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Research Article

A Fuzzy Intelligent Computing Approach for Energy/Voltage Control of Microgrids

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The control and energy management problems of microgrids (MGs) are challenging due to the high level of uncertainties and disturbances such as changes in demands, mechanical powers, and solar energies. So, intelligent computing is needed to be developed for these systems. This paper uses an optimal and robust fuzzy controller for automatic voltage and frequency regulation. The fuzzy logic develops the resistance against uncertainties and disturbances such as irradiation, wind power changes, and load demand variation. The introduced controller uses appropriate and effective criteria that include rising time, settling time, overshoot, and the degree of resistance of the control system to uncertainties and perturbation effects. Through simulations and compassion with conventional regulators, the better accuracy of the suggested approach is demonstrated.

1. Introduction

The change in active power mainly affects the system frequency, while the reactive power has minor sensitivity to frequency and is dependent on voltage changes. The LFC regulates actual power and frequency, and the AVR also regulates the reactive power and voltage magnitude. LFC and AVR are the main control loops of the generator. Due to the continuous load changes in the system, the output is automatically adjusted to set the frequency to the nominal value. This method is called AC. In recent years, significant research has been done to increase the stability of power networks [1, 2].

One of these methods is to improve the stability and access to stable nominal voltage levels in electrical networks, controlling the excitation field of the generator using automatic AVR by reducing costs further. But such a system, in the case without an effective controller, has a relatively poor performance for various reasons including some output fluctuations, slow reaction, and steady-state error against some disturbances and uncertainties such as sudden changes in load and so on. In this project, a functional, efficient, and robust controller based on the PID structure is designed and analyzed to control an automatic voltage regulator. Generalization of the AC system and consideration of the excitation system were observed. In the PID controller, setting Kp, Kd, and kI coefficients is very important. In this project, these coefficients are adjusted by the fuzzy and classical Ziegler–Nichols methods, considering the AC system [3, 4].

A fuzzy LFC is improved in [5], and the impact of demand response is studied, also a full interconnected MG is considered for evaluation. A PID is suggested in [6], and the chaotic sine-cosine algorithm is used for tuning PID. In [7], a hybrid controller is designed for LFC problem and pitch angle regulation. The optimality of PID is analyzed in [8], and the effect of wind power in frequency is studied. In [9], a fractional-order controller is developed, and by online getting data, the stability is analyzed. In [10], a PID is designed, and by a real-time examination on MG, the LFC accuracy is investigated. In [11], the efficiency of a PI is analyzed, and by sine-cosine algorithm, the parameters are adjusted. In [12], the impact of LFC on size of the battery is studied, and an approach is suggested to determine the optimal size of the battery.

In a network, a significant frequency drop may lead to solid magnetic currents in induction motors and cause irreparable damage. On the other hand, the wide use of synchronous electric clocks requires good maintenance of synchronous time, so the frequency and its integral must be adjusted and controlled. The frequency stability of a power system is related to the actual power balance. Any variation in power demand is directly reflected in the form of a frequency change throughout the system. And since a vast number of generators provide the power required for an extensive power system, the power demand change must be divided among the units. Of course, the load is divided between the generators, and the initial speed control is done by the governors installed on the generators; however, to fine-tune the frequency to the nominal value, additional control is needed, which must be done in the main control center. Modern energy control centers (ECCs), equipped with timely computer networks, process information and control by taking data from remote units, which are called the SCADA system [13].

Many perturbations are effective on the accuracy of LFC. A few studies analyze the LFC robustness. For example, in [14], error feedback LFC is designed, and in isolated MG, the robustness is analyzed. A fuzzy PID is designed in [15], and the uncertainty of solar power is studied. In [16], neural networks are used for forecasting the power of solar panels that are effective in accuracy development of LFCs. In [17], an LFC is designed, and the effect of attacks by wrong data injection is investigated. A self-structuring fuzzy LFC is introduced in [18], and the better efficiency of FLSs is shown. In [19], a fuzzy LFC is suggested for wind-diesel MGs, and the better regulation accuracy of FLS-based LFCs is analyzed.

