Coordinating the Participation of Energy Sources and Wind Units in Micro-grid Frequency Control by Delaying Micro-grid Parameter Measurement Systems

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Abstract- In this paper, an intelligent method based on an intelligent algorithm based on teaching and learning is used to find the most optimal parameters of the controller, and the results obtained are compared with the controller whose parameters are obtained by the usual method. The proposed simulation including all resources, energy storage, and control system is simulated by MATLAB/SIMULINK, and the intelligent algorithm based on teaching and learning is also coded by MATLAB so that the optimal values of the controller parameters can be obtained. The frequency behavior of the microgrid has been investigated in the presence of wind and energy storage and by applying various control parameters such as telecommunication delay in sending and receiving power and frequency information according to the objective functions. The results show that in microgrids connected to the grid, any sudden change in the consumed load or production power can be compensated by the grid's production units or energy storage. But in case the microgrid is not connected to the grid, it is the wind unit that participates in the frequency control, and the grid frequency control is done favorably according to the types of renewable energy sources and loads so that the total production of the renewable unit can be easily changed.

Keywords: Intelligent controller; Optimization; Micro-grid; Frequency control; Contribution; Wind unit; TLBO

1. Introduction

Microgrids can be considered as a set of consumers with different loads, distributed energy sources, control devices, and a local control system, which are dynamic in both grid-connected and island states [1-3]. The design of the control system of micro-grids is such that they control and support the activities of the system in both distribution network-connected and island states with great safety and security. This control system is formed based on a central control system or in each island forming the microgrid in distributed conditions [4]. When an island is disconnected from the main power grid, the control system is responsible for controlling the local voltage level and generation frequency, calculating the difference between the generation and consumption of active and reactive power in the island, and taking the necessary measures for the stability of the network. It should also protect the microgrid against errors, incidents, shutdowns, and accidents and keep consumers in the best condition [5]. On the other hand, there are big challenges for the control systems with the introduction of renewable energy technologies to power grids. In a microgrid based on new energies, resources are connected to the grid using power electronics. So, due to the prevailing transistor regime, the low moment of inertia of the resources prepares much less opportunity to deal with disturbances. In recent papers, it has been shown that increasing the use of wind energy causes challenges for the system. One of these challenges is the issue of frequency control, which is discussed in [6] about DFIG and the study of the effect of the wind power plant connected to the system and its effect on the frequency response of the power grid. In the isolated micro-grids, the imbalance of the generated and consumed electrical power causes frequency deviation [7] and it is possible to cause a lot of damage to frequency-sensitive loads. Frequency is one of the stability indicators of power networks. It is necessary to control the frequency of the electrical load in the microgrid [8]. The most important energy sources in the microgrid are renewable energy sources, which have random properties [9]. These fluctuations cause a loss of stability. In the last decade, studies have been carried out on the participation of wind power plants in the inertial response of the system as well as the primary frequency control [10]. In [11], have presented an optimal design of automatic generation control regulators for an interconnected power system including DFIG based on a wind turbine. The eigenvalues of the closed loop are obtained to check the stability of the system. The simulation results prove the effective presence of wind turbines in frequency regulation. In [12], the effects of the energy storage system in the battery on the load frequency have been investigated, and by considering the ability of the energy storage systems in the battery to provide high-speed active power, it is possible to use them to control the load frequency. This paper has used the BESS system for studies on frequency control. The results show that the use of the area control error signal (ACE) as the input of the BESS system will significantly reduce the deviations in the frequency and power of the communication line between the two areas derived from disturbances in the electrical load. In [13], an online intelligent technique is presented in addition to using the combination of fuzzy logic technologies and PSO to optimize the setting of the most common frequency controllers based on PI parameters in micro-grid systems. In the proposed control strategy, the adjustment of PI parameters occurs automatically using fuzzy rules according to online measurements. To achieve optimal performance and also to determine the parameters of the membership function, we can use the PSO method online. The proposed optimal adjustment scheme has different advantages for controlling the frequency of a microgrid with several DGs and RES. This is true when the old control methods do not provide the possibility to provide the desired performance in a wide range of operating conditions. This is true when the old control methods do not provide the desired performance in a wide range of operating conditions. In a micro-grid, the intelligent PSO-Fuzzy PI control scheme will have a significant effect on AC secondary frequency control. In [14], a method for providing coordinated control of wind turbine blades and electric hybrid vehicles, based on predictive control, is presented to reduce power and frequency fluctuations in the MG. In [15], the design of the hierarchical structure of frequency control has been proposed based on different categories of network load changes, as well as the control characteristics of the BS system and diesel generator (DG). The primary frequency adjustment of the battery converter is based on the Droop control strategy, which is to improve the transient frequency response. An integral adjustment solution for diesel generator frequency error is chosen to adjust the secondary frequency and restore a new stable frequency mode. In [16], the internal model control solution, with two degrees of freedom 0 (TDF IMC), has been proposed to control the electric load, and the frequency of a multi-zone system with wind turbines. TDF IMC only needs to set two parameters. And it destroys disturbances well. Practically, IMC controllers are similar to PID controllers, a frequency response dynamic model containing a simple wind turbine is used for the design. In [17], the design of LFC for frequency minimization of the interconnected power system with multiple sources in the presence of variable-speed wind turbines has been discussed. To calculate the performance index of the system, the integral of multiplying the time by the absolute magnitude of errors 0 (ITAE) has been used. Jeeves-Hookes algorithm has been used to determine the optimal gain value of the PI system controller. In [18], a hybrid deep learning algorithm is presented to classify network islanding and disturbances. In [19], the authors developed the approach of controlling Tie-Line switches with a central controller to communicate and transmit electric power between the microgrid and the electric power distribution center from an active distribution network. In [20], in the space of a smart grid, it is able with more information, such as some loads of subscribers with the ability to store electrical energy, such as EWH, are considered suitable for participating in the balance between production and demand. In the state of connection to the network, the frequency and voltage of the sub-network are the same as the main network, and the frequency and voltage can be adjusted in the same way as mentioned earlier. It conveys the meaning that by conventional ancillary services, however, the frequency and voltage regulation of MGs should be investigated in an isolated and separate manner, especially in the absence of ancillary services that are customary (such as rotating and non-rotating reserves). When distributed sources of renewable energy are also present in the MG, frequency and voltage regulation and other power quality issues are more and more considered. In [21], points to the importance that in the last ten years, while paying attention to the increasing necessity of the global energy pressure and the many losses with the scale of very bulky devices of the power system, the distribution production technology that is used by the solar energy production system and the energy production system is provided, it is not clear. In this way, many issues such as the high cost of a single machine that is connected to the power grid, problems in control, and high impact on the power grid are being developed. Expanding MG technology is one of the most effective ways to solve this problem. In [22], the effect of increasing the amount of distributed generation (DG) on the control and operation management of transmission and distribution systems is discussed. This study affects the DG penetration on frequency control in normal and emergency operating conditions. In addition, the acceptance of different types of DG control in connection with frequency control has been investigated and studied, and the case study is based on the analysis of frequency control features for the interconnected power system of the Baltic region. Here, the foundation of a method to analyse the different characteristics of DG penetration, in terms of determining the hosting capacity and the maximum possible level of DG penetration, which provides optimal frequency control, is formed. In [23], the effectiveness of increasing the penetration of DERs on the issue of system load frequency has been investigated. Now, distributed energy resources (DERs) have become more attractive due to feeding local loads such as MG. Indeed, the new parts of the power system have different dynamics compared to conventional power plants (CPPs). Most of them do not include rotational inertia at all and most of them are connected to the grid using power electronic equipment. In [24], the controlling parameters of a Bees Algorithm micro-grid have been searched. The appropriate summary of the references raised in recent years in the field of micro-grids is mostly around the following topics: Its equipment, such as energy storage, converters, controllers, etc.; Economic analysis and electricity markets; Control and operation of micro-grid systems that are connected to the network; Planning and design of micro-grids; Reliability and resiliency; Responding to demand; With the increasing expansion of renewable energy sources, the problem of reducing the inertia of the power network against disturbances caused by load is raised, so that by changing the structure of wind turbines and controlling their performance, this possibility has been created so that in the event of a disturbance, wind units can participate in controlling the frequency of the network. The participation of the wind unit is generally based on the presence at the point of maximum power transfer to the grid so that the full capacity of the wind unit is used. By changing the working area of the wind turbine and using the energy stored in the rotating objects, it is possible to take advantage of the more effective participation of the wind unit in the frequency control of the network. Therefore, the main objectives of this research are as follows: Participation of wind units in micro-grid load frequency control - investigation of measurement system delays in frequency control. The comparison of the latest investigations with the proposed method is shown in Table 1.

