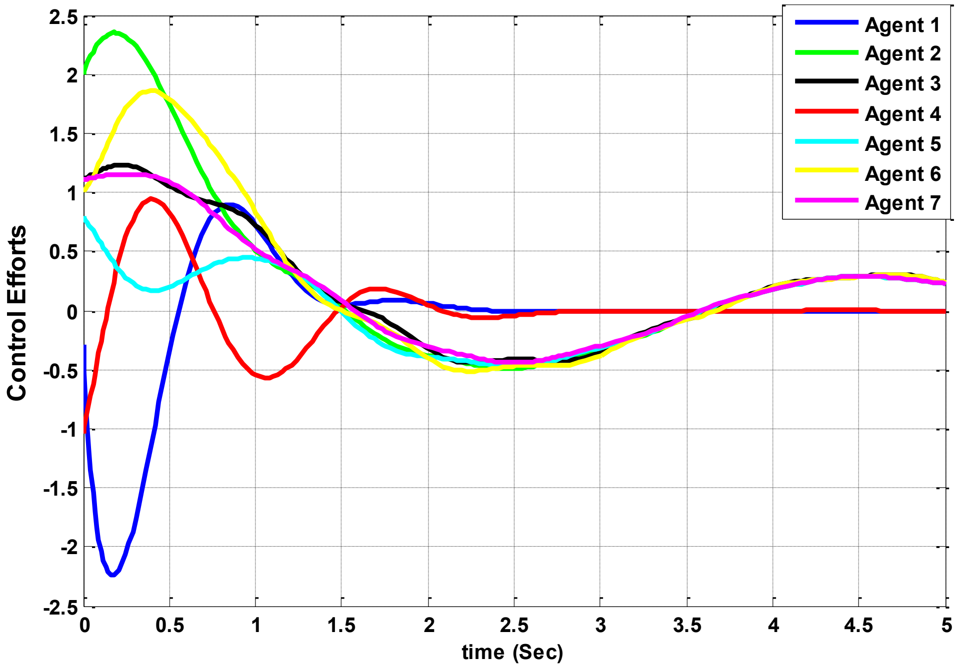

Fig. 9. Designed distributed cooperative controller control efforts

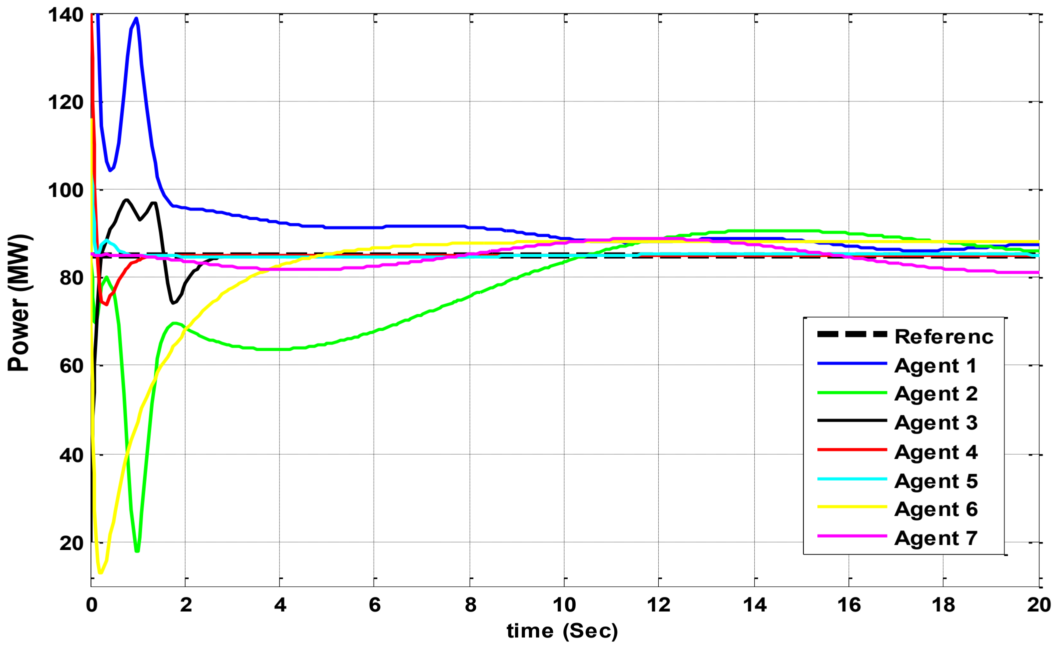

Fig. 10. Stabilization of the septet agents' power of the micro-grid power system under a distributed cooperative controller in the presence of disturbance input

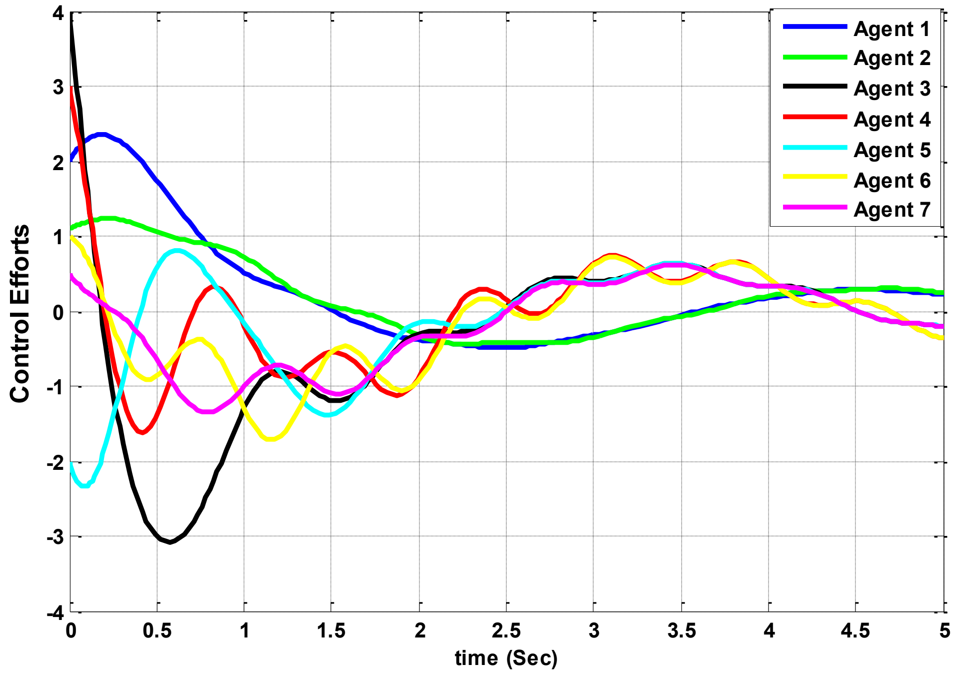

Fig. 11. Distributed cooperative controller control efforts in the presence of disturbance