2. System Description

The induction of voltage in the rotor of a synchronous machine (which has acquired electromagnetic properties) is called machine excitation. Therefore, the system that supplies the current is called the excitation system. The amount of current supplied depends directly on the electromagnetic force and thus on the voltage level induced on the stator. For a synchronous generator, the field winding (which is magnetized) is always on the rotor, and this is because the amount of current in the field winding is much less than that of the stator winding, making it easier to arrange the shaft. If the field winding is placed on the stator, the volume of the winding will increase, and as a result, the order of movement of the shaft will be more difficult. Today, with the advancement of technology, power semiconductors such as diodes and thyristors can better control the excitation machine's characteristics. Depending on its type and shape, the equipment may be extensive in any excitation system. Still, in each excitation system, there are a series of fixed and main components, which we will describe as some of the main components of the excitation system [20].

2.1. Components of the Excitation System

2.1.1. Rotor Current Generation. The car rotor must be powered by a current, for example, the car rotor is powered by a high-power electronic converter (this method is direct), or a small current feeds the excitation machine, which regularly increases the rotor current (indirect method).

2.1.2. Power Supply. The excitation system needs a power supply to generate current. The power supply is used in both parallel and series power supply. Parallel power is the power taken from the car terminals, and series power is the power taken from the auxiliary power.

2.1.3. Automatic Voltage Adjustment System. The AVR is a closed-loop controller that compares a signal proportional to the generator output voltage with a constant base voltage and uses the resulting voltage error to control the output of the excitation unit. If the generator's load changes, the output voltage of the generator also changes, which lead to the sending of an error signal. The voltage regulator amplifies the voltage error and is used to reduce or increase the excitation rate to return the generator output voltage to its original value. The rapid and stable response of the microcontroller to load changes is of particular importance. The AVR receives the output voltage of the generator through its corresponding voltage transformer. The voltage signal is then rectified and compared to the base voltage. It is possible to change the base voltage according to the system's needs by the operator. In addition to the main task of voltage control, the AVR has other vital tasks. The AVR includes other control loops to control the extra megawatt and flow rate [5].

2.1.4. Auto Tracker Circuit. In the dual-channel AVR, both control channels can be activated simultaneously, and each channel can meet half of the excitation system needs. Another way is to activate one channel and have another channel reserved, and if the active channel fails, the reservation channel will follow the task of the active channel.

2.1.5. Stimulation Control. In addition to the voltage control loop, modern excitation equipment consists of a number of lateral limiting circuits that act as controllers in parallel with the voltage control circuit and replace the voltage signal if the limiting variable exceeds the specified limit.

2.1.6. Rotor Current Limiter. Excitation systems can supply more than the required amount of excitation current to the generator to operate at maximum continuous load. This great feature is used when an error occurs in the system and additional reactive power is required to amplify the synchronous rotor torque. However, this excess excitation current must be controlled in time so that overheating the rotor does not lead to loss of rotor conductor insulation. To prevent the rotor from overheating, the rotor current limiting circuit detects excitation currents greater than 110% of the maximum allowable continuous load. In the event of a fault, the microcontroller activates by increasing the excitation current, which usually does not last more than a few milliseconds, and the switch cuts off the short circuit. For maximum support, usually after a delay of about 5 seconds, the circuit of the rotor current limiter sends a signal that opposes the signal sent from the AVR and reduces the excitation current to the allowable range.

