Soft Computing Journal, vol. 12, no. 1, pp. 2–7, 2022
https://doi.org/10.22052/scj.2022.246259.1058

University of Kashan

Contents lists available at SCJ

Soft Computing Journal

Journal homepage: https://scj.kashanu.ac.ir/

Microgrid frequency regulation by using electric vehicles controlled by a fuzzy controller with optimized rules and membership functions ✧

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ARTICLE INFO.

Article history:
Received April 9, 2022
Accepted July 31, 2022

Keywords:
Optimized fuzzy controller
Vehicle to grid
Frequency regulation
State of charge
Microgrid

ABSTRACT

The increasing reliance on electric power and the environmental pollution caused by fossil fuels has created a need for new energy sources for electric power production. Renewable energy sources such as wind and solar can be employed to produce electric power, however, their output powers are unpredictable due to stochastic environmental situations. These changes lead to frequency deviations in the power grid, potentially making it unstable. This issue can be more challenging in standalone microgrids since they have low inertia. To overcome this challenge, energy storage systems (ESSs) can be used, although they require significant investment and may not always be cost-effective. Electric vehicles (EVs) can help power systems balance generation and consumption and compensate for renewable energy output changes. This is achieved through the EV batteries, which can be charged when the grid frequency is high and discharged when it is low, a concept known as Vehicle to Grid (V2G). In this paper, we present a new method for controlling EVs in a microgrid in order to reduce frequency deviations. To this end, we introduce a fuzzy controller with optimized membership functions and rules. In the proposed method, the state of charge (SOC) of an EV battery can be controlled while regulating frequency. Simulations conducted in the MATLAB environment demonstrate the effectiveness of the proposed method.

1 Introduction

Renewable energies such as wind and solar energies can be alternatives for producing electric power. To better control these renewable sources, they are usually employed in microgrids. A microgrid can operate in grid-connected and standalone modes. When it is in grid-connected mode, voltage and frequency are controlled by the main grid but when it operates in standalone mode, voltage and frequency should be controlled by itself. Renewable energy sources (RESs) such as wind and solar energies suffer from uncertainties in their output power due to stochastic environmental situations which can lead to frequency deviations in grids. This problem can be more challenging in standalone microgrids due to their low inertia.

Nowadays using of electric vehicles is increasing. According to [1], the number of EVs in the United States in 2030, and 2050 will reach 51%, and 62%, respectively. It is possible to use electric vehicle batteries to balance generation and consumption in microgrids so that they can be charged when grid fre-

✧ Article type: original research (short paper)

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How to cite this article: S. F. Aliabadi, S. A. Taher, "Microgrid frequency regulation by using electric vehicles controlled by a fuzzy controller with optimized rules and membership functions", *Soft Comput. J.*, vol. 12, no. 1, pp. 2–7, 2022, doi: 10.22052/scj.2022.246259.1058.

quency is high and discharged when frequency is low. This concept is introduced by Vehicle to Grid (V2G) phrase. Using EV batteries for frequency regulation can reduce the need for investment, which has been employed in literature [2–11].

In [2], a power management scheme has been presented to leverage the participation of EVs for secondary frequency regulation. This paper considered multiple objectives and formulated the problem of frequency support as a "Mixed Integer Linear Programming (MILP)" problem. In [3], the authors employed small-signal analysis to investigate which droop or virtual inertia method is more suitable for cooperation between wind generators and plugin hybrid electric vehicles (PHEVs) in order to participate in primary frequency regulations in power grids. In [4], a novel frequency control strategy is proposed for EVs to participate in the primary and secondary frequency regulations of microgrids. In this paper, virtual inertia and virtual damping are introduced using a virtual synchronous generator through AC/DC control. In [5], a novel strategy is described to properly design the frequency-droop controller of plugin electric vehicles (PEVs) for primary frequency control (PFC). It is demonstrated that PEVs using the well-designed droop controller significantly improve the PFC response while successfully preserving the frequency stability. In this paper, a new control technique is suggested to alternate some portion of PEV's reserve after a certain time by the reserve of conventional units during PFC. Furthermore, a method is proposed to evaluate the positive economic impact of PEV's participation in PFC. In [6], the authors proposed a method to demonstrate the participation of EVs for load frequency control (LFC) under a deregulated environment along with other conventional sources. In this paper, a new fractional order (FO) controller is suggested in all the areas for robust LFC considering bilateral transactions. Using of EVs for frequency regulation during grid restoration is mentioned in [7]. This paper employed an adaptive optimal controller for this aim. In [8], an "aggregator-based hierarchical control mechanism" for secondary frequency regulation (SFR) is presented using a fleet of EVs. In this paper, EVs' scheduling problem has been formulated to provide optimal SFR, while satisfying EVs' energy demands under battery degradation constraints. In [9], a new coordination of EV, wind farm (WF), and photovoltaic (PV) for microgrid frequency regulation is proposed. In the control design, an adaptive PI controller incorporating with a small delay consideration in the control loop is used to regulate frequency at various operating points. In [10], two controllers are suggested by considering different charging profiles, state of charge (SOC) of electric vehicle batteries, and a varying number of electric vehicles in an electric vehicle fleet. These controllers provide bidirectional power flow, which can provide primary frequency control during different contingencies that an industrial microgrid may face during a 24-hour period. In [11], the authors proposed a hierarchical framework for control of the governor/turbine and EVs in order to provide primary frequency support. The work has two layers; one layer dispatches the primary reserve references and another dispatches the aggregated EV power change.