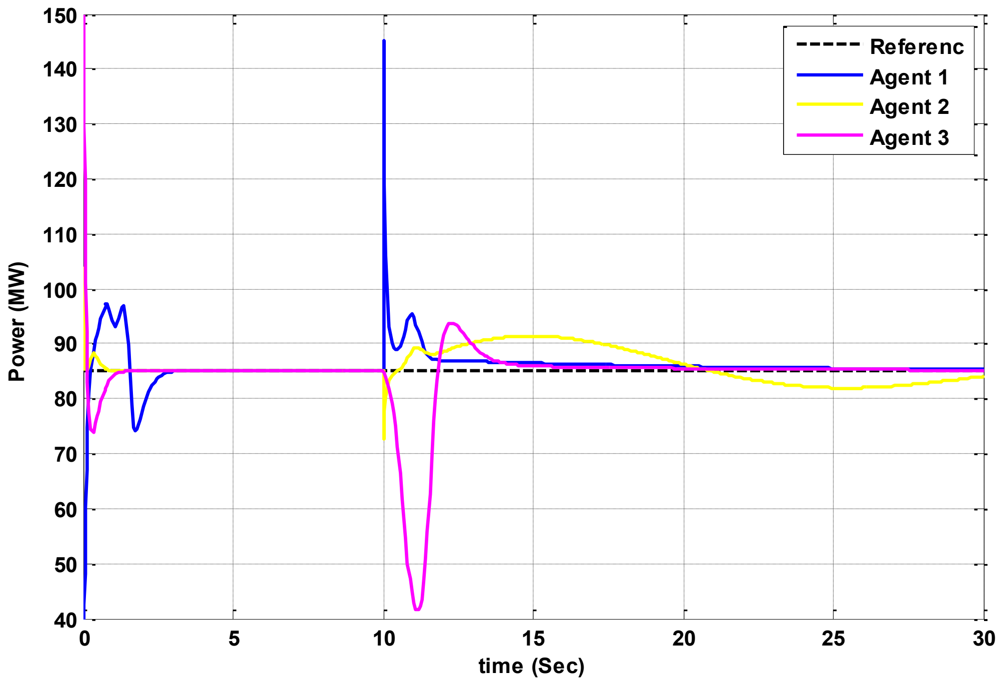

Fig. 12. The effect of removing a number of load consuming agents in the system

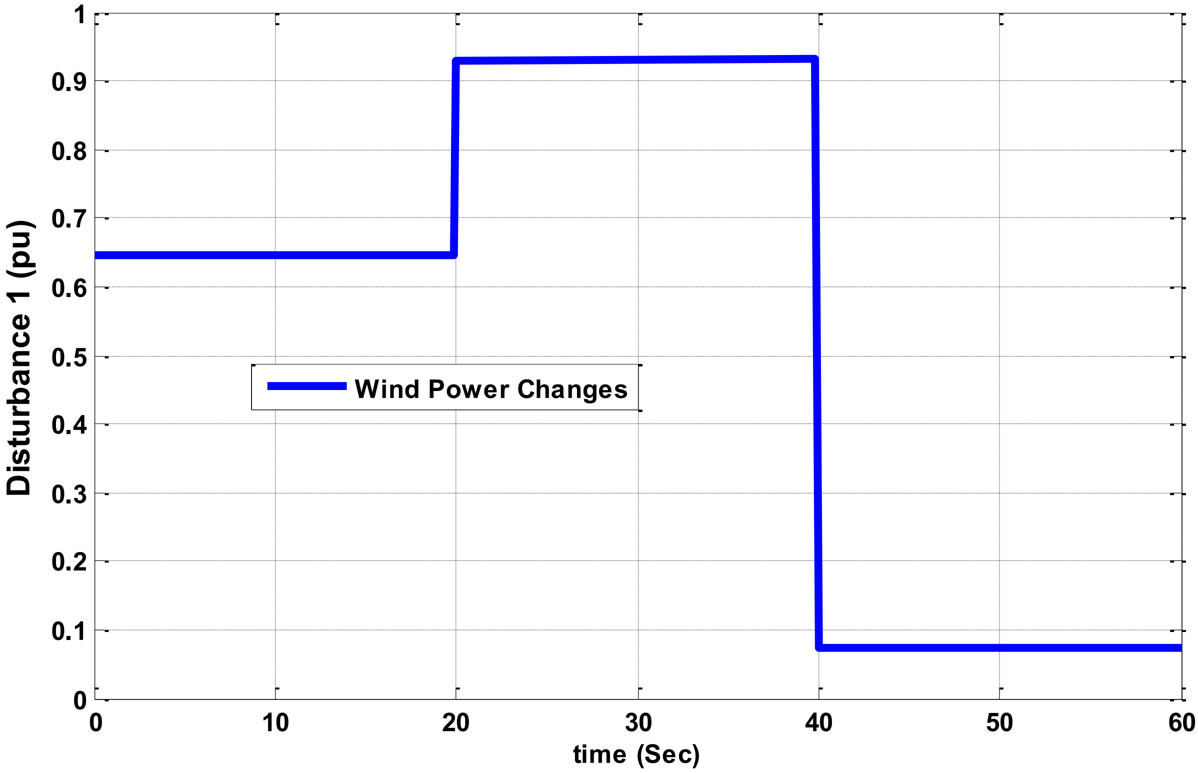

Fig. 13. Disturbance in wind power entered the wind turbine agent

As shown in Fig12, triple agents (mentioned in the studied power system) are initially fluctuated slightly and reached a stable state after approximately 3 seconds. Afterwards, at 10th second of the simulation, four consumption agents are removed from the power system. Looking carefully at the obtained diagrams, it can be seen that there are significant changes in the residual agents, which are described below:

- The wind turbine consuming agent take a lot of power from the grid at the 10th second, so it consumes 60 MW more power than what is considered for this agent (ie 80 MW). This phenomenon is highly destructive and may damage the multi-agent micro-grid. As can be seen, due to the existence of a controller based on the structure of the Lyapunov function, the turbine power consumption is decreased after this event, and after a short range fluctuation for approximately 3 seconds, it is converged to its stable state. Therefore, the cooperative controller designed in this research has an acceptable performance for the wind turbine agent.
- The battery generating agent, experiences a slight drop in the amount of power delivered to the studied micro-grid at the 10th second. The rate of this drop is about 14 MW. After compensating this drop by the cooperative controller, it is observed that the generation power of this agent has experienced short-range fluctuation (with a range of about 5 MW) and this fluctuation is continuous. Therefore, it can be said that the studied controller could not perform well for this agent.
- The generation agent of the rotating wheel experienced a sharp drop in the amount of power delivered to the grid at the 10th second. The rate of this drop is about 34 MW. After this drop, while compensating for this drop after a period of approximately 5 seconds, the controller effort converges the power of this agent to its desired value.
-

4- 2- Investigating the Controller Stability in Facing the Disturbance Inputs

In this section, the ability of the controller in the presence of unwanted disturbance inputs is investigated in two experiments, which are discussed below.