2.1.7. Reactive Power Limiter. Modern AVR equipment can control the work of the generator at load angles of 130 to 140 degrees, which is related to the transient mode, and usually, the work of the generator is limited to an angle of 75 degrees. The allowable prephase reactive power of the generator is changed by the square of the generator output voltage. If the generator excitation is low, an increase in the load angle (δ) will soon cause the generator to receive reactive power from the mains. To prevent this, in practice, when the amount of turbine steam increases, or in other words, the input power from the turbine to the generator increases, the current flow of the generator must also increase with it, and a limited megawatt is installed in the AVR. If the amount of reactive power of the generator prephase exceeds a specific limit, the basic function of the AVR is to regulate the voltage at a constant value, overshadowing and increasing the current to a value that does not increase δ, thus preventing the generator from becoming unstable.

2.1.8. Additional Flux Limiter. In addition to the additional flow protection circuit, modern AVR equipment also includes an additional flow limiting circuit. It is a closed loop control that detects the voltage to the frequency ratio when the generator is operating asynchronously, and if it exceeds the predetermined value, the limiter sends a signal that reduces the excitation and prevents additional flow in the unit transformer.

2.2. Power Control. Power has two positive and negative values for consumers where there is a phase difference between voltage and current. This means that the consumer sometimes draws power from the network and gives it power. This creates reactive power. Since it is not possible to zero the phase difference in these consumers, the result is that reactive power cannot be eliminated.

In a straightforward and general expression, since the impedances of the components of the power system are primarily reactive, active power transmission requires a phase angle difference between the voltages at the beginning and end of the line, which is practical in a relatively wide range. While for reactive power transmission, the magnitude of these voltages must be different, which is only practical in a minimal range. But why do we want to transfer reactive power? Is not this a troublesome concept created by theorists and should be ignored? The answer is that not only do most components of the system consume reactive power, but most electrical charges also consume reactive power; therefore, reactive power consumption must be supplied locally. If we cannot transport it quickly, we must produce it where it is needed. There is a fundamental and essential relationship between reactive and active power transmission. As we have said, active power transmission requires a phase shift of voltages. But the amount of voltage is just as significant. Not only should they be high enough to support loads, but they should also be low enough to not damage the insulation of the equipment. Therefore, if necessary, we must control the voltages at critical points and apply them with limited support. This control operation can be carried out on a large scale by generating or consuming reactive power at critical points. Although this aspect of reactive power has long been considered, today it has become essential, at least for the following reason: the first reason is the increasing pressure to operate the transmission systems as much as possible, and the second reason is that new types of controllable static reactive compensators have been developed. Synchronous capacitors have been used for many years in developing electrical power networks to support voltage and improve the ability to transmit power. At the same time, parallel capacitors were used in the distribution unit to improve the voltage and reduce line loading and losses (by modifying the power factor). The rapid and economic development of parallel capacitors led to their replacement by synchronous capacitors in transmission systems. It was observed that in practice, what synchronous capacitors could do could be achieved by switching parallel capacitors at a much lower cost. There are signs that the method has been revived, and a controllable reactive power supply has been introduced as a static device. Of course, from an economic point of view, a system engineer still has to determine how much capacitor (or constant inductance) to use, how much to switch, and finally, how much to control continuously and quickly (for example, during turbulence) [21]. Of course, the question remains how many synchronous generators provide reactive power?

Reactive power control has become increasingly important for several reasons, some of which are briefly mentioned here. The first reason is that the need for optimal use of power systems has increased due to the price of fuel. The losses are downsized by minimizing the power distribution to distribute a certain amount of power. This principle can be applied throughout the system in the simple form of an inductive power factor correction capacitor or the form of advanced algorithms used in an extensive network and controlled by a computer. The second reason is that due to the high-interest rates in general and the problems related to the privacy of transmission lines in some instances, the development and construction of transmission networks are prevented as much as possible. In many cases, attempts have been made to increase the transmission power of existing lines by using reactive power control devices and improving stability. The third reason is that the need for high-quality nutrition has increased due to the increasing consumption of electronic devices (especially computers and color television) and the growth of continuous process industries. Decreasing the voltage or frequency adversely affects such loads, and power outages can be very damaging and costly. Reactive power control is essential in maintaining the quality of power supply, mainly to prevent voltage perturbations, the most common type of perturbation. Specific industrial loads, including electric furnaces, drilling rigs, and welding machines, receive rapid and wide-ranging changes by receiving active/reactive power from the power supply system. It is often necessary to reduce these changes using voltage stabilizers such as static reactive power compensators. The fifth reason is that, with the development and construction of DC transmission lines, it became necessary to control the reactive power on the ac side of the converters to stabilize the voltage and assist in the commutation of the converter [22].