Table 1. Taxonomy of recent research works

Ref.	Years	Solving algorithm	Sources			Methodology	Achievements
			FC	Battery	RE		
[11]	2022	Robust planning	✓	✱	✓	systematic review methodology	Energy Management- ESS-Reliability and flexibility
[14]	2022	Mathematical planning	✱	✓	✓	N/A	Frequency stability
[15]	2021	SA	✓	✓	✱	systematic review methodology	evolution of DC MG, various aspects of DC MG planning, operation, energy storage systems,
[18]	2022	PSO	✓	✱	✓	systematic review methodology	Increasing the flexibility of the MG with the presence of renewable resources
[20]	2023	MPC	✓	✓	✱	systematic review methodology	Common frequency control
[23]	2022	GWO	✱	✓	✓	systematic review methodology	MG control strategies, the infrastructure's major issues, and MG optimization methods
[26]	2022	NSGA-II MOPSO	✱	✓	✱	systematic review methodology	High damping of frequency fluctuations - increasing minimum costs
This Paper	2023	TLBO	✓	✓	✓	citation network analysis (CNA) methodology	Increasing the flexibility of the MG with the presence of renewable resources

2. Research Method

2.1 Statement of the Problem

Today, modern societies are moving towards the exploitation of Renewable Energy Sources (RESs). Wind energy does not cause pollution and is one of the most widely used renewable energies, and the cost of this energy is much lower than the cost of electricity produced by coal and nuclear fission. The possibility of extracting the maximum power from wind energy at different wind speeds and reducing the pressure on the turbine shaft is one of the reasons why wind turbines with high-generation power are designed and operated more than variable speed types. On the other hand, a doubly-fed induction generator (DFIG) is considered the most common structure among variable-speed wind turbines. In recent papers, it has been shown that increasing the use of wind energy causes challenges for the system. One of these challenges is frequency control. In the last decade, there have been studies on the participation of wind power plants in system inertial response as well as primary frequency control. However major works have not been done in the field of participation of wind power plants in load-frequency control. In this research, we investigate the possibility of participation of these units in secondary frequency control on a system similar to the structure of the sample micro-grid system by adding a control loop to the control structure of wind units. Among the common solutions to control the frequency of micro-grids, we can mention the use of governor settings of diesel generators to compensate for the difference in generation between renewable sources and the consumption of electric load. For the synchronous machine to work properly with other sources, it is necessary to synchronize this equipment with the power grid, and therefore the working frequency is defined in a certain range, which must be located in that range. It is possible with the help of a frequency control strategy applied to power sources. This paper has helped to improve the damping of frequency fluctuations while adjusting the control signal and then the output of controllable power sources. Due to the inherent inertia of the power sources in response to the control signal, as well as constraints of the generation slope or the generation rate constraint (GRC), frequency fluctuations can be predicted in the microgrid. The solution is to improve the damping of frequency fluctuations with appropriate values of control parameters that have a special role in the performance of controlled units. Because the electric power receiving and generating units are connected to the power grid in parallel, it is necessary to obtain the power versus frequency loss (p-f) characteristic with algorithms or justified trial and error solutions for the equipment so that a stable feedback loop is available. Also, to share the consumed electric power among the producers or its absorbers in a static state, it is necessary to determine the inverse relationship of R according to the nominal value of that electric power source. In addition, each electric power source includes a control parameter to adjust the output electric power according to frequency fluctuations called frequency Bias (B). To adjust the frequency of the current power systems, in addition to controlling the first side, we need to control the second side using the information obtained from the reported telecommunication platforms. In microgrids, the information obtained at the SCADA level is not of significant use due to slow sampling (we need sampling with slopes of a few hundredths to a few milliseconds for frequency control). The technology of phasor measurement units (PMU) is expressed and used to solve the mentioned problem. If the PMU is placed in a suitable place in the micro-grid, it will be possible to establish a telecommunication or Internet platform with different inputs (different people) for data exchange with the control center [25]. With the increasing expansion of renewable energy sources, the problem of reducing the inertia of the power network against disturbances caused by the load is raised, so by changing the structure of wind turbines and controlling their performance, this possibility has been created so that in the event of a disturbance, wind units can participate Find the network frequency control. The participation of the wind unit is generally based on the presence at the point of maximum power transfer to the grid so that the full capacity of the wind unit is used. By changing the working area of the wind turbine and using the energy stored in the rotating objects, it is possible to take advantage of the more effective participation of the wind unit in the frequency control of the network. Therefore, the main objectives of this research are as follows: - 56 participation of wind units in MG load frequency control - Checking the delays of the measurement system in frequency control.

In this paper, the following significant measures are intended: While being inspired by real research of micro-grid and practical constraints in the generation or absorption of electric power, planning of electric power generation in transient or permanent mode has been developed based on the central controller of micro-grid. This strategy has three main parts (i.e. controllable sources, renewable units, and energy storage devices) and performance constraints related to each of the equipment and electric power sources. In this paper, an intelligent solution based on the intelligent teaching and learning algorithm is used to find the most optimal controller parameters, and the results obtained are compared with a controller whose parameters are obtained in the usual way. The proposed simulation consists of all resources, energy storage, and control systems that will be simulated by MATLAB/SIMULINK software, also the teaching and learning algorithm is coded by MATLAB software to obtain the optimized values of the controller parameters. The most important innovation of this article is the participation of wind units along with other sources in frequency control and optimization of controller parameters based on the TLBO method.

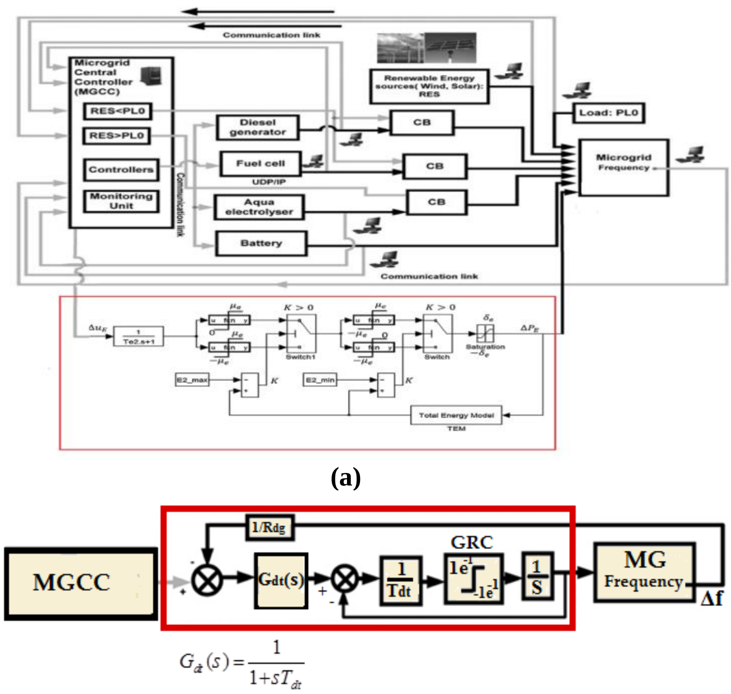
3. Modeling of Microgrids

In the modern world, special attention has been paid to the reduction of polluting gases emitted by fossil power plants. Because it is still not possible to completely prevent the operation of conventional machines and fossil fuel power plants in the current conditions or the near future. Today, modern societies are moving towards the exploitation of renewable energy sources (RESs). These renewable sources have a small generated power and therefore, due to the low output voltage level, they are connected to the distribution networks in general through the inverter. Renewable sources are often distributed sources connected to the energy distribution network, which reduce transmission and distribution losses due to their proximity to load centers. Power distribution networks that include electric power sources with low nominal power values are called emerging MGs or active power distribution networks [26]. MGs, which are part of the electricity distribution network, generally operate in grid-connected mode. However, random events such as errors on the side of the national electricity grid, electric voltage fluctuations with unacceptable amplitude and duration, and changes in the frequency of the electricity distribution network cause the forced disconnection of the MG from the distribution network. In micro-grids connected to the power grid, any unexpected change in the consumed electric load or the generated electric power can be compensated by the generation units or the energy storage of the power grid. While working independently from the grid, different sources are used, these sources can adjust the power exchange with the grid and can respond to the disruptions of renewable sources, in this way, the frequency and power balance are controlled. For example, one of the common solutions to control the frequency of MGs is to use diesel generator governor settings to compensate for the difference between the generation of renewable resources and the consumed electric load. For the synchronous machine to function properly with other sources, it is necessary to synchronize this equipment with the power grid, and therefore the working frequency is defined in a certain range, which should be located in that range. This problem is possible with the help of a frequency control strategy applied at the level of power sources. In this research, adjusting the control signal and then the output of controllable power sources, has helped to improve the damping of frequency fluctuations. Due to the inherent inertia of power sources in response to the control signal, as well as the limitation of the generation slope or the generation rate constraint (GRC), frequency fluctuations are not far from expected in the MG. The solution is to improve the damping of frequency fluctuations with appropriate values of control parameters that have a special role in the performance of controlled units [27]. Because from the control point of view, the electric power receiving and generating units are connected to the power grid in parallel, to obtain a stable feedback loop, the characteristic of the frequency drop against the power (p-f) must be determined with an algorithm or a justified trial and error method for the equipment. In addition, to share the consumed electric power among its producers or consumers in a static state, it is necessary to specify the inverse relationship of R concerning the nominal value of that electric power source. In addition, for the performance of power generation and absorption systems, each electric power source includes a control parameter to adjust the output electric power according to frequency fluctuations called frequency bias (B). In this paper, an autonomous micro-grid isolated from the national power grid, which contains Renewable Energy Sources (RESs) of wind power and solar power, Diesel generator (DE), Fuel Cell (FC), Aqua Electrolyzer (AE), battery bank, and Electric Vehicle (EV) has been selected for study. Electric power generation by renewable energy sources is considered fixed and uncontrollable.