4- 2- 1- The First Experiment (Disturbance in Wind Power)

At times of 0, 20 and 40 seconds, step changes in wind power are applied, as shown in Fig.13.

4- 2- 2- The Second Experiment (Disturbance in Solar Radiation Power)

Step changes in solar radiation power are applied at times of 0, 20 and 40 seconds, as shown in Fig. 14.

The disturbance shown in Fig.13 and Fig.14 will be applied simultaneously to the micro-grid multi-agent system. This has a practical justification, because what actually happens is that the changes in wind and solar power are continuous and simultaneous. In Fig.15 to Fig.21, it can be seen

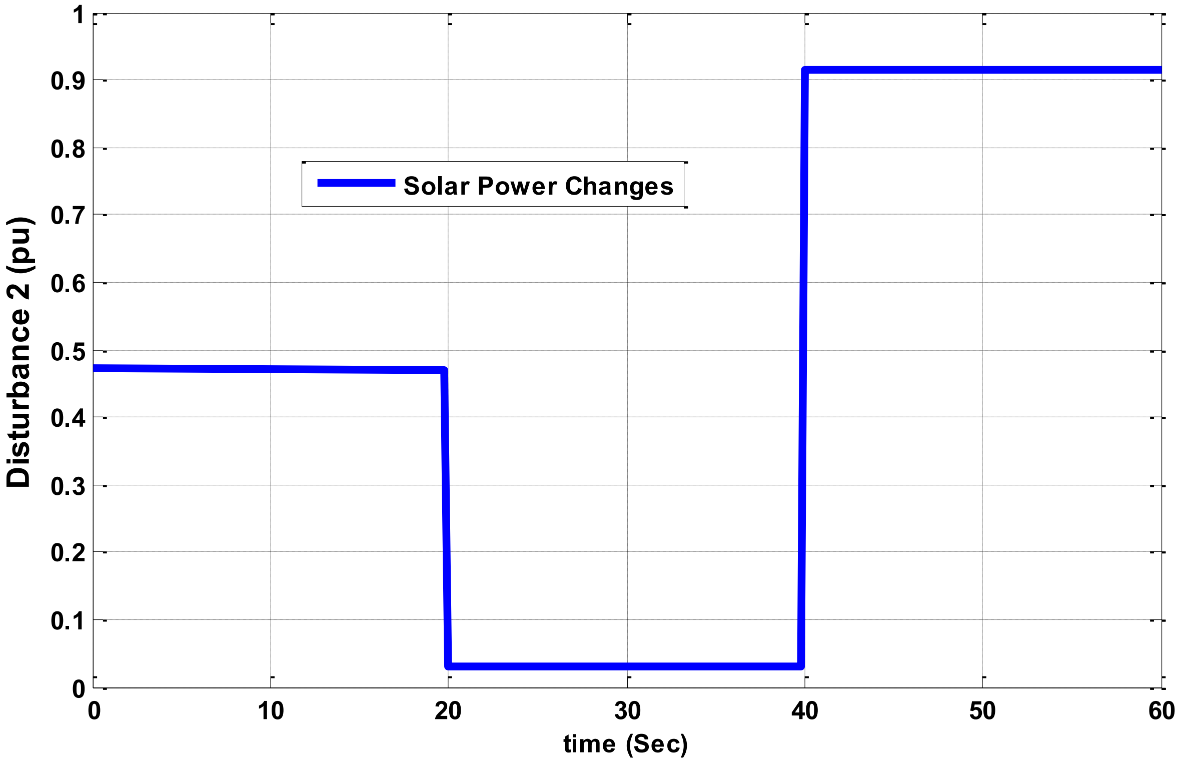

Fig. 14. Disturbance in solar radiation power input to the solar cell agent

that the controller designed in this study has the necessary efficiency to control the output power of micro-grid agents. Although, the behavior of agents facing input disturbances is not the same, and the agents act differently both in terms of the number of fluctuations and the range of fluctuations. In the first agent, namely the wind turbine, it is clear that the disturbance in the wind power entered this agent has the greatest impact.

4- 3- Comparing the Obtained Results with Similar Previous Works

In order to compare the algorithm presented in this paper with the ability of the designed Lyapunov-based cooperative control law, the method presented in the research conducted by Thomas Morstyn and Branislav Redzak in 2016 is completely new, and an algorithm for creating simultaneous and coordinated behavior in agents with completely similar dynamics has been selected [4]. In the mentioned study, the creation of coordinated and simultaneous behavior for a micro-grid power system has been investigated by using the dynamic feedback controller with the following control law, where c and k must be specified. Among the obvious differences in these two studies is the modeling of micro-grid power system in study [4] with three factors, while the model is more comprehensive and seven agents influencing on the behavior of the micro-grid power system are considered in this paper. These agents include wind turbines and Diesel Generators as power consumer agents and battery as power generator agents in the grid. The diagrams obtained for the output power of these three agents in the present study and the research conducted in [4] are shown in Fig 22 to Fig 24.

As it can be seen in Fig 22 to Error! Reference source not found.24, the output variable of power generation/consumption for triple agents in study [4] has been much slower and converged with more fluctuations than the results of the method presented in this study. Therefore, it can be said that the results obtained in the current study are more favorable and have better conditions in terms of both fluctuations and convergence speed. According to the studies, the reason for the improvement of this performance can be for the existence of Lyapunov function in the cooperative controller structure designed in this research since the controller designed in study [4] has not provided a solution to ensure system stability. The control parameters of both methods are extracted and are compared in

. As it can be seen, the control strategy designed in this study was able to perform better than the study in terms of both reducing the amount of control effort and achieving control goals.