2.3. Automatic Voltage Regulator. In general, the AVR system is one of the two main control loops (voltage control loop and frequency control loop) of the generator. Usually, the AVR control loop, which is simpler and faster than the load frequency control loop, provides stability and local voltage stability of the generator terminals as long as the load frequency control loop provides stability throughout the system. An AVR system consists of five main parts, including the amplifier unit, the excitation unit, the generator unit, the sensor unit (filter and rectifier), and the comparator unit. As mentioned, the increase in reactive power of a generator is associated with a decrease in the terminal voltage. Voltage measurement is sensed through a single-phase voltage transformer. This signal is rectified and compared to the reference signal. The excitation current of the generator is increased which leads to an increase in the emf produced. Reactive power generation is changed to a new equilibrium point, which returns the terminal voltage to an acceptable level. Now, in brief, simple models of the elements that make up an AVR system will be examined [23].

2.3.1. Converter Unit Conversion Function. This unit is the core and in fact the decision unit in the AVR system. The control mechanism that changes the final behavior of the system in order to achieve the control objectives is in this unit.

2.3.2. Amplifier Unit Conversion Function. The signal is smoothed to compare with a DC reference signal in the comparator block. After this error, the voltage obtained from the comparison process is amplified and applied to the input of the control unit. The amplifier block conversion function is in the form of relation (1):

$$\frac{V_R(s)}{V_e(s)} = \frac{K_a}{1 + \tau_a s}, \tag{1}$$

where K_a is the amplifier gate and τ_a is the amplifier time constant.

2.3.3. Excitation Unit Conversion Function. There is a great variety in different types of excitation systems. However, in the simplest form, they ignore the phenomenon of saturation and other nonlinear factors. The conversion function of the excitation unit is in the form of relation (2) [14]:

$$\frac{V_F(s)}{V_R(s)} = \frac{K_E}{1 + \tau_E s}, \tag{2}$$

where K_E is the amplifier gate and τ_E is the excitation time constant.

2.3.4. Generator Unit Conversion Function. The purpose of an AVR unit is to regulate the generator terminal voltage. The generator conversion function can be expressed as (3):

$$\frac{V_t(s)}{V_F(s)} = \frac{K_g}{1 + \tau_g s}, \tag{3}$$

where K_g is the amplifier gate and τ_g constant excitation time.

2.3.5. Sensor Unit Conversion Function. In an AVR system, the generator terminal voltage is continuously measured by a voltage level sensor. The sensor conversion function is in accordance with the conversion function (4):

$$\frac{V_s(s)}{V_t(s)} = \frac{K_s}{1 + \tau_s s}. \tag{4}$$

3. Designed Controller

The general view of the suggested structure is shown in Figure 1. The parameters defined in Figure 1 are defined in Table 1.

Active power must be generated when needed, and because the load consumption varies at different times of the day and night, the generating power of the generators must also be controlled. The output power of a generator is regulated by changing input mechanical power. To do this, by opening or closing the steam valve or water valve, the steam/water flow on the turbine is regulated and controls the mechanical power and consequently the active power of the generator output. If the load consumption increases, the steam valve or water valve should be opened further to increase the generator output power by the same amount, and if the power consumption of the load is reduced, the steam valve or water valve should be closed to such an extent that it reduces the generating power of the generator to the same extent, and thus the active power balance is established.