3.1. Micro-grid Central Controller

The control structure in micro-grids generally includes three hierarchical levels: Micro-grid Controllers (MC) placed in specific locations and controllable electric Load Controllers (LC); Micro-Grid Central Controller (MGCC); Distribution Management System (DMS). In this paper, the focus is on the MGCC. This controller receives different information and sends appropriate signals. The task of the central controller of the microgrid system is to maximize the value of the microgrid and improve its performance against disturbances. This controller takes advantage of the price signal of the electricity and gas market and the security challenges of the MG to determine the amount of electric power exchanged between the MG and the national electricity grid, and thus optimize the electric power generation capabilities of the scattered units in the micro-grid. Here, since the microgrid is separate from the national electricity grid, the electric power range of each unit is optimized so that the big challenge of the microgrid, i.e. frequency, is in good condition. To express the concept of frequency control method and to effectively use the available resources, the concept of multi-agent systems is proposed. In this plan, each electric load and each electric power generation unit is introduced in the form of an agent, which is addressed through a special IP. The micro-grid central controller acts as the main server, which receives the status of the agents and generates and sends appropriate control signals considering the IP number of the agents. The control variable (frequency), the real electric power generated by various sources, and the consumed power are often received through different transducers. While ignoring the control unit, MGCC maintains the states of resources and loads and also acts as a monitoring system [28]. Figure 1 shows the abbreviated block diagram of the smart microgrid, neglecting the real power losses, from the point of view of the real power change and as a result, the frequency change. In the following, 3 rules are considered for the proposed control method, including:

First rule: if the amount of electric power generated by renewable or under control units is more than the amount of desired load power in permanent mode, the aqua electrolyzer comes into operation in the condition that the electric vehicle, fuel cell, and diesel generator do not have any contribution in power generation. Of course, the battery will come to the aid of the grid and absorb additional electrical power at a high speed if needed in the transient mode.



(a)

$$G_{dt}(s)=\frac{1}{1+sT_{dt}}$$

(b)

Fig. 1. (a) Block model of microgrid with telecommunication platform; (b) Dynamic model of diesel generator unit [6].

Second rule: If the share of power generation by renewable or under control units is less than the power consumption of the load in a permanent state, there is no need to use an aqua electrolyzer. Fuel cells, electric vehicles, and diesel generators also inject electric power with the help of the control units in the central controller section according to the certain share.

Third rule: the battery improves the frequency behavior by injecting or rapidly absorbing electric power in different modes of the network, but it injects or absorbs the absorbed or injected electric power at a low speed after the disturbance occurs, to keep the battery charge level constant and the average transmitted electric power becomes zero over time [29]. MGCC calculation steps include prediction of power difference and distribution as follows.

Step 1: In the first step, after an error occurs, MGCC collects and monitors the information from all MGLCs.

Step 2: then the power difference created by the SMES storage is compensated during the initial frequency control period.

Step 3: MGCC predicts the power difference by the equation and distributes this difference to the DG and the controlled loads in the secondary frequency control stage.

Step 4: The reference active power calculated by MGCC is distributed to DGs and controlled loads. Also, after the initial control, the output of the storage device should be set to zero to maintain its capacity, and it should be charged to its maximum capacity as soon as possible to provide the necessary storage for future conditions.

In the first step, the power difference and frequency error are performed using the ROCOF method for quick estimation. If the rate of changes of frequency and the equivalent constant of inertia H are available, the power difference is obtained. Based on the method presented in [8], the equivalent constant of inertia of the islanding MG can be determined.

3.2. Modeling of a Controllable Power Source Based on a Rotating Machine (diesel generator)

The governor and droop systems used in diesel generators are the equipment used to control the frequency. The diesel fuel valve is controlled by the governor to control the input fuel. The diesel used can be gasoline or diesel so this system works in the form of a turbine and then moves a synchronous generator to generate alternating current. The generator of this system is modeled in the form of a first-order model, presented in Equation (1) [30].

$$G_{dgs}(s)=\frac{1}{1+sT_{dgs}} \tag{1}$$

The turbine of this system is modeled as a first-order model, expressed in Equation (2).

$$G_{dt}(s)=\frac{1}{1+sT_{dt}} \tag{2}$$

Therefore, the dynamic model of the whole complex will be as follows.

$$G_{dgt}(s)=\frac{1}{1+sT_{dgs}}\times\frac{1}{1+sT_{dt}} \tag{3}$$

The control signal sent to this unit as a command is communicated by the central controller.

3.3. Controllable Source Modeling for Voltage Source Converter

When the output electrical voltage is a DC source, it generally uses a converter to connect to the grid. Converters are generally of the voltage source inverter type. With this equipment, we can control the active and reactive power while adjusting the angle and range of the generated electric voltage relative to the power grid. Active power injection occurs from the power source, but reactive power does not need a power source. By implementing a simple control loop, we can adjust the real power. Therefore, this system will inherently include delay and the conversion function can be expressed by Equation (4) [31].

$$G(s)=\frac{1}{1+sT} \tag{4}$$

3.4. Modeling of the Aqua Electrolyzer

The aqua electrolyzer is used to store the excess energy of the power grid. The existence of this additional energy is probably due to the low load or over-production of renewable resources. By absorbing energy, the aqua electrolyzer separates water into hydrogen and oxygen, which is expressed by Equations (5) and (6). The complete chemical reaction that occurs in electrolysis is expressed by relations (5) to (7) [32].

$$H_2O+2e^- \rightarrow H_2\uparrow +2OH^- \tag{5}$$

$$2OH^- \rightarrow \frac{1}{2}O_2\uparrow +H_2O+2e^- \tag{6}$$

$$H_2O \rightarrow H_2\uparrow +\frac{1}{2}O_2\uparrow \tag{7}$$

The noteworthy point is that the produced hydrogen can be used to provide a part of the fuel cell fuel to supply the power shortage of the power grid. According to Faraday's law, the rate of hydrogen produced by water electrolysis is expressed in the form of the following Equation: [33].

$$\frac{dH_2}{dt}=\eta_e\frac{I}{2F}(moles/s) \tag{8}$$

Where,

η_e, the number of electrons participating in the reaction is equal to 2. Also, F is Faraday's constant. The transfer function of Equation (8) will be as follows:

$$sH_2(s)=\frac{2}{2F}\times I(s) \tag{9}$$

It is assumed that the direct voltage applied to the aqua electrolyzer is constant during the simulation and does not fluctuate, therefore we have:

$$H_2(s)=\frac{1}{VF}\times\frac{1}{S}P(s) \tag{10}$$

To calculate the total volume of hydrogen produced by the aqua electrolyzer, the following equation can be considered:

$$H_2(s) = \frac{1}{VF}\int P_{ae}(t)\,\mathrm{dt} \tag{11}$$

In addition to these issues, the aqua electrolyzer acts as a voltage source converter and needs a converter to connect to the power grid. As a result, this system also includes chemical and electrical delays and the transfer function of an aqua electrolyzer will be like Equation (4).

$$\mathrm{G}_{ae}(s) = \frac{1}{1+sT_{ae}} \tag{12}$$

3.5. Fuel cell Modeling

A fuel cell is one of the equipment for generating electric power with renewable and environmentally friendly fuels, which is based on chemical reactions. The performance of fuel cells is a combination of physical and chemical reactions. In this technology, the power goes through a process called polarization in the form of a reversible potential to combine hydrogen and oxygen. The chemical processes in this equipment can be briefly written as follows: [34].

$$\begin{aligned} &\text{Anode side:}H_2 \rightarrow 2H^+ + 2e^- \\ &\text{Cathode side:}2H^+ + 2e^- + \frac{1}{2}O_2 \rightarrow H_2O \end{aligned} \tag{13}$$

$$\text{Overal reaction:}H_2 + \frac{1}{2}O_2 \rightarrow H_2O\text{+Heat} \tag{14}$$

Considering that the function of this system when connected to the power grid is similar to a voltage source converter, the conversion function of this power source should be determined similarly to Equation (4) while selecting the appropriate time delay [35].

$$\mathrm{G}_{fc}(s) = \frac{1}{1+sT_{fc}} \tag{15}$$

To calculate the total hydrogen produced, taking into account the exchange power, the amount of hydrogen consumed by the fuel cell is calculated.

$$H_{2fc}(s) = \frac{1}{VF}\int P_{fc}(t)\,\mathrm{dt} \tag{16}$$

3.6. Battery Modeling

The battery is a voltage-based source that is used to balance power and then reduce frequency fluctuations. The battery is connected to the power grid through a two-way structure. The battery enters the circuit with high-power operation in transition mode. For the battery to always remain at the appropriate charge level, it is necessary to reduce the average power exchange of the battery with the network to zero. For example, if power is injected into the grid in a short period, this delivered energy must be slowly taken from the grid in a permanent state. Considering these requirements, two control loops are proposed. Like other equipment, the battery along with the converter has a first-order conversion function and it is expressed in the form of Equation (17) [36].

$$\mathrm{G_b(s)} = \frac{1}{1 + \mathrm{sT}_B} \tag{17}$$

3.7. Modeling of Controllable Wind Source

The mechanical power that can be received by the wind is presented in the form of Equation (18) [37].

$$p_w = \frac{1}{2}\rho\pi R^2 \upsilon_\omega^3 \tag{18}$$

Where is air density, R is turbine radius, and V_w is wind speed. While paying attention to the specifications of the wind turbine, are presented in the following form:

$$P_m = \frac{1}{2}\rho\pi R^2 \upsilon_\omega^3 C_p(\lambda,\beta) \tag{19}$$

In the above Equation, the turbine power factor and a non-linear function of screw angle β are presented as follows:

$$C_P(\lambda,\beta) = 0.5176(\frac{116}{\lambda_i} - 0.4\beta - 5)\exp(\frac{-21}{\lambda_i}) + 0.0068\lambda \tag{20}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + (0.08\beta)} - \frac{0.035}{\beta^3 + 1} \tag{22}$$

Wind turbines are economically designed to work at their optimum power. As a result, they do not participate in frequency regulation. For this reason, sufficient storage capacity must be available in each system for each frequency deviation. Operation in de-load mode is a new method to ensure the power reserve margin by changing the operating point of the wind turbine from the optimal power level to the low power level. The mechanical output power obtained from the wind turbine is determined based on the aerodynamic behavior of the wind turbine by the following Equation:

$$P_m = \frac{1}{2}\rho A C_P(\lambda,\beta)v^3 \tag{23}$$

Where λ is the apex speed ratio determined by the following Equation.

$$\lambda = \frac{\omega_r R}{v} \tag{24}$$

It is clear from equation (24) that the output power of the wind turbine depends on the speed ratio λ and pitch angle B. In general, the de-loading method has two types of control systems: speed control and pitch angle control.