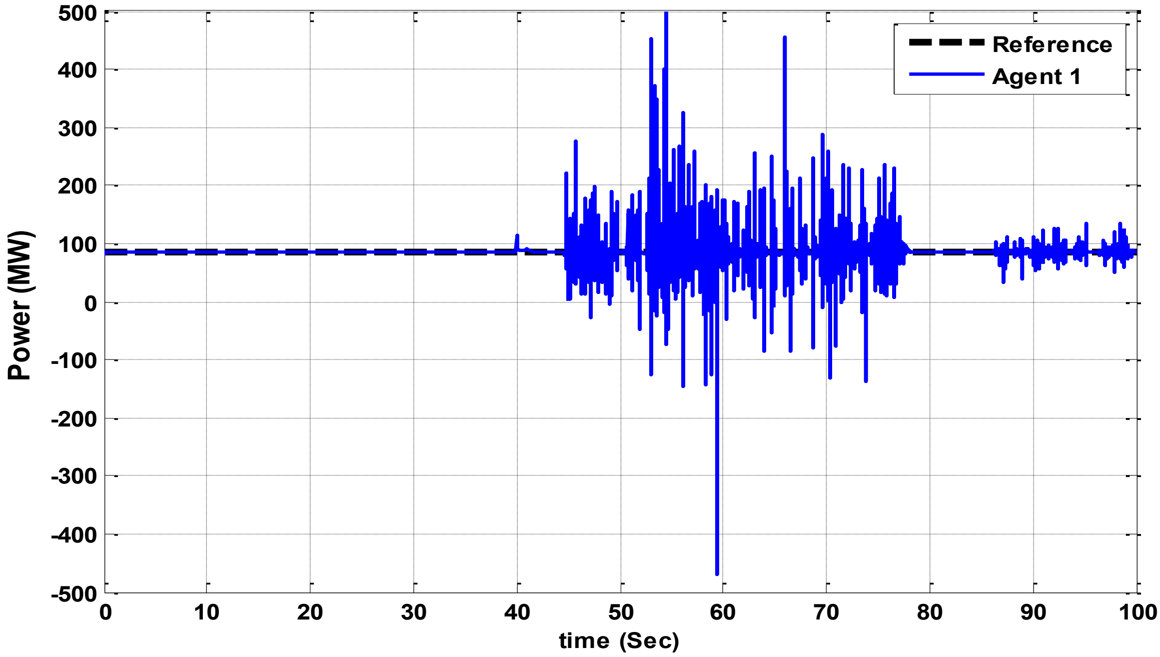

Fig. 15. The output power of the first agent when applying disturbance in wind power and solar radiation power

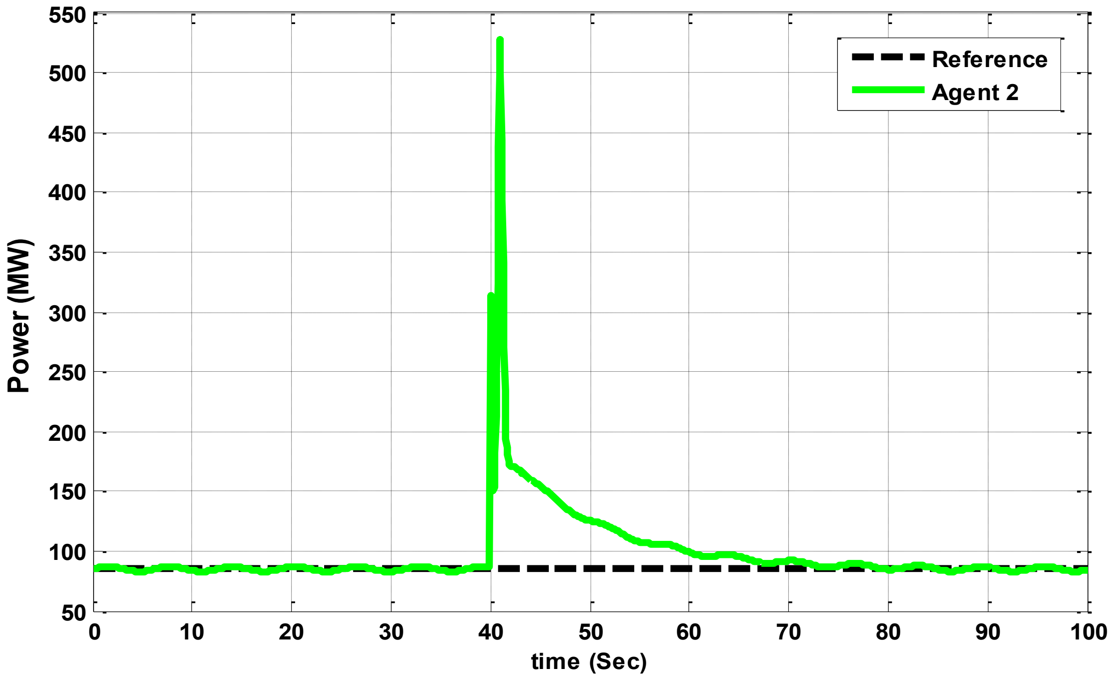

Fig. 16. The output power of the second agent when applying disturbance in wind power and solar radiation power

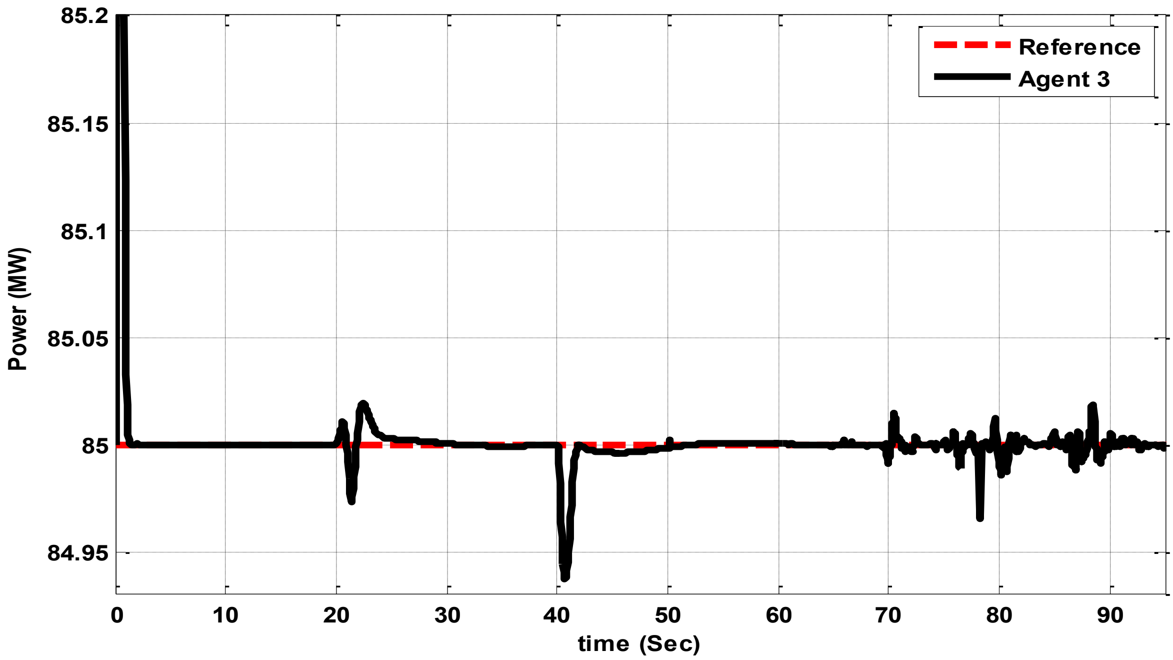

Fig. 17. The output power of the third agent when applying disturbance in wind power and solar radiation power