In this paper, a new method for control of electric vehicles (EVs) in a microgrid is proposed in order to decrease frequency deviations. For this purpose, a fuzzy controller with optimized membership functions and rules is introduced. Moreover in the proposed method, the SOC of the EV battery can be controlled along with frequency regulation. Imperialist Competitive Algorithm (ICA) has been employed for optimization. To the best knowledge of the authors, this study has not been reported in the literature.

The rest of the paper is organized as follows. In the second part, an understudy microgrid is introduced. The suggested method is then described in the next part. In the fourth part, simulations are conducted and the results are discussed. In the last part, a conclusion is given.

2 Understudy microgrid

The understudy microgrid is shown in Fig. 1. The elements of this microgrid are the PV system, wind energy system, BESS, diesel generator, EVs and loads. In the following, we describe the modeling of systems [12–15].

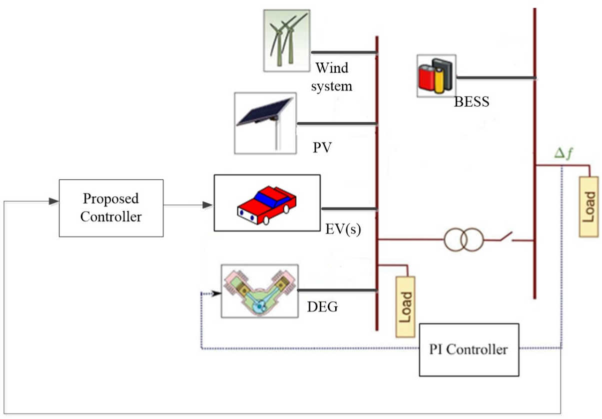

Fig. 1. Understudy microgrid

PV system model: A lag transfer function is assumed for PV cells as follows:

$$G_{PV}(s) = \frac{\Delta P_{sol}}{\Delta \Phi} = \frac{K_{PV}}{1 + sT_{PV}} \quad (1)$$

where $\Delta\Phi$ is the intensity of radiation and ΔP_{sol} is the output power of PV. T_{PV} shows the time constant of PV system response and K_{PV} is PV system gain. In an AC microgrid, the PV system is connected to the microgrid by using of inverter and filter. Dynamic modeling of output inverter and filter according to input is as follows:

$$G_{inv}(s) = \frac{\Delta P_{PV,AC}}{\Delta P_{sol}} = \frac{1}{(1+sT_{IN})(1+sT_{I/C})} \quad (2)$$

where T_{IN} and $T_{I/C}$ are time constants of the inverter and filter respectively. For the intensity of radiation, a random signal is produced by a uniform random number block of MATLAB.

Wind turbine generator: For modeling the wind turbine generator, a lag transfer function is supposed as follows:

$$G_{wtg}(s) = \frac{\Delta P_{WTG}}{\Delta P_{W_m}} = \frac{K_{WTG}}{1+sT_{WTG}} \quad (3)$$

where T_{WTG} and K_{WTG} show the time constant and gain of the wind turbine generator system respectively. In this study, wind velocity changes are obtained by a method as same as the intensity of radiation.

Diesel generator: The relation between frequency changes and the output power of the synchronous generator is modeled as follows:

$$G_{deg}(s) = \frac{\Delta P_{DEG}}{\Delta f} = \frac{K_{DEG}}{(1+sT_G)(1+sT_{DE})} \quad (4)$$

where K_{DEG} is the final gain of the diesel generator system to microgrid frequency changes and T_G and T_{DE} are time constants of synchronous generator and diesel respectively.