3.1. Load Frequency Control System. The goals of the LFC system are to maintain a permissible frequency, distribute loads between generators, and control power exchange programs on communication lines. The changes in

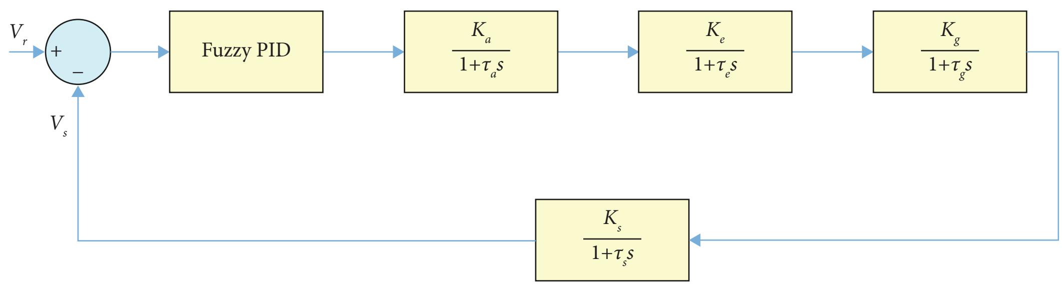

Figure 1: Structure of the suggested controller.

Table 1: Parameter description.

V_e	Error signal
τ_E	Time constant of exciter
K_A	Gain constant of the amplifier
τ_A	Time constant of amplifier
K_D	Derivative gain of controller
K_E	Gain constant of exciter
K_G	Gain constant of generator
τ_R	Time constant of sensor
K_p	Proportional gain of controller
K_I	Integral gain of controller
K_R	Gain constant of sensor
τ_G	Time constant of generator

frequency and actual power are measured in the communication line, which is the change in rotor angle (δ), i.e., $\Delta\delta$ error that must be modified. Error signals Δ_f and ΔP_{tie} are converted into the true ΔP_V command signal, which is sent to the primary actuator to increase the input torque. Therefore, the primary actuator changes the output of the generator by ΔP_g, which in turn changes the values of Δ_f and ΔP_{tie} to a predetermined accuracy.

3.1.1. Generator Model. The oscillation equation is

$$\frac{2H}{\omega_s}\frac{d^2\Delta\delta}{dt^2} = \Delta P_m - \Delta P_e, \quad (5)$$

where H is the inertia constant of the machine at the base power of the system. ΔP_m and ΔP_e are the equipment of mechanical power input and electrical output power of the generator, respectively. The angle of power in terms of electric radians and ω_s is the angular velocity in terms of electric radians per second. Equation (5) for a small deviation in velocity is written as follows:

$$\frac{d\Delta(\omega/\omega_s)}{dt} = \frac{1}{2H}(\Delta P_m - \Delta P_e). \quad (6)$$

Using the speed on pu (without mentioning pu) you can write

$$\frac{d\Delta\omega}{dt} = \frac{1}{2H}(\Delta P_m - \Delta P_e). \quad (7)$$

By obtaining the Laplace transform, we have the sides of (7):

$$\Delta\Omega = \frac{1}{2Hs}(\Delta P_m(s) - \Delta P_e(s)). \quad (8)$$

3.1.2. Load Model. The load-velocity characteristic of a combined load is approximated as follows:

$$\Delta P_e = \Delta P_L + D\Delta\omega, \quad (9)$$

where ΔP is not sensitive to frequency changes but $D\Delta\omega$ is sensitive to frequency changes. Quantity D is the ratio of the percentage change in load to the percentage change in frequency. For example, if the load changes by 1.6% due to a 1% change in frequency, then $D = 1.6$.