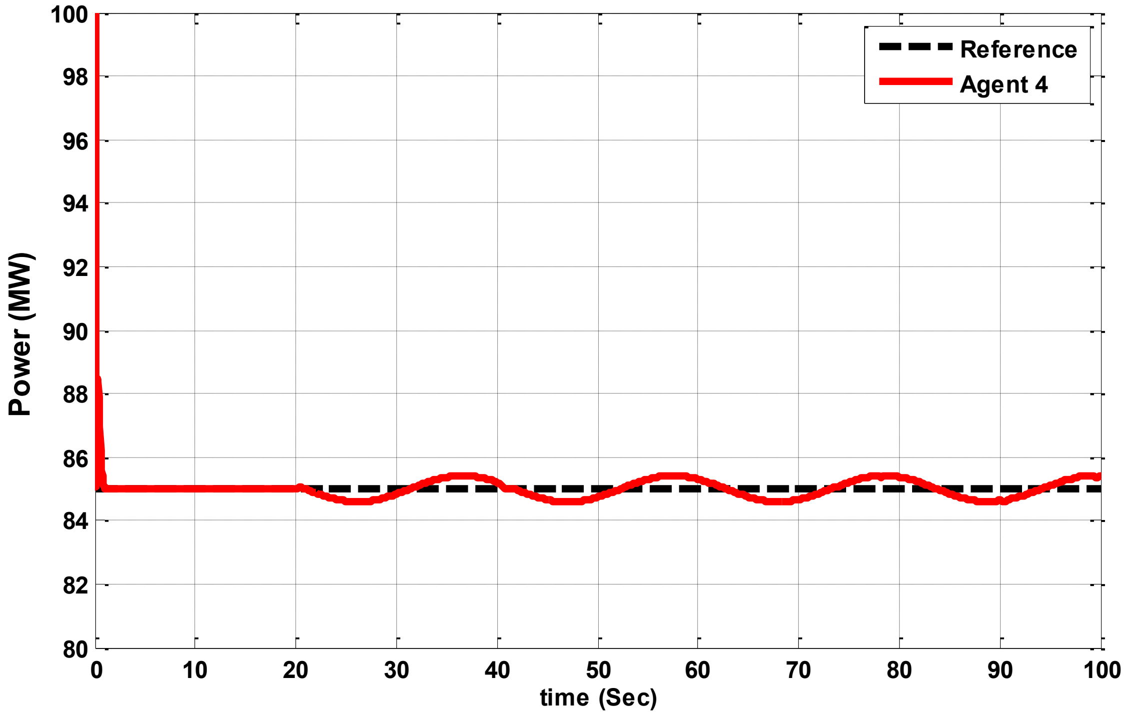

Fig. 18. The output power of the fourth agent when applying disturbance in wind power and solar radiation power

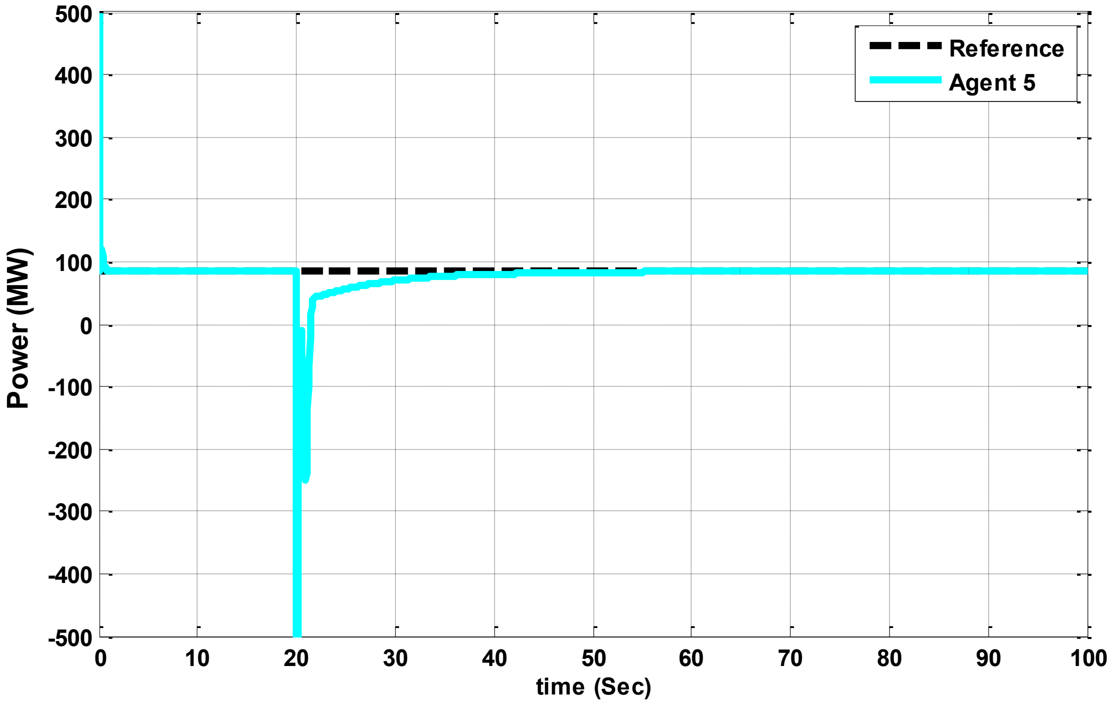

Fig. 19. The output power of the fifth agent when applying disturbance in wind power and solar radiation power

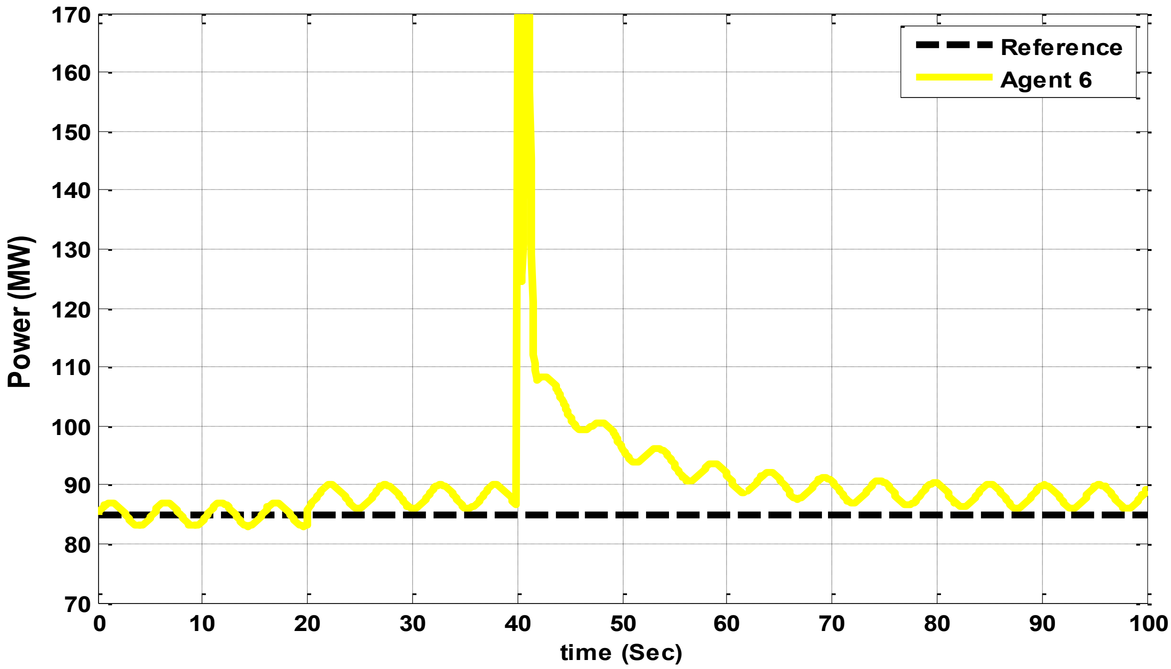

Fig. 20. The output power of the sixth agent when applying disturbance in wind power and solar radiation power