3.8. De-load by Speed Control

Speed control is proposed to change the speed factor λ by moving the operating point to the left or right of the maximum power point, as shown in the figure below.

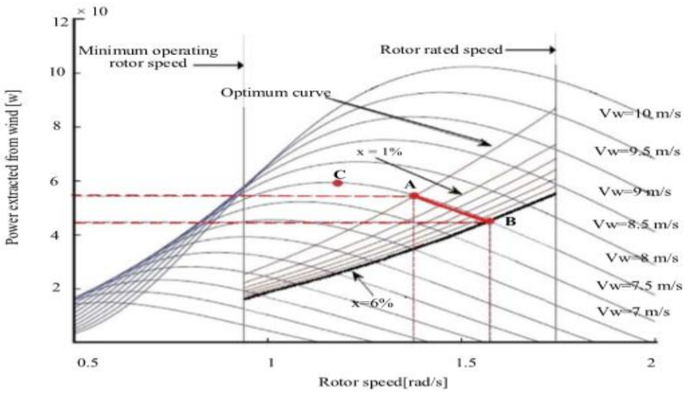


Fig. 2. Performance of the de-load function of a wind turbine [38].

This figure shows the performance of the de-load function of a DFIG with maximum power (x-1) at a specified wind speed (Vω). The wind turbine located at point A can be moved by high-speed or low-speed control. For low-speed control, the operating point of the wind turbine moves to point C, while for high-speed control, the operating point moves to point B.

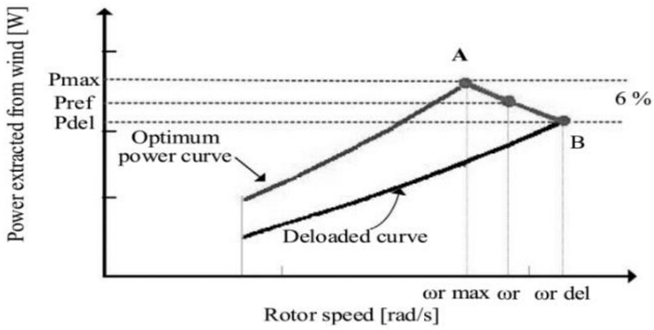


Fig. 3. The de-loading curve of a wind turbine [24,39]

According to the figure above, when the system's frequency decreases, the wind turbine releases a certain amount of its active power in proportion to the frequency deviation, so the operating point between A and B is placed with Pref, which Pref is determined by the following equation.

$$P_{ref} = P_{del} + (P_{\max} - P_{del}) \times \left[\frac{\omega_{r_{del}} - \omega_r}{\omega_{r_{del}} - \omega_{r_{\max}}} \right] \tag{25}$$

Where P_{max} is maximum power (per unit), P_{del} is de-load power (per unit), ω_{max} is rotor speed at maximum power, ω_{max} is rotor speed at de-loading power, and $\omega_{r\ del}$ is rotor speed at reference power. In general, high-speed control de-loading is used at moderate wind speeds [40].

3.9. De-load by Pitch Angle Control

The pitch angle is the second controller that is used to increase the blade angle of the wind turbine. When the wind turbine generator reaches the allowed speed and also the high-speed controller is not able to perform this operation, this controller is preferably activated. Figure 4 shows the power-speed curve of a wind turbine rotor at different pitch angles. This figure shows the de-loading method for the wind turbine at point A [40].

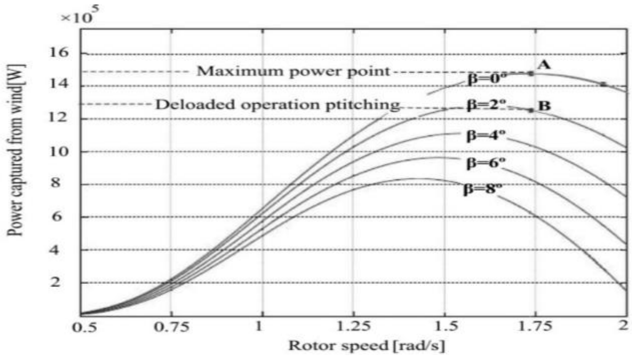


Fig. 4. Power-speed curve of 1.5 MW wind turbine rotor at different pitch angles [24].

3.10. Modeling of Uncontrollable Solar Source

Like the wind power generation system, maximum power tracking has been implemented for the solar system. Therefore, no control has been applied to the output power of the solar system, and this system does not play a role in frequency control.

3.11. Modeling of Electric Vehicle

The security of energy supply and distribution is expanding with the use of renewable resources with a promising approach. Since the main sources of these renewable energies are nature and climate, and these two cannot change over many years, we can rely on the use of these energies for many years. However, the challenge of these resources is the unstable and fluctuating nature of their output, which causes uncertainty in the power produced. For example, the power of solar units is completely dependent on the level of radiation and temperature. In cloudy weather, darkness, or temperature changes, the generated power decreases and even reaches zero. Therefore, power generation by renewable units is not continuous and we need energy storage to support renewable units. Types of energy storage systems have been introduced for use in distribution and smart networks. For example, the supply of thermal energy includes a significant part of electricity consumption in countries near the poles of the earth [25,26]. Especially in the morning and afternoon, the consumption of electrical energy is high during the cold days of winter. As a result, the network is overloaded and a lot of costs are imposed on the network. This has necessitated the shift of consumed power from on-peak hours to off-peak hours and, as a result, the use of energy storage. Due to the lack of technology expansion of energy storage systems and the high cost of using them on large power scales, these systems do not contribute much to the existing electricity systems. While having a battery, electric vehicles can store the necessary energy. Due to the positive approach of using these vehicles, by increasing their number, a set of them can act as large energy storage units in connection with their special parking lots [27].

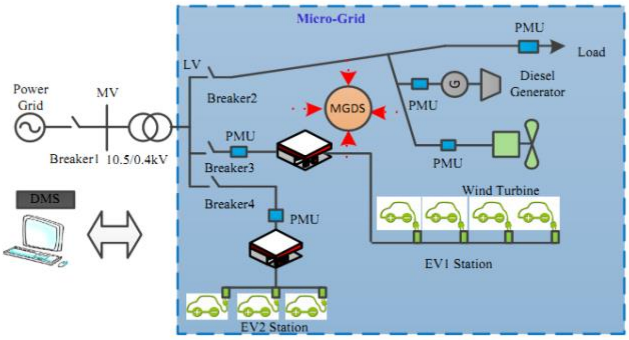


Fig. 5. Connecting electric vehicle stations with V2G capability to the power grid [28].

In different countries, consumers of electric vehicles use them with different behaviors. But what is known is that the use of these vehicles in the city with short distances causes most of the battery energy to remain unused, and therefore they can be a suitable alternative to absorb excess power during off-peak hours and transfer it to the electricity network during peak hours. This feature reduces the deviations of the consumed power of the entire network (Figure 6) and then reduces the active losses of the power network (Figure 7). [27,28].

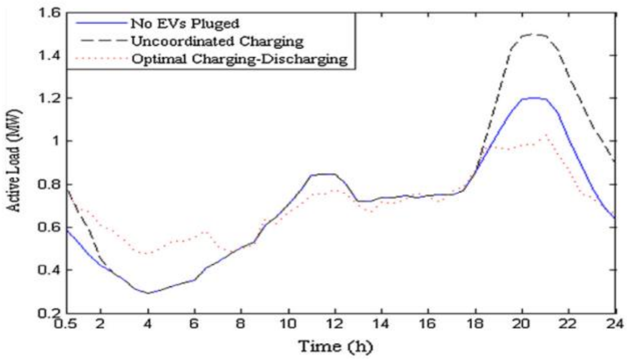


Fig. 6. Daily network load curve in the presence of EV [28].

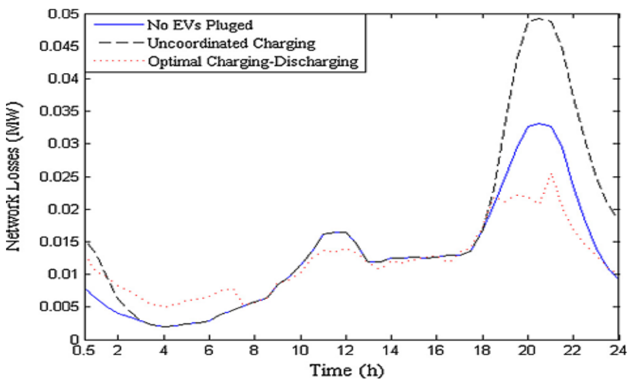


Fig. 7. Reduction of network active losses in the presence of EV [28].