3.1.3. Primary Control. Different turbines have different characteristics. The simplest model of the steam turbine actuator without reheating has the simplest initial actuator model which can be approximated only by a time constant τ whose conversion function is as follows:

$$G_T(s) = \frac{\Delta P_m(s)}{\Delta P_V(s)} = \frac{1}{1+\tau s}. \quad (10)$$

The time constant τ is in the time range of 0.20 to 2.1 seconds. For stable performance, the governor is designed to slow down as the load increases. The slope of this curve represents the velocity adjustment coefficient R. These governors have a speed adjustment factor of 5 to 6 percent from zero to full load. The speed control scheme operates as a comparator, in which, output ΔP_g is the difference between the reference ΔP_{ref} and the power of $1/R\Delta\omega$, which is determined as

$$\Delta P_g = \Delta P_{\mathrm{ref}} - \frac{1}{R}\Delta\omega. \quad (11)$$

Or in domain s we have

$$\Delta P_g(s) = \Delta P_{\mathrm{ref}}(s) - \frac{1}{R}\Delta\Omega(s), \quad (12)$$

where ΔP_g is converted to steam command ΔP_V via a hydraulic booster. Considering a linear relation and a simple time constant τ_g, we have

$$\Delta P_V(s) = \frac{1}{1+\tau_g}\Delta P_g(s). \quad (13)$$

4. Setting the PID Controller

The PID controller can be used to develop the transient and permanent state response of the control system. The purpose of setting the PID controller is to determine the three coefficients of the controller. This controller calculates the amount of error between the output of the process and the desired input or reference value. The goal of the controller is to try to minimize the error by adjusting the process control inputs. The input of this controller is an error and its output is a control signal. The relationship between system error and control command at the output of the control unit and in the time domain is as follows:

$$u(t) = k_p\left(e(t) + \frac{1}{T_i} * \int e(\tau)\mathrm{d}\tau + T_d * \frac{d}{dt}e(t)\right). \quad (14)$$

The proportional term $k_p e(t)$ in the control input proportional to the current error affects the control signal. This coefficient plays a significant role in the performance of response speed. A large selection of this coefficient may cause the behavior of the controlled system to fluctuate or, in some cases, lead to instability. This coefficient can effectively reduce the error between the system output and the desired value, but zeroing the error with the help of the proportional coefficient will not be possible. The term $k_1 \int e(\tau)\mathrm{d}\tau$ affects the control signal according to the number of previous errors. In fact, by integrating past errors so far, it tries to reduce the error value to zero. This term creates an adaptive property for the controller and always directs the output of the controlled system to the desired value by adding up the previous errors and changing the control command in proportion to the amount of error. The derivative term $k_D d/dt e(t)$, as an error prediction term, can also affect the rate of change of system error. Therefore, derivatives can be used to reduce system response fluctuations. Note that in the presence of noise in the control system, the derivative term can reduce the performance of the control system or in some cases, cause system instability. Despite the unique features that this type of controller has, it also has drawbacks. One of the most important disadvantages of this control strategy is that the process of fine-tuning its parameters is relatively difficult and is controlled by the nature of the system. Failure to properly adjust the coefficients of this controller will prevent access to proper and optimal performance for the control system. In this section, Ziegler–Nichols' methods and fuzzy logic are used to tune the coefficients of the PID. According to Ziegler–Nichols' theory, the system oscillates for $K_u = 1.22$ and $T_u = 1.37$.

The simulations (see Table 2) verify that the designed controller has somewhat reduced system output fluctuations and improved system performance. But it seems that more appropriate answers should be found for the system. In the following, we will try to use intelligent techniques such as fuzzy logic to design and optimize the controller. The choice of fuzzy controller for the AVR system is mainly due to some special and unique capabilities of this control technique, including the inherent resistance property of fuzzy control. Because in the modeling done for the AVR system, we are basically faced with some uncertainties that should be considered in some way regarding the robustness of the controller.

Table 2: The results for conventional PID.