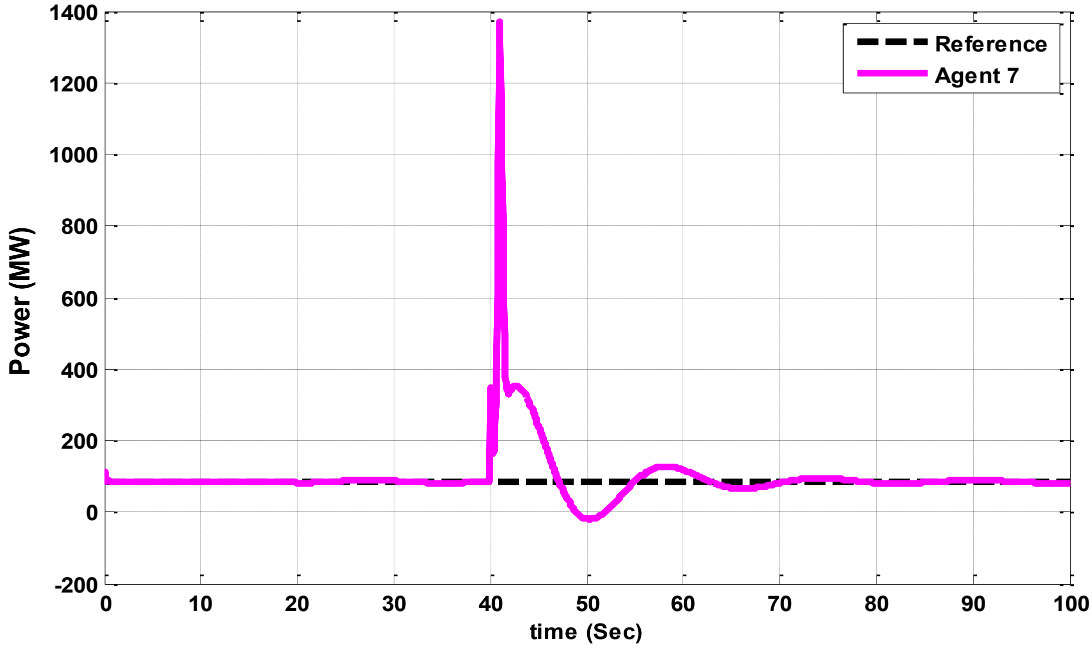

Fig. 21. The output power of the seventh agent when applying disturbance in wind power and solar radiation power

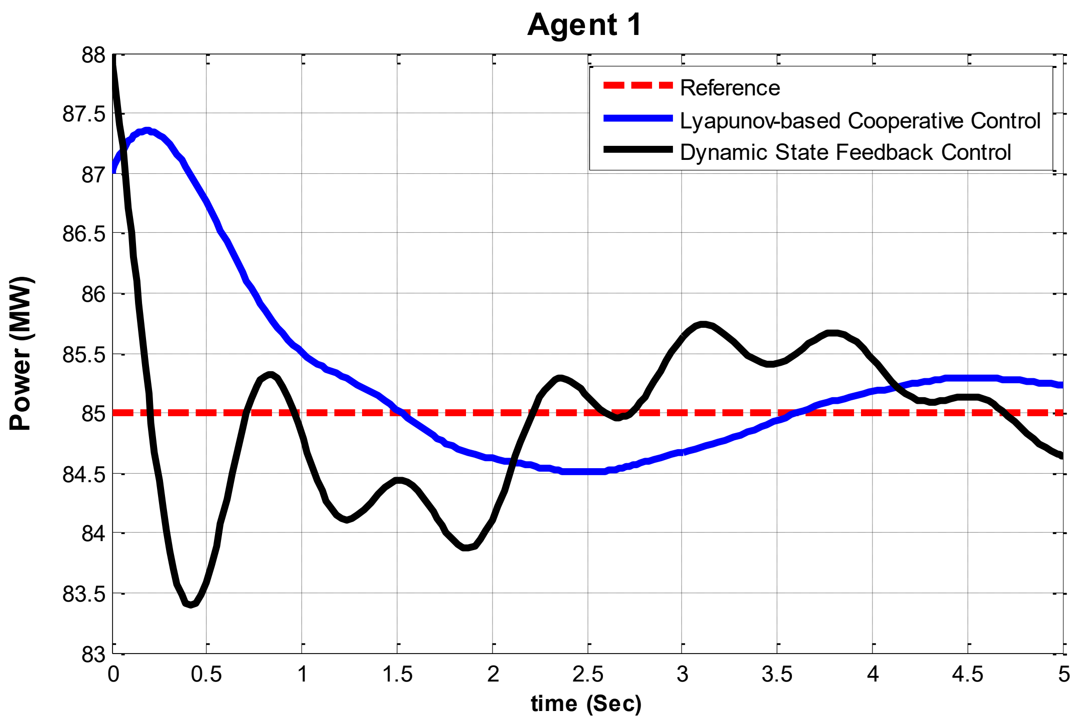

Fig 22. The output power of wind turbine agent in the presence of Lyapunov-based cooperative controller (present study) and state feedback controller