To investigate the participation of electric vehicles in adjusting the micro-grid frequency, it is necessary to use a suitable dynamic model of electric vehicles. The equivalent circuit of an electric vehicle (EV) is shown in Figure (8), which is generally used in frequency behavior analysis. The behavior of the battery, converter, and control system is applied in this model.

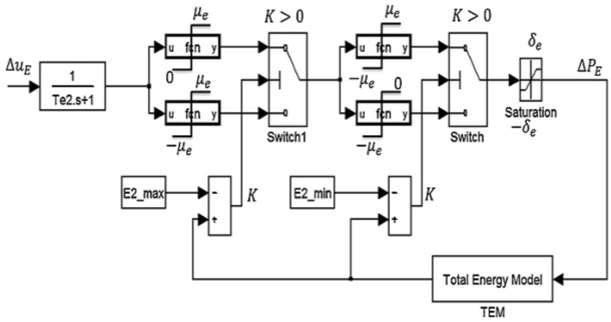


Fig. 8. Electric vehicle model in micro-grid for load frequency control [29].

In Figure (8), the time constant of the EV is denoted by Te. Δu_e is a control signal issued from the control center. In this model, are the nominal power of the converter and the rate of change of power per unit. E is the energy of the electric vehicle containing the battery, which are the minimum and maximum controllable energy, respectively. ΔP_E specifies charging and discharging power [29].

3.11.1. Detailed Schematic of the System in the Presence of an EV

In the electrical network containing the synchronous generator, if there is an imbalance between power generation and load consumption, the frequency deviation will be positive or negative depending on the amount of generation or consumption. We define the difference between power generation PG and power consumption PL as power deviation. While paying attention to the oscillation relationship of the synchronous machine, the mathematical model of the generator is derived as follows [30].

$$\Delta f = \frac{f_{sys}}{2H_s}[\Delta P_G - \Delta P_e] \tag{26}$$

In the above equation, we have:

$$P_G = P_W + P_s + P_{dg} + P_{fc} - P_{ae} \pm P_b \tag{27}$$

We can write that:

$$\Delta P_e = \Delta P_L + D\Delta f \tag{28}$$

In equation (28), we have the dependence of the first part on the load, while it does not depend on the frequency, but the second part is sensitive to the frequency of the load [31]. So, the conversion function of system frequency changes in the form of per unit will be in the form of equation (29).

$$G_{sys}(s) = \frac{\Delta f}{\Delta P_G - \Delta P_L} = \frac{1}{D + (2H/f_{sys})s} = \frac{K_{ps}}{1 + sT_{ps}} \quad (29)$$

If we pay attention to the given descriptions and explanations, micro-grid modeling with energy storage and generation equipment can be implemented as shown in Figure 9.

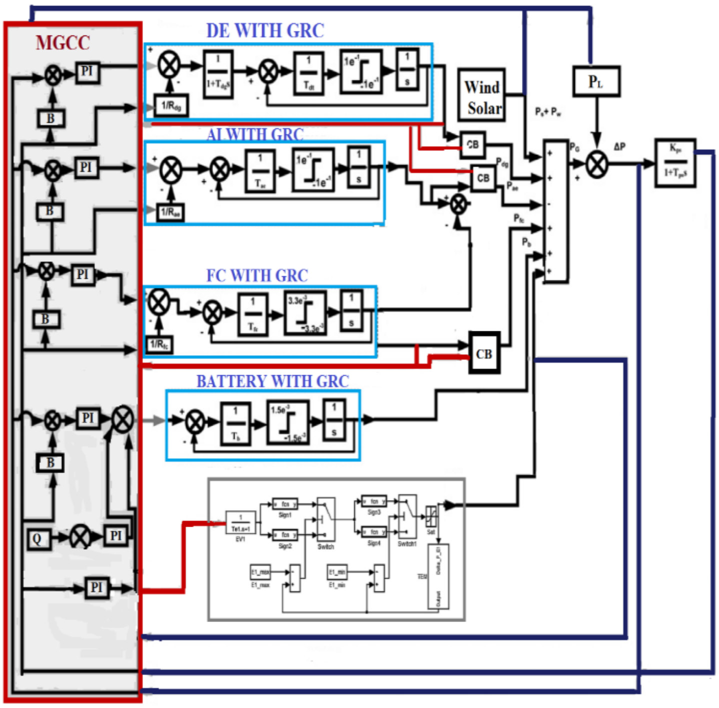


Fig. 9. Micro-grid modeling with energy storage and generation equipment

4. Optimization Algorithm Methods

To find the best possible state, the defined optimization problem should be solved using one of the existing methods. In this paper, the efficient TLBO algorithm is used to solve this problem [32]. Therefore, in the following, we will briefly introduce this innovative algorithm.

4.1. Teaching and Learning Based Optimization (TLBO)

An algorithm based on teaching-learning is an efficient optimization method that was first introduced by Mr. Rao and colleagues [33]. This solution, like other algorithmic optimization techniques, is derived from nature and works based on the influence of a teacher on class learning. This algorithm uses a population of answers to achieve the overall answer. It is based on the impact of a teacher on the output of students in a class and generally an individual teacher is determined in a class that includes a better value and has a higher level than the students and can share his knowledge with the students. A good teacher creates a better average for students. In each step and repetition, the teacher is the best member of the class and also has the best objective function. Although it is possible to change the teacher at each stage. This algorithm is a very desirable option in engineering matters. This algorithm is inspired by the teaching and learning process in the classroom. In this way, when the teacher presents the lesson, he finally evaluates it and the students also get marks. The TLBO algorithm is divided into three optimization phases: teacher phase - student phase - and jump phase. Figure (10) shows the flowchart of the TLBO algorithm. This shows the stated algorithm in a summary form [34].

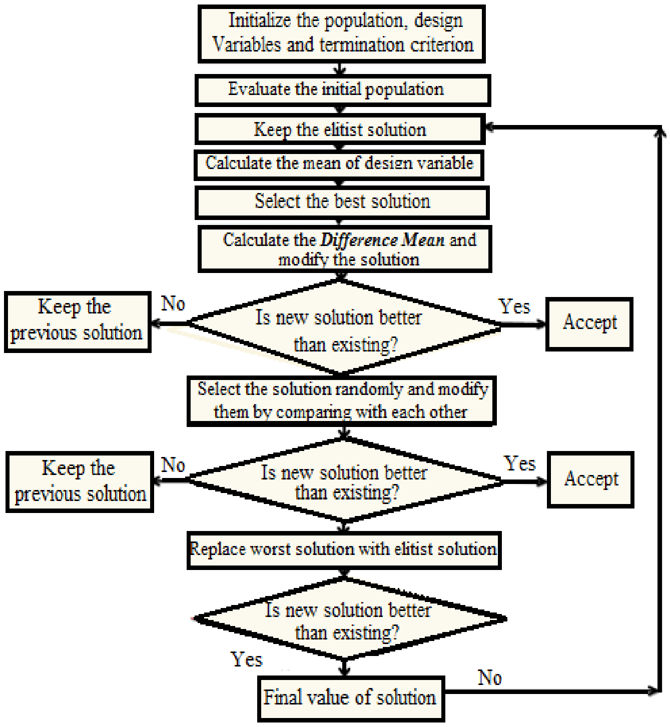


Fig.10. TLBO flowchart [35].

The study utilizes the TLBO algorithm as an efficient optimization method to solve the defined optimization problem in the context of micro-grid frequency control. By applying the TLBO algorithm, the control parameters of the microgrid can be optimized to achieve optimal power balance and frequency control. In the following, it is provided with an idea of how the TLBO algorithm is used in this research:
1. Problem Formulation: The optimization problem is formulated, taking into account the specific objectives and constraints of micro-grid frequency control. The objective function is defined to represent the desired behavior of the microgrid, such as minimizing frequency deviations or maximizing power balance. **2.** Parameter Selection: The control parameters that affect the operation of the microgrid units are identified. These parameters may include the power generation levels of renewable and controllable units, the contribution of different units like the electric vehicle, fuel cell, and diesel generator, and the charging/discharging rates of the battery bank. **3.** Initialization: The TLBO algorithm begins by initializing an initial population of potential solutions. Each solution represents a combination of control parameter settings for the microgrid units. **4.** Evaluation: Each solution in the population is evaluated by simulating the behavior of the microgrid using the defined objective function. The evaluation step quantifies the performance of

each solution in terms of the desired objectives, such as frequency control. **5.** Teaching and Learning Phases: The TLBO algorithm simulates the teaching and learning processes to improve the solutions in the population. In the teaching phase, the best solution (teacher) in the population shares its knowledge with the other solutions. This knowledge transfer helps guide the learning process in the population. In the learning phase, each solution adjusts its control parameter settings based on the information obtained from the teacher's solution. **6.** Update Population: After the teaching and learning phases, the population is updated by considering the adjusted solutions. This step ensures the exploration of the solution space and the potential discovery of better solutions. **7.** Termination Criteria: The algorithm checks if the termination criteria have been met. This can be a maximum number of iterations, a predefined convergence threshold, or specific conditions related to the objective function. **8.** Output: Once the termination criteria are satisfied, the TLBO algorithm outputs the best solution found during the optimization process. This solution represents the optimized control parameter settings for the microgrid units [36].