0.53	t_r	Rising time
0.9	t_p	Peak time
2.5	t_s	Settling time
57.14%	M_p	Overshoot
0	E_{ss}	Steady-state error

4.1. Adjusting the Parameters of PID for AVR Loop. Another controller that has made its way into control systems is fuzzy logic-based controllers. This type of controller, like other controllers, has advantages and disadvantages. One of the essential advantages of this controller is its resistance to uncertainty and system disturbances, which has led to it being referred to as a controller with inherent resistance. But in addition to this unique feature, it may still be possible to consider a weakness of this controller. Since one of the steps in designing a fuzzy controller is to extract the appropriate fuzzy rules for controlling the system, it requires sufficient language experience and understanding of the controlled system to extract rules to control system variables well. Therefore, not having enough information and experience about the controlled system will lead to the extraction of incorrect rules and, consequently, an unfavorable response. In this section, by combining these two strategies, a controller is designed to have the characteristics of both of the abovementioned controllers simultaneously and eliminate the defects proposed for them. It combines a PID controller with intelligent fuzzy logic to create a fuzzy PID controller that allows you to access the unique features of a PID fuzzy controller simultaneously. In short, the use of fuzzy control overcomes the uncertainty of the mathematical model of the process under control and, in fact, creates a robustness property for a controller. The PID will also improve the static and dynamic performance.

The input of this controller is an error signal. The issue now is that the error signal, in addition to entering the PID controller system, also enters a fuzzy system (fuzzy logic controller). What the fuzzy system does as shown below is changing the PID controller coefficients. In general, this fuzzy system changes the coefficients by looking at the error signal and the error derivative.

In this system, instead of the coefficients k_p, k_i, and k_d, we define the coefficients k_p, k_d, and α (one number), where $\alpha = T_i/T_d$, in fact, T_i can be obtained by having α and T_d. The T_d parameter is obtained from the k_p and k_d parameters. Therefore, k_i can be obtained according to the following equation:

$$k_i = \frac{k_p^2}{\alpha k_d}. \quad (15)$$

Due to the fact that the system and the gain of the systems are different, these coefficients are normalized to make the k_p and k_d coefficients independent of the system.

$$k_p' = \frac{k_p - k_p^{\min}}{k_p^{\max} - k_p^{\min}}. \quad (16)$$

So the fuzzy system has two error inputs and error derivatives and three k_p, k_d, α outputs. Finally, by applying mathematical relations to the fuzzy system outputs, it automatically adjusts the proportional, derivative, and integral coefficients of the PID controller.

The most important part of designing controllers based on fuzzy logic is correctly extracting the rules and creating an appropriate fuzzy rule database. At this stage, the designer must have sufficient mastery and understanding of the system, and the various behaviors of its variables to be able to extract the rules correctly. Lack of sufficient information and experience with the controlled system will lead to the extraction of incorrect rules and, consequently, an unfavorable response. In this section, we try to extract the rules extraction process for designing a fuzzy controller with the help of the system step response. Here, the system response is divided into different parts, and in each part, the function of the control signal that must be applied to the system by the controller is expressed in simple language. For example, if the system response is in region B (equivalently, if the error and the error derivative are both negatives), the output of the system is moving away from the reference input signal and, therefore, a force in a contrary direction of output of the system, i.e., a relatively sizeable opposing force is required to apply to the system. By having an error and an error derivative, all response situations can be identified as follows:

(i) If the error is positive, and error derivative is negative, the response is in zone A and no force is required, and the response is close to the desired value

(ii) If the error is negative, and error derivative is negative, the response is in region B, so a relatively large negative force must be applied to the system

(iii) If the error is negative and the error derivative is positive (area C), the response is moving towards the desired value, and no force is required

Similarly, appropriate controller and stimulus responses can be determined for the various behaviors that the system exhibits. The fuzzy membership functions are defined in Table 3. The fuzzy rules of K_p and K_d are given in Tables 4 and 5, respectively. The table of fuzzy rules of coefficient α is given in Table 6. As it turns out, in this case, we will have a total of 49 fuzzy rules. For example, according to the table of fuzzy rules K_d, if the error has an NB value and the error derivative also has a PS value, then the controller must apply S force to the system. Similarly, according to the above tables, the pattern "if -then" is valid for all other cases. For future studies, the suggested method can be improved by the fuzzy approach of [24–26].