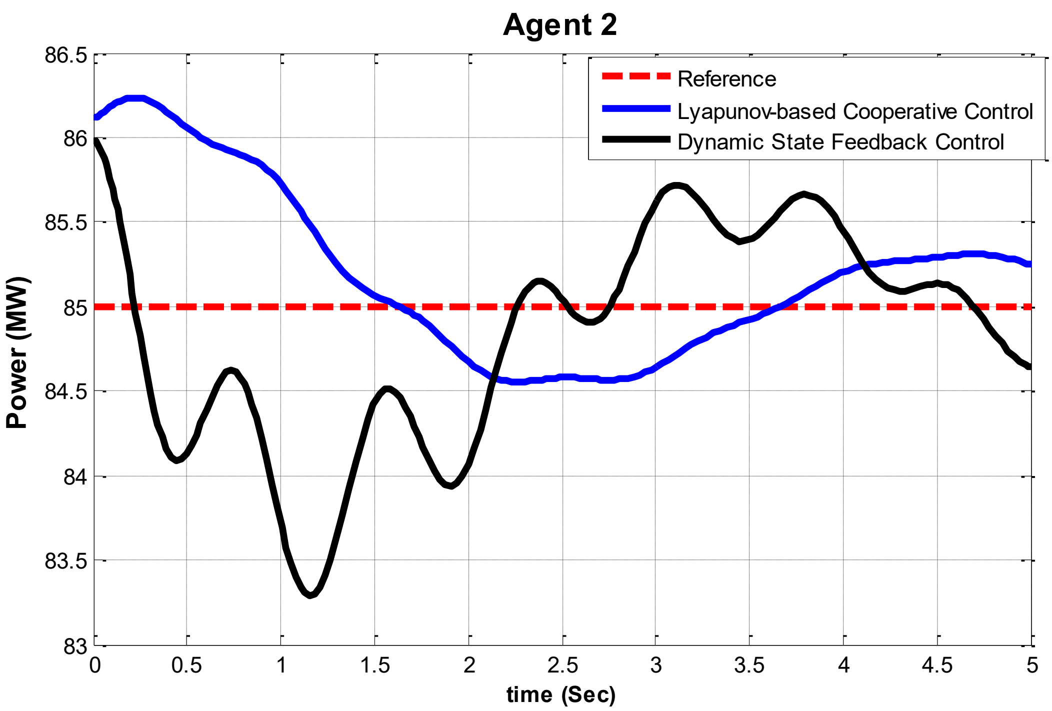

Fig 23. The output power of Diesel Generator agent in the presence of Lyapunov-based cooperative controller (present study) and state feedback controller

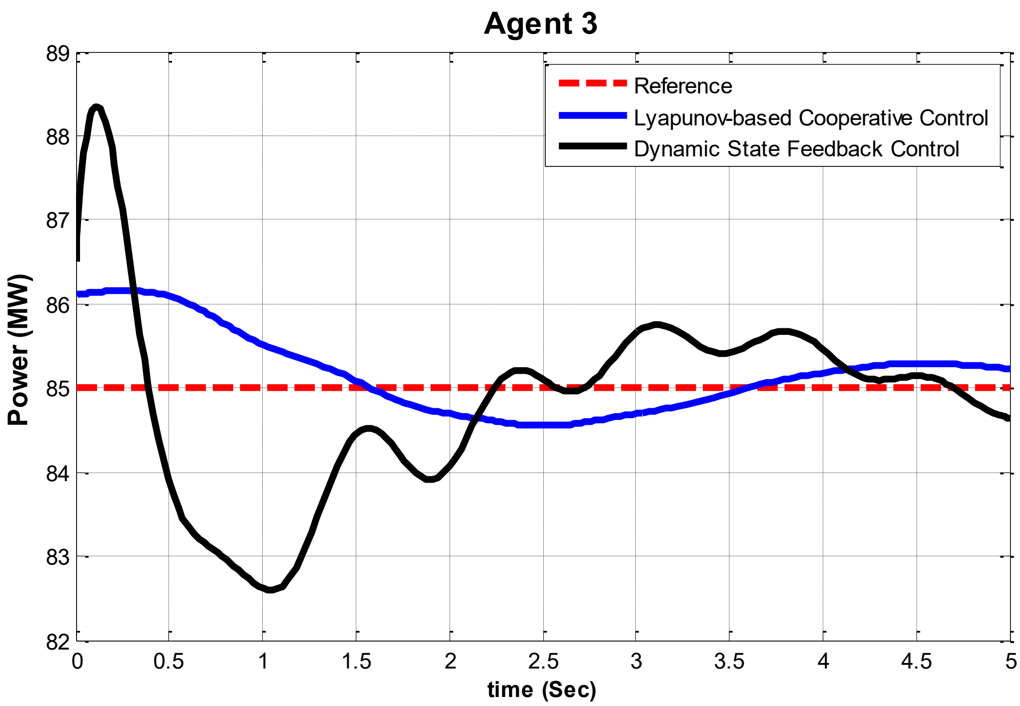

Fig 24. The output power of battery agent in the presence of Lyapunov-based cooperative controller (present study) and state feedback controller

Table 3. Quantitative comparison of results

Compared parameters \ Studied reference	The previous studies	The current study
Implemented control strategy	feedback control of dynamic state	Lyapunov-based cooperative control
Controller surface integral for the control signal in the first agent	10.2	8.7
Controller surface integral for the control signal in the second agent	9.8	5.4
Controller surface integral for the control signal in the third agent	9.3	7.8
Maximum overshoots of agents	3.3 MW	2.4 MW
Most time of agent settling time	unlimited	unlimited

5- Conclusion

The strategy discussed in this paper, as a robust method with decentralized configuration, covers a small part of the problems faced by cooperative control in multi-agent systems. Of course, there are other problems in designing this type of controllers in different ways that may not be consistent with the process presented in this study. In simpler terms, despite the possibility of combining different control objectives and agent's conditions, the presented configuration is not responsive. Despite the acceptable flexibility in Lyapunov-based cooperative controller design to achieve coordinated and simultaneous behavior in the components of the micro-grid multi-agent system, the discussion of cooperative control design is only considered for the power parameter in the agents of the micro-grid power system, and other important and effective parameters, such as voltage and frequency of agents have not been investigated. What has been hypothesized throughout this research is the certainty in the multi-agent system considering the Laplacian matrix as a constant. However, the topology of the multi-agent power system in systems with many agents is practically uncertain. Therefore, the extension of existing methods to a more realistic situation of time-varying communication network should be investigated.

References

[1] W. Qi, Towards Optimal Operation, Planning and Control of Data Center Microgirds: Clarkson University, 2018.

[2] K. Bhargavi, N. Jayalakshmi, D. Gaonkar, A. Shrivastava, and V. K. Jadoun, "A comprehensive review on control techniques for power management of isolated DC microgrid system operation," IEEE Access, vol. 9, pp. 32196-32228, 2021.

[3] H. Cai and G. Hu, "Distributed nonlinear hierarchical control of AC microgrid via unreliable communication," IEEE Transactions on Smart Grid, vol. 9, pp. 2429-2441, 2016.

[4] T. Morstyn, B. Hredzak, and V. G. Agelidis, "Cooperative multi-agent control of heterogeneous storage devices distributed in a DC microgrid," IEEE Transactions on Power Systems, vol. 31, pp. 2974-2986, 2015.

[5] A. J. Veronica and N. S. Kumar, "Control strategies for frequency regulation in microgrids: A review," Wind Engineering, vol. 45, pp. 107-122, 2021.

[6] E. Smith, D. Robinson, and A. Agalgaonkar, "Cooperative Control of Microgrids: A Review of Theoretical Frameworks, Applications and Recent Developments," Energies, vol. 14, p. 8026, 2021.