4.2. Objective Functions

To check the performance of the Teaching and Learning Optimization algorithm, three objective functions are considered in this article. These three objective functions are described below [37].

4.2.1. Integral of Absolute Error (IAE) Objective Function

The sum of the range of frequency changes in this objective function is desirable. In the state of balance between the load of electric power and the generation in an ideal form, the sum of the frequency fluctuations must be zero. With the help of this objective function, the sum of these frequency fluctuations during the simulation is tried to reach its minimum value, and we generally approach the minimum deviation from the zero value.

$$IAE = \int_{t=0}^{t=t_{sim}} |\Delta f * 60| \, dt \qquad (30)$$

4.2.2. Integral of Square Error (ISE) Objective Function

In the next step, attention is paid to the square amplitude of frequency fluctuations. In this objective function, we try to magnify the smallest frequency deviation and reduce the intensity of fluctuations, so the objective function is defined as follows [38].

$$ISE = \int_{t=0}^{t=t_{sim}} |\Delta f * 60|^2 \, dt \qquad (31)$$

4.2.3. Integral of Time Multiplied Absolute Error (ITAE) Objective Function

In the previous two objective functions, attention has been paid to the fluctuation range. In the category of frequency, time is also important. So, it is introduced by presenting the objective function in which both time and range of fluctuations can be taken into consideration [39].

$$ITAE = \int_{t=0}^{t=t_{sim}} |\Delta f * 60| * t \, dt \qquad (32)$$

5. Simulation Results

In this part, taking into account the control diagram and the method of connecting different resources to the network, which is explained in the previous section, the frequency behavior of the micro-grid in the presence of the indicated generation and storage resources is discussed by applying various types of control parameters according to the objective functions. The parameter values of the control systems as well as their constraints for simulating the system are specified in two Tables (2) and (3), respectively.

Table 2. Basic values of energy storage systems and power generation sources

Parameter	Value	Parameter	Value
H(sec)	5	**Tb(sec)**	0.1
Dv(p.u./Hz)	0.012	**Tfc(sec)**	4
Tdg(sec)	2	**Tae(sec)**	0.2
Tdt(20)	20	**K**	1
GRCdg	10%	**GRCae**	10%
GRCfc	10%	**GRCb**	30%

Table 3. Control parameters of energy storage controllers without optimization

Parameters	EV	FC	AE	Diesel generator
Kp	0.9	0.7	4	0.25
K_I	0.5	0.6	0.2	0.5
K_d	0.1	0.1	-	0.9
R	0.5	0.2	-	0.1
B	0.2	0.2	-	0.4

The system is simulated in the condition that the output power of the renewable units is constant and equal to 0.6 per unit. Here, it is assumed that the electric charge consumption increases from 0.6 to 0.66 per unit and reaches 0.52 per unit at the 600th second and again to 0.66 at the 800th time. In addition, we should note that with the TLBO algorithm, the control coefficients of the system are obtained by considering the proposed objective functions. First, the system is executed in a non-optimal position and the characteristics of the system and power units are studied. Then the frequency behavior of the system is studied in the presence of various objective functions.

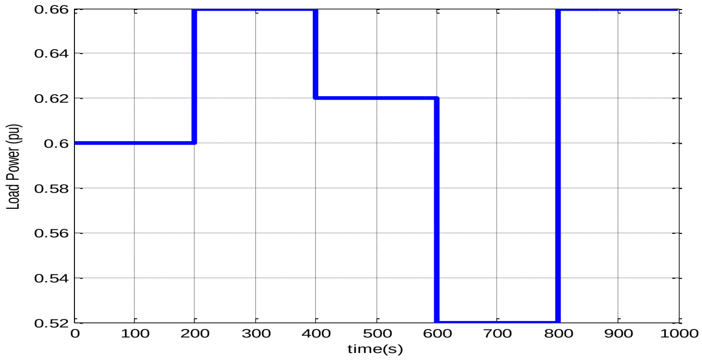


Fig. 11. Load step changes.

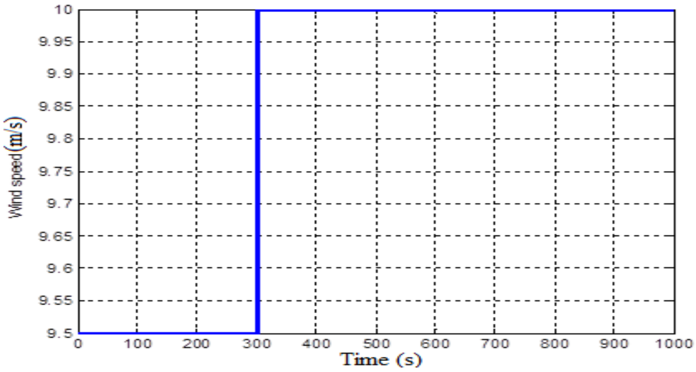


Fig. 12. Step changes in wind speed

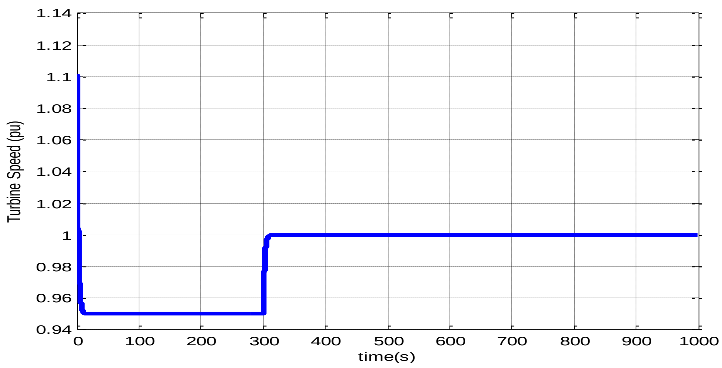


Fig. 13. Wind turbine speed changes without participation in frequency control.

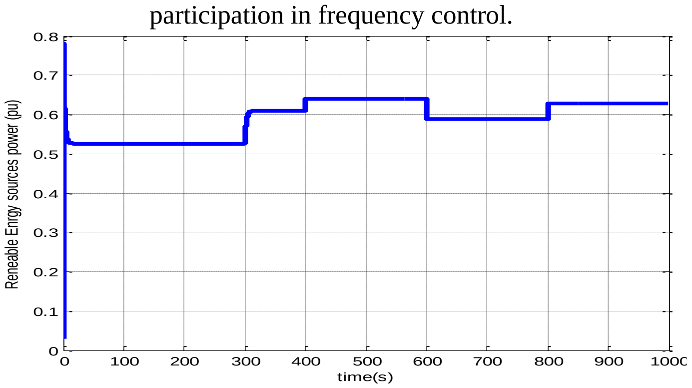


Fig.14. Power changes of the renewable unit without the participation of the turbine in the frequency control.

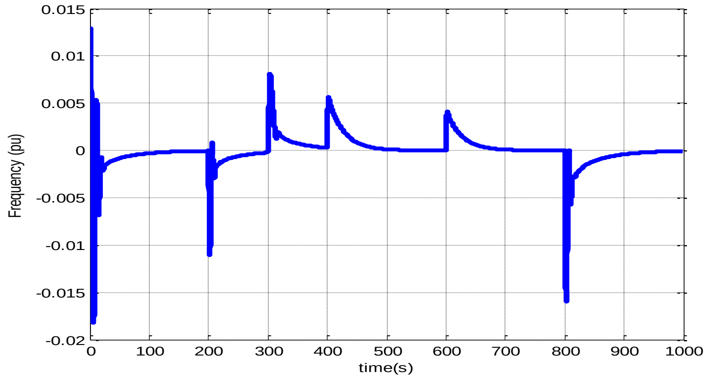


Fig.15. Variations of load frequency in Non-optimal state without turbine participation in frequency control.

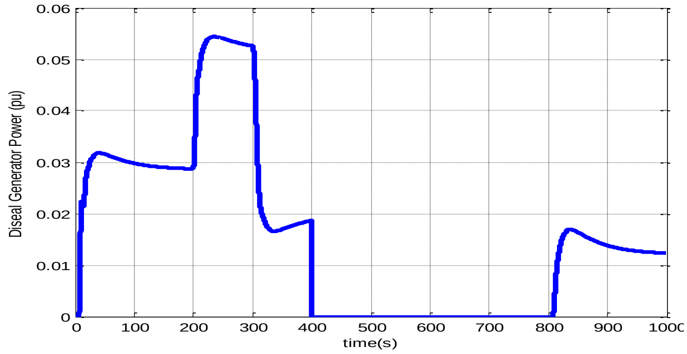


Fig. 16. Fluctuations of diesel generator in non-optimal mode and without turbine participation in frequency control

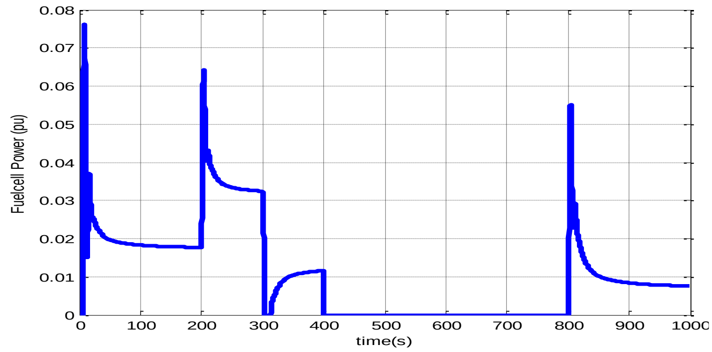


Fig.17. The amount of power generated by the fuel cell in a non-optimal state without the participation of the turbine in the control of frequency.