Battery energy storage system: The following transfer function is used to model the BESS in order to frequency analysis:

$$G_{BESS}(s) = \frac{\Delta P_{BESS}}{\Delta f} = \frac{K_{BESS}}{1+sT_{BESS}} \quad (5)$$

where K_{BESS} is the gain of BESS to microgrid frequency changes and T_{BESS} is the time constant of it.

EV model: To model EV for frequency analysis, a first-degree transfer function is used as follows:

$$G_{EV}(s) = \frac{\Delta P_{EV}}{\Delta f} = \frac{1}{1+sT_{EV}} \quad (6)$$

where T_{EV} is the time constant of the model.

With respect to above mentioned, the frequency model of a microgrid is shown in Fig. 2. In this figure, D and H show the damping and inertia constant of the microgrid respectively.

3 Proposed controller

The structure of the proposed controller is shown in Fig. 3. In this figure, the frequency deviation of the microgrid and SOC of the EV battery are considered as two inputs of the controller and with respect to their values, the output power of the EV battery for charging and discharging is computed.

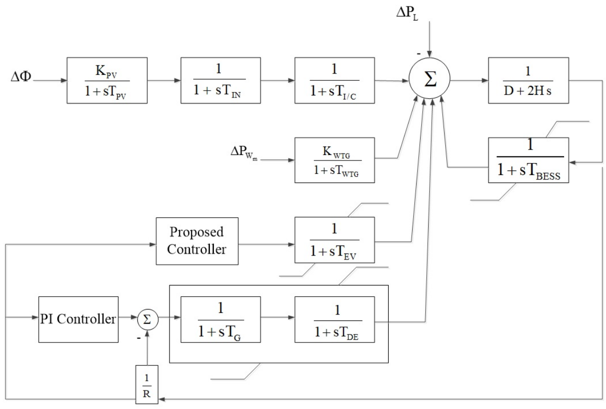

Fig. 2. Frequency model of microgrid

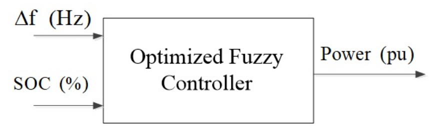

Fig. 3. Structure of the proposed method

Initial membership functions and rules of the controller are shown in Fig. 4 and Table 1 respectively. In Fig. 4, points A to F are optimized so that frequency deviation becomes minimum. Moreover, the rules of Table 1 (excluding Zero rules) are optimized. It is supposed that frequency deviation and SOC have symmetrical membership functions. In other words, VL, NM, and NS should be the same as PL, PM and PS respectively and the Zero membership function should be symmetrical with respect to zero value. This subject is also true for SOC and output membership functions. According to the above descriptions, the following relations should be established in Fig. 4.

$$A' = -A \quad (7)$$
$$B' = -B \quad (8)$$
$$C' = 100 - C \quad (9)$$
$$D' = -D \quad (10)$$
$$E' = -E \quad (11)$$
$$F' = -F \quad (12)$$

The rules of Table 1 are optimized so that the negative rules should be the same as the positive rules according to size. For example, when the frequency deviation is VL and SOC of EV is M then the output is obtained as PM, while when the frequency deviation is VH and SOC is M, the output should be NM. In Table 1, the intended rules for optimization are identified by a number. By specifying positive outputs, negative outputs can be identified. It is supposed that 50% SOC is enough for EVs so membership functions of SOC are symmetrical than 50% and the rules of the fuzzy controller are symmetrical with SOC equal to 50% and frequency deviation equal to zero.

Eq. 13 demonstrates the fitness function of the proposed optimization.