[7] A. Mohammed, S. S. Refaat, S. Bayhan, and H. Abu-Rub, "AC microgrid control and management strategies: Evaluation and review," IEEE Power Electronics Magazine, vol. 6, pp. 18-31, 2019.

[8] Y. Zhang, Y. Song, and S. Fei, "A distributed step-by-step finite-time consensus design for heterogeneous battery energy storage devices with droop control," CSEE Journal of Power and Energy Systems, 2020.

[9] Y. Dai, L. Zhang, K. Yan, Q. Chen, and Z. Zhou, "An Integrated Cooperative Control Strategy for EVs Accessed Community Uninterruptible Power System," IEEE Transactions on Intelligent Vehicles, 2022.

[10] A. Bidram, F. L. Lewis, and A. Davoudi, "Synchronization of nonlinear heterogeneous cooperative systems using input–output feedback linearization," Automatica, vol. 50, pp. 2578-2585, 2014.

[11] Y. Wu, D. Meng, and Z.-G. Wu, "Transient Bipartite Synchronization for Cooperative-Antagonistic

Multiagent Systems With Switching Topologies," IEEE Transactions on Cybernetics, 2021.
[12] S. Butenko, R. Murphey, and P. M. Pardalos, Cooperative control: models, applications and algorithms vol. 1: Springer Science & Business Media, 2013.
[13] Y. Xu, J. Zhang, P. Wang, and M. Lu, "Research on the bi-level optimization model of distribution network based on distributed cooperative control," IEEE Access, vol. 9, pp. 11798-11810, 2021.
[14] S. Mo, W.-H. Chen, and X. Lu, "Distributed hybrid secondary control strategy for DC microgrid group based on multi-agent system," in 2021 33rd Chinese Control and Decision Conference (CCDC), 2021, pp. 109-114.
[15] C. M. Colson and M. H. Nehrir, "Algorithms for distributed decision-making for multi-agent microgrid power management," in 2011 IEEE Power and Energy Society General Meeting, 2011, pp. 1-8.
[16] S. Kahrobaee, R. A. Rajabzadeh, L.-K. Soh, and S. Asgarpoor, "A multiagent modeling and investigation of smart homes with power generation, storage, and trading features," IEEE Transactions on Smart Grid, vol. 4, pp. 659-668, 2012.
[17] B. Krishna Metihalli and J. Narayana Sabhahit, "Disturbance Observer Based Distributed Consensus Control Strategy of Multi-Agent System with External Disturbance in a Standalone DC Microgrid," Asian Journal of Control, vol. 23, pp. 920-936, 2021.
[18] E. Kuznetsova, Y.-F. Li, C. Ruiz, and E. Zio, "An integrated framework of agent-based modelling and robust optimization for microgrid energy management," Applied Energy, vol. 129, pp. 70-88, 2014.
[19] E. Kuznetsova, C. Ruiz, Y.-F. Li, and E. Zio, "Analysis of robust optimization for decentralized microgrid energy management under uncertainty," International Journal of Electrical Power & Energy Systems, vol. 64, pp. 815-832, 2015.
[20] N. Eghtedarpour and E. Farjah, "Power control and management in a hybrid AC/DC microgrid," IEEE transactions on smart grid, vol. 5, pp. 1494-1505, 2014.
[21] C. Gouveia, D. Rua, F. Ribeiro, L. Miranda, J. M. Rodrigues, C. Moreira, et al., "Experimental validation of smart distribution grids: Development of a microgrid and electric mobility laboratory," International Journal of Electrical Power & Energy Systems, vol. 78, pp. 765-775, 2016.
[22] B. M. Radhakrishnan, D. Srinivasan, and R. Mehta, "Fuzzy-based multi-agent system for distributed energy management in smart grids," International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems, vol. 24, pp. 781-803, 2016.
[23] L. Raju, R. Milton, and A. A. Morais, "Autonomous Energy Management of a Micro-Grid using Multi Agent System," Indian Journal of Science and Technology, vol. 9, pp. 1-6, 2016.
[24] M. Marzband, H. Alavi, S. S. Ghazimirsaeid, H. Uppal, and T. Fernando, "Optimal energy management system based on stochastic approach for a home Microgrid with integrated responsive load demand and energy storage," Sustainable cities and society, vol. 28, pp. 256-264, 2017.
[25] A. A. Hamad and E. F. El-Saadany, "Multi-agent supervisory control for optimal economic dispatch in DC microgrids," Sustainable Cities and Society, vol. 27, pp. 129-136, 2016.
[26] A. Kaysal, S. Köroğlu, and Y. Oğuz, "Hierarchical energy management system with multiple operation modes for hybrid DC microgrid," International Journal of Electrical Power & Energy Systems, vol. 141, p. 108149, 2022.
[27] M. Askari, M. Ab Kadir, H. Hizam, and J. Jasni, "A new comprehensive model to simulate the restructured power market for seasonal price signals by considering on the wind resources," Journal of Renewable and Sustainable Energy, vol. 6, p. 023104, 2014.
[28] M. T. Askari, M. Z. A. A. Kadir, M. Tahmasebi, and E. Bolandifar, "Modeling optimal long-term investment strategies of hybrid wind-thermal companies in restructured power market," Journal of Modern Power Systems and Clean Energy, vol. 7, pp. 1267-1279, 2019.
[29] H. Cai and G. Hu, "Consensus-based distributed nonlinear hierarchical control of AC microgrid under switching communication network," in 2016 12th IEEE International Conference on Control and Automation (ICCA), 2016, pp. 571-576.
[30] H. Cai and G. Hu, "Consensus-based distributed package-level state-of-charge balancing for grid-connected battery energy storage system," in 2016 12th IEEE International Conference on Control and Automation (ICCA), 2016, pp. 365-370.
[31] S. Adhikari and F. Li, "Coordinated Vf and PQ control of solar photovoltaic generators with MPPT and battery storage in microgrids," IEEE Transactions on Smart grid, vol. 5, pp. 1270-1281, 2014.
[32] R. Jabeur, Y. Boujoudar, M. Azeroual, A. Aljarbouh, and N. Ouaaline, "Microgrid energy management system for smart home using multi-agent system," International Journal of Electrical and Computer Engineering (IJECE), vol. 12, pp. 1153-1160, 2022.
[33] T. Ma, L. Zhang, and Z. Gu, "Further studies on impulsive consensus of multi-agent nonlinear systems with control gain error," Neurocomputing, vol. 190, pp. 140-146, 2016.
[34] H. Bevrani, M. R. Feizi, and S. Ataee, "Robust frequency control in an islanded microgrid: ${H} _ {\infty} $ and $\mu $-synthesis approaches," IEEE transactions on smart grid, vol. 7, pp. 706-717, 2015.
[35] J. Liu, D. Munoz de la Pena, P. D. Christofides, and J. F. Davis, "Lyapunov-based model predictive control of nonlinear systems subject to time-varying measurement delays," International Journal of Adaptive Control and Signal Processing, vol. 23, pp. 788-807, 2009.

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