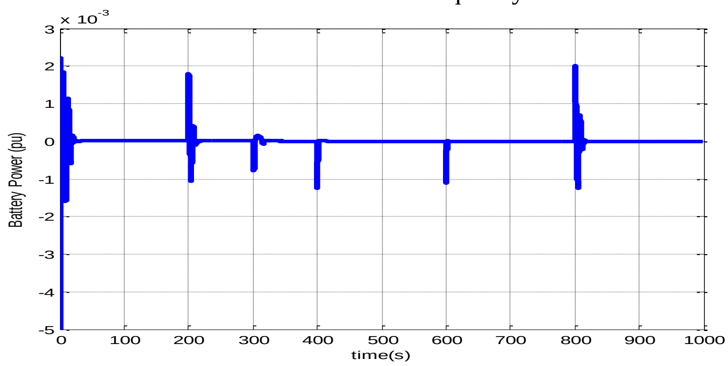


Fig.18. The amount of power generated by the battery in a non-optimal state and without the participation of the turbine in the freq

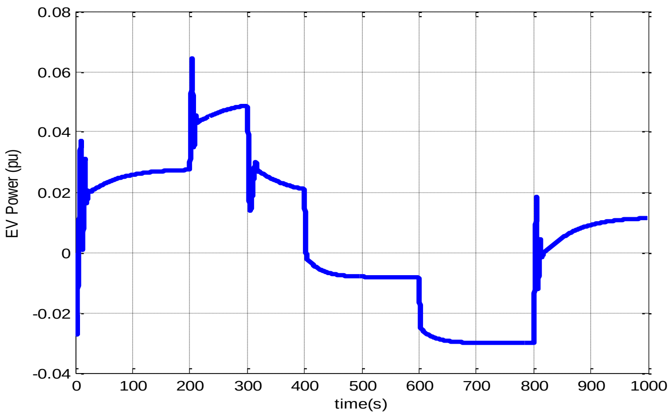


Fig.19. The amount of power generated by the electric vehicle is in a non-optimal state and without the participation of the turbine in the frequency control.

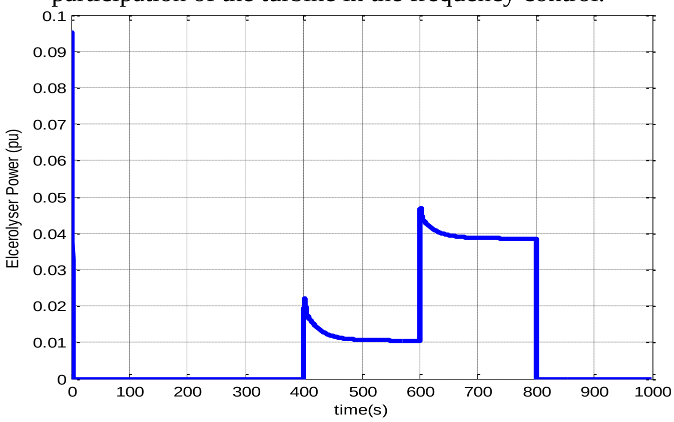


Fig.20. The amount of power absorbed by the aqua electrolyzer in a non-optimal state and without the participation of the wind turbine in the frequency control.

In another case, the micro-grid has been used due to the participation of the wind unit in the frequency control. At times when the wind turbine participates in the grid frequency control, the turbine speed changes, unlike the normal grid conditions. When the turbine tends to increase the frequency by reducing the injected power to the grid, then the speed of the wind turbine increases. On the contrary, when there is a frequency drop in the network due to the increase in injected power, the speed of the wind turbine will also decrease in this state. Therefore, the productive power of the renewable unit in the network can be easily changed.

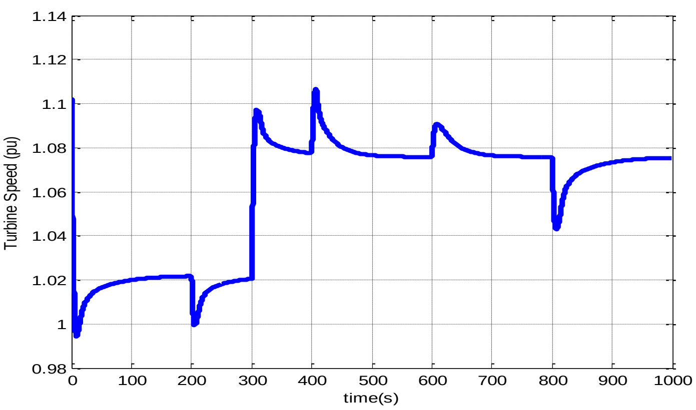


Fig. 21. Wind turbine speed changes with participation in frequency control.

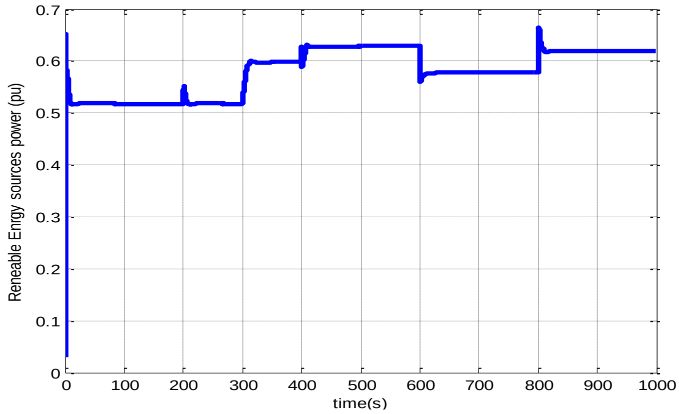


Figure 22. Power changes of the renewable unit without the participation of the wind turbine in the frequency control.

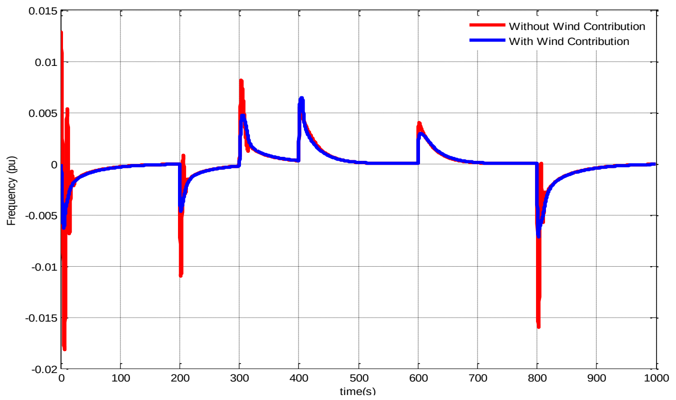


Fig.23. Comparison of load frequency fluctuations in non-optimal mode with/without participation of wind turbine in frequency control.

Then, the micro-grid was used in the presence of wind turbine participation and by applying telecommunication delay in sending and receiving power and frequency information. According to Figure 24, when the wind turbine participates in the control of the grid frequency, the information related to the grid frequency is received with a delay, but the participation of the turbine in the grid frequency control is still possible. In this mode, the speed of the turbine changes, unlike the normal state of the network. By reducing the power injected into the network, the wind turbine does not participate in controlling the frequency of the network and prevents the increase of the frequency of the network, in this case, the speed of the wind turbine increases. In the opposite situation, i.e., with the increase of injected power to the network and in the case of a decrease in the frequency of the network, the speed of the wind turbine decreases. In this way, the amount of productive power of the renewable unit in the network can be easily changed. Also, telecommunication delays will increase overshoot and undershoot in all modes. Therefore, the telecommunication delay may cause the frequency overshoot or undershoot to be higher than the normal mode at some times.

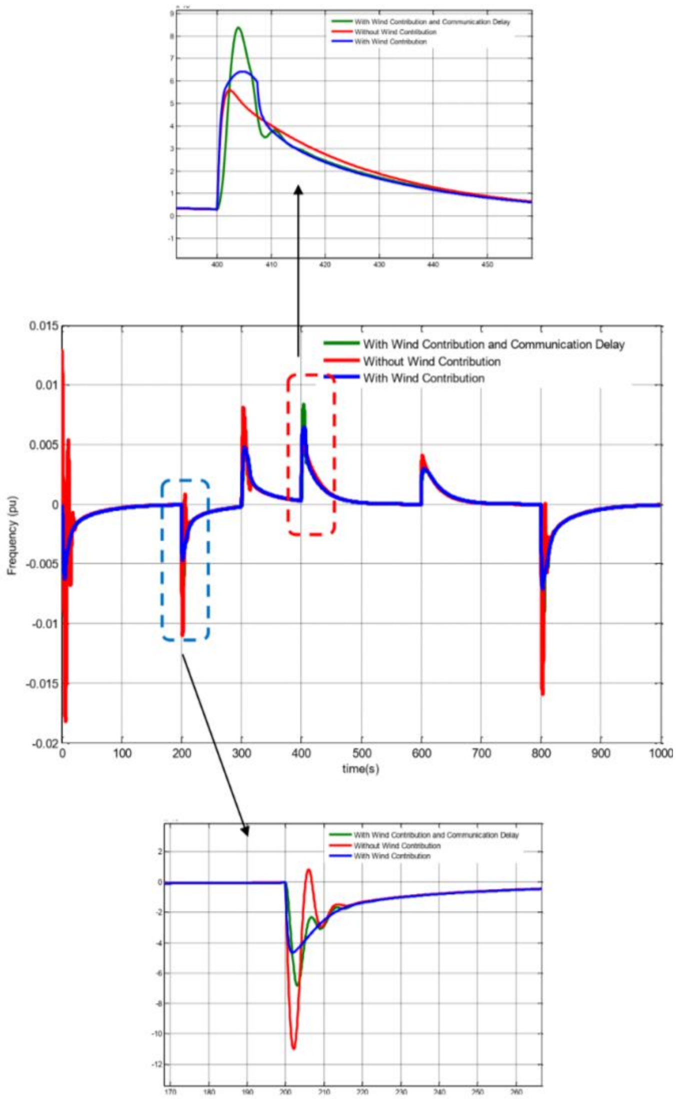


Fig. 24. Comparison of load frequency fluctuations in the non-optimal state with/without participation of wind turbine in frequency control and application of telecommunication delay.