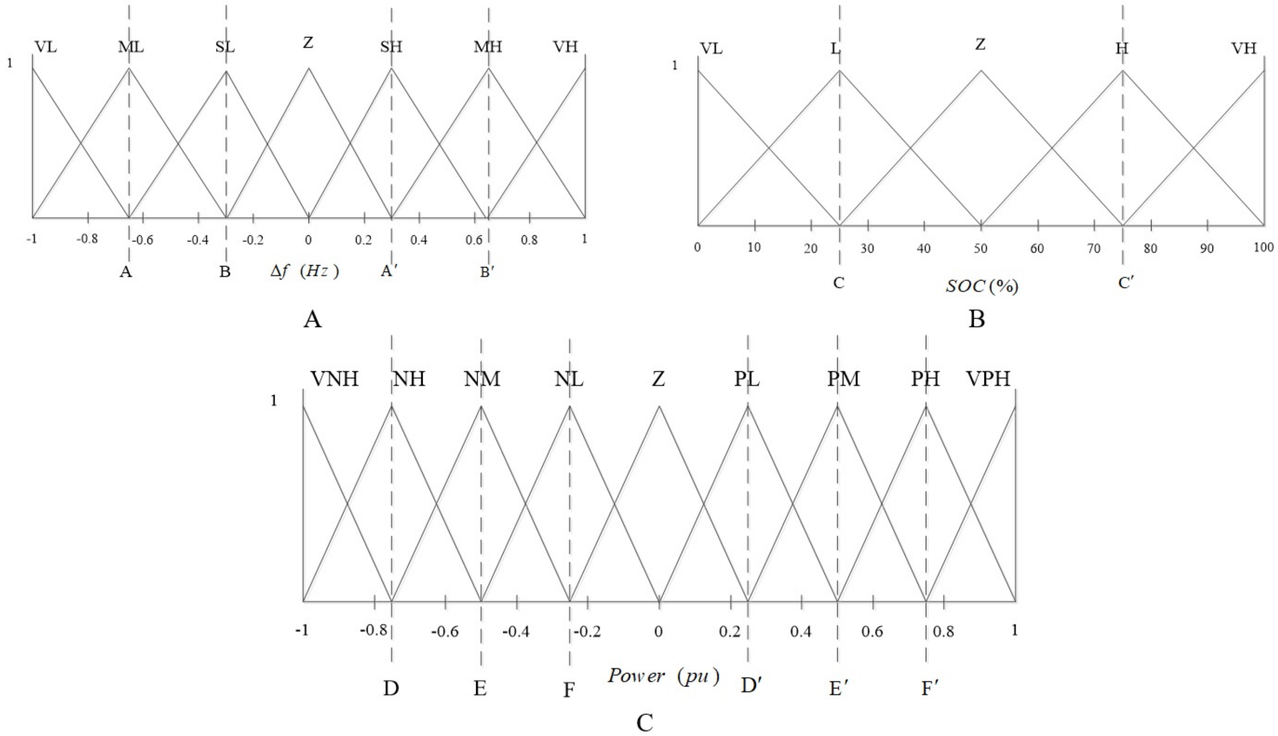

Fig. 4. Initial membership functions of the proposed controller: (A) Frequency deviation, (B) SOC, and (C) Power.

Table 1. Initial rules of the proposed controller

SOC	Δf						
	VL	**ML**	**SL**	**Z**	**SH**	**MH**	**VH**
VL	Z	Z	Z	Z	NM	NH	VNH
L	Z	Z	Z	Z	NL	NM	NH
M	PM (1)	PL (2)	Z	Z	Z	NL	NM
H	PH (3)	PM (4)	PL (5)	Z	Z	Z	Z
VH	VPH (6)	PH (7)	PM (8)	Z	Z	Z	Z

$$F = \int_0^t |\Delta f| t dt \qquad (13)$$

An imperialist competitive algorithm (ICA) is employed for optimization. The explanation details of the ICA are given in [16] and not repeated here to abbreviate. Table 2 shows the optimum rules. Values of A to F are obtained as follows by the ICA:

$$A = -0.5,$$
$$B = -0.1,$$
$$C = 40,$$
$$D = -0.89,$$
$$E = -0.4,$$
$$F = -0.3$$

4 Main results

4.1 Frequency deviation in the presence of renewable energies

In this case study, the frequency deviation of microgrid is evaluated in the presence of changes in wind and solar power plants. We assume that there are no load changes in this study. The frequency deviation of the microgrid is displayed in Fig. 5 by employing the proposed method and the fuzzy controller with initial rules and membership functions. The results illustrate that the frequency deviation is decreased by the proposed controller. The maximum frequency deviation is -0.3375 Hz with the initial fuzzy controller while it is -0.110 8Hz by the proposed controller which shows the frequency deviation of the microgrid is decreased by 67% by the proposed controller.

Table 2. Optimized rules of the proposed controller

SOC	Δf						
	VL	**ML**	**SL**	**Z**	**SH**	**MH**	**VH**
VL	Z	Z	Z	Z	NM	NH	VNH
L	Z	Z	Z	Z	NL	NH	Z
M	Z	VPH	Z	Z	Z	VNH	Z
H	Z	PH	PL	Z	Z	Z	Z
VH	VPH	PH	PM	Z	Z	Z	Z

4.2 Loss of the PV system

In this case study, we assume that the PV system loses 0.1 pu of its power at an instant of 10 s. Changes in the frequency deviation of the microgrid are shown in Fig. 6. It illustrates that with the initial fuzzy controller, frequency deviation has high fluctuations but by using the proposed method, fluctuations of frequency deviation are decreased significantly. More-

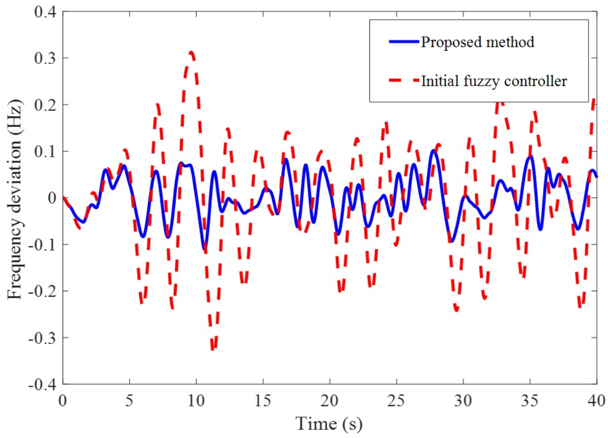

Fig. 5. Microgrid frequency deviation in the presence of renewable energies.

over, the proposed controller could reduce the maximum frequency deviation by 42%.

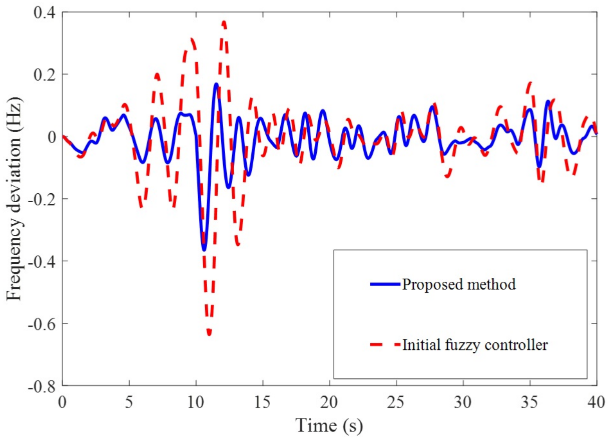

Fig. 6. Microgrid frequency deviation by decreasing the PV system power.

4.3 SOC evaluation

The performance of the proposed controller in control of SOC of EV batteries is carried out in this case study. For this reason, it is supposed that there are three groups of EVs with different initial battery SOCs 47%, 50% and 53% in the microgrid. Load changes with zero mean are considered for this case study. Fig. 7 shows changes in SOCs of EVs for 3600 s. The results state that by the proposed controller, the SOC of EVs with 53% initial SOC is decreased toward 50% and the SOC of EVs with 47% initial SOC is increased toward 50%. Moreover, the SOC of EVs with 50% initial SOC does not change.

5 Conclusion

In this research, we introduce a new method for frequency regulation in a microgrid. The proposed method employs a fuzzy controller with optimized rules and a membership function. The frequency deviation of the microgrid and SOC of the EV battery are considered as the inputs of the controller. We verify the performance of the proposed controller in reducing microgrid frequency deviation in the presence of renewable energies and load changes. The simulation results show that the proposed method could better decrease the frequency deviation of a microgrid than the initial fuzzy controller. Moreover, the ability of the proposed method to control the SOC of the EV batteries is evaluated and the results illustrate the appropriate performance of this controller.

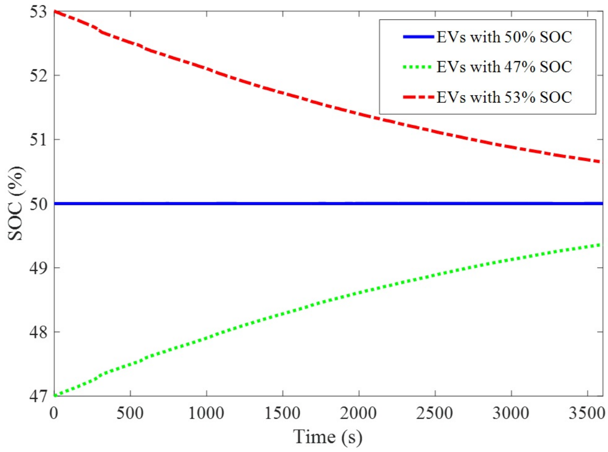

Fig. 7. Changes in EV SOCs.

Conflict of interest

The authors declare that they have no conflict of interest.

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