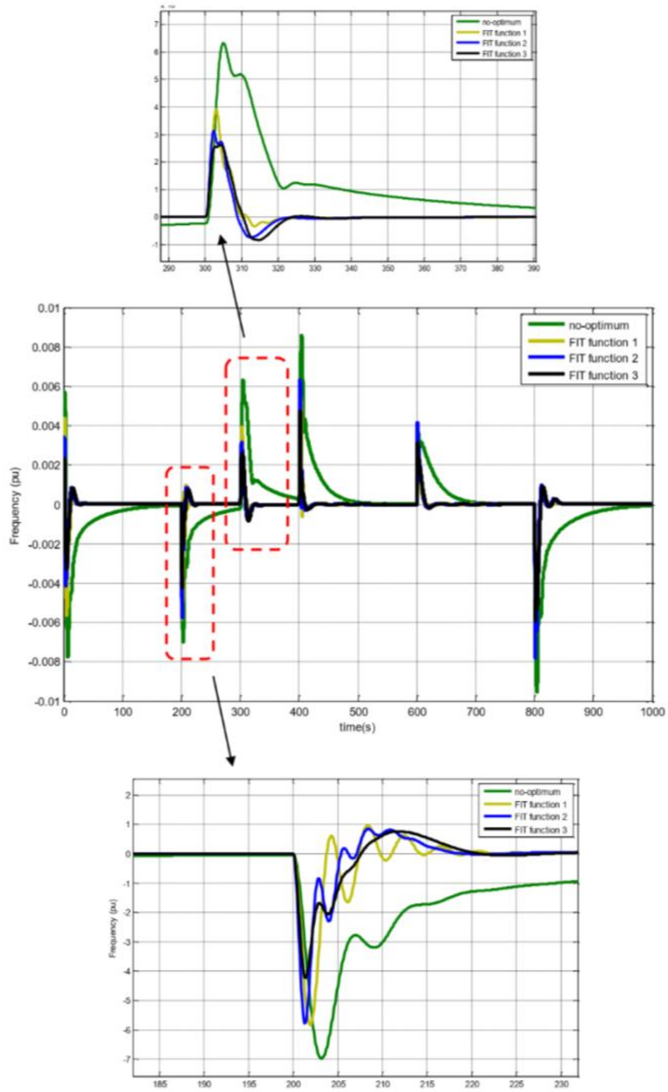


Fig. 25. Comparison of load frequency fluctuations in optimal mode with/without participation of wind turbine in frequency control and application of telecommunication delay.

To check the effectiveness of the obtained optimal parameters, the frequency fluctuation curve of the system in the presence of the non-optimal controller and the three objective functions mentioned in the previous section are shown in Figure 25. As seen in the figure below; In the presence of objective functions, the amplitude of oscillations and the damping time are reduced.

6. Conclusion and Discussion

Microgrids are generally independent networks consisting of sensitive and non-sensitive electrical loads, renewable and non-renewable sources in the form of distributed generation, as well as energy storage such as batteries. Due to the use of different types of distributed generation sources and energy storage, these networks are immune from the negative effects caused by disturbances in the national electricity network. This leads to the fact that storing, buying, and selling energy in different periods increases the economic justification of micro-grids. Due to their high reliability, these microgrids are suitable for sensitive applications such as medical centers, defense bases, or data and information processing centers, and they are safe from the dangers of natural and terrorist events. Avoiding frequency fluctuations and reducing the cost of operation are the usually discussed issues related to microgrids. The issue of frequency is investigated for a time interval of a few milliseconds to a few seconds. But we know that economic issues are often discussed for long periods. To control the frequency, the spinning reserve policy in large networks is examined with the term spinning reserve in low voltage power grids. A spinning reserve is defined as a part of the unused generation capacity of the network, but it is ready to enter the circuit in a short period to compensate for unexpected disturbances, such as rapid changes in the electric load or its sharp reduction. In addition, with the development of penetration of renewable units in the grid, severe frequency fluctuations are expected due to production fluctuations. The mismatch between the predicted electric power and the available electric power of the energy sources will be created due to the variable nature. A lot of research has been done on the issue of load shedding in micro-grids, each of which has used a special solution of equipment and obstacles to overcome the mentioned problems. Due to the different economic and technical motivations for using microgrids to provide electric power and the optimal level of reliability for feeding sensitive loads, the problem related to frequency control with planning in the transient and steady-state generation of electric power in microgrids is discussed in this paper. The following significant measures are intended in this paper: A planning of transient or steady state electric power generation based on a micro-grid central controller has been developed with inspiration from real research of micro-grid and practical constraints in the generation or absorption of electric power. This strategy includes three main parts (i.e. controllable sources, renewable units, and energy storage devices) and performance constraints related to each of the equipment and electric power sources. In this paper, an intelligent solution based on the intelligent teaching and learning algorithm is used to find the most optimal parameters of the controller, and the results are compared with the controller whose parameters are obtained in the usual way. The proposed simulation consists of all resources, energy storage, and control systems that will be simulated by MATLAB/SIMULINK software. Also, the teaching and learning algorithm is coded by MATLAB software to obtain the optimized values of the controller parameters. In microgrids connected to the power grid, any unexpected change in the consumed electric load or the produced electric power can be compensated by the production units or the energy storage of the power grid. Therefore, the frequency of the grid, but in the case that the microgrid is not connected to the grid, the frequency of the grid is controlled while paying attention to various types of renewable energy sources and many times through different methods. In this paper, an autonomous microgrid isolated from the national power grid containing a wind power source, diesel generator, solar light power source, fuel cell, electric vehicle, aqua electrolyzer, and battery bank is intended for study. Electric power generation by renewable energy sources is considered fixed and uncontrollable. To direct the future of this research, it also considered things such as the participation of distributed solar generation sources in microgrid control. Also, as another research field, different control methods can be considered for frequency control or other intelligent algorithms can be used. The innovations and advancements in micro-grid frequency control and renewable energy integration in this study can be summarized as follows:

- Delayed parameter measurement systems: The study proposes and evaluates the use of delayed measurement systems for micro-grid parameters. Delaying the measurement of certain parameters, such as frequency or voltage, could allow for a more accurate representation of the system's behavior and dynamics. This delay could be intentional to account for communication latency or to capture delayed responses of renewable energy sources.
- Coordinated participation of energy sources: The study investigates innovative methods for coordinating the participation of different energy sources within the microgrid. This involves developing advanced control strategies that consider the specific characteristics of each energy source, such as wind units, and optimize their contribution to frequency control while maintaining system stability.
- Integration of renewable energy sources: The study explores novel techniques for integrating renewable energy sources, particularly wind units, into micro-grids for frequency control purposes. This involves designing specialized control algorithms that leverage the intermittent nature of renewable energy sources to enhance frequency regulation and maintain grid stability.
- Enhanced frequency control methods: The study proposes improved frequency control methods that leverage the coordinated participation of energy sources and wind units. These methods involve advanced control algorithms, predictive modeling, or advanced optimization techniques to actively regulate and stabilize the microgrid frequency.
- Aqua electrolyzer (AE) utilization: The study introduces the concept of an aqua electrolyzer as a means to balance the power generation and load requirements in the microgrid. The AE operates when the electric power generated by renewable or controllable units exceeds the desired load power. By utilizing the AE, excess power can be converted into hydrogen gas through electrolysis, which can be stored or used for other purposes.
- Intelligent Control Strategy: The proposed control method employs three rules to govern the operation of the micro-grid units. These rules consider the power generation levels of renewable and controllable units, the role of the battery bank in absorbing or injecting power, and the coordination of different units such as the electric vehicle, fuel cell, and diesel generator. This intelligent control strategy ensures efficient power management and frequency control in the microgrid.
- Teaching and Learning-Based Optimization (TLBO) Algorithm: The study utilizes the TLBO algorithm as an efficient optimization method to determine the best possible state of the microgrid. By applying the TLBO algorithm, the control parameters of the microgrid can be optimized to achieve optimal power balance and frequency control. This

application of the TLBO algorithm in micro-grid frequency control is a novel approach in this study.

- Communication and control systems: The study considers innovative approaches to communication and control systems within the micro-grid. This includes the development of robust communication protocols, efficient data exchange mechanisms, and intelligent decision-making algorithms to enable effective coordination and control of energy sources and wind units. These contributions advance the understanding and implementation of autonomous microgrids and pave the way for more efficient and sustainable energy systems.

Availability of Data and Materials: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval: This paper does not contain any studies with human participants or animals performed by any of the authors.

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