Table 3: Fuzzy membership functions.

A_3	Positive big
A_2	Positive medium
A_1	Positive small
A_0	Zero
B_1	Negative small
B_2	Negative medium
B_3	Negative big
C_1	Small
C_2	Big

Table 4: Fuzzy rules for K_p.

		B_3	B_2	B_1	ZO	A_1	A_2	A_3
	B_3	C_2	C_2	C_2	C_2	C_2	C_2	C_2
	B_2	C_1	C_2	C_2	C_2	C_2	C_2	C_1
	B_1	C_1	C_1	C_2	C_2	C_2	C_1	C_1
E	ZO	C_1	C_1	C_1	C_2	C_1	C_1	C_1
	A_1	C_1	C_1	C_2	C_2	C_2	C_1	C_1
	A_2	C_1	C_2	C_2	C_2	C_2	C_2	C_1
	A_3	C_2	C_2	C_2	C_2	C_2	C_2	C_2

5. Simulations

The designed fuzzy controller is examined in this section, and the results are compared. The controllers operate under certain conditions and control small loads, voltages, and frequencies. Slight variation in real power remarkably depends on variation in the angle of the rotors and, consequently, the frequency. Reactive power also depends on the size of the voltage (or in other words, the generator's excitation). Therefore, because the coupling between the AVR and LFC loops is insignificant, the excitation system's time constant is smaller than the time constant of the generator actuator (mainly turbines) time constant. The transient mode is faster than it can affect LFC. Therefore, LFC and excitation control are generally considered separately.

The parameters of PID for the excitation system (AVR) are adjusted by the Ziegler–Nichols method and the fuzzy method, and the results of steady-state and transient state response are compared with the state in which the LFC system was examined separately in the presence of the AC and AVR systems. The simulation results are given in Table 7. A comparison of AVR loop step response without control system and control system is given in Figure 2. The LFC and AVR step response without PID is shown in Figure 3. For the Ziegler–Nichols setting mode, the LFC and AVR step response with PID is shown in Figure 4.

In the case of the fuzzy method, the LFC and AVR step response with fuzzy PID is shown in Figure 5. The values of the transient and permanent state parameters in the

Table 5: Fuzzy rules of K_d.

		B_3	B_2	B_1	ZO	A_1	A_2	A_3
E	B_3	C_1	C_1	C_1	C_1	C_1	C_1	C_1
	B_2	C_2	C_2	C_1	C_1	C_1	C_2	C_2
	B_1	C_2	C_2	C_2	C_1	C_2	C_2	C_2
	ZO	C_2	C_2	C_2	C_2	C_2	C_2	C_2
	A_1	C_2	C_2	C_2	C_1	C_2	C_2	C_2
	A_2	C_2	C_2	C_1	C_1	C_1	C_2	C_2
	A_3	C_1	C_1	C_1	C_1	C_1	C_1	C_1

Table 6: Fuzzy rules of α.

		B_3	B_2	B_1	ZO	A_1	A_2	A_3
E	B_3	2	2	2	2	2	2	2
	B_2	3	3	2	2	2	3	3
	B_1	4	3	3	2	3	3	4
	ZO	5	4	3	3	3	4	5
	A_1	4	3	3	2	3	3	4
	A_2	3	3	2	2	2	3	3
	A_3	2	2	2	2	2	2	2

Table 7: Simulation results.

With controller PID	No. of controller	Parameter symbol	Parameter
0.53	0.2534	t_r	Rising time
0.9	0.7737	t_p	Peak time
2.5	19.0812	t_s	Settling time
57.14%	82.7933%	M_p	Overshoot
0	0.0905	E_{ss}	Steady-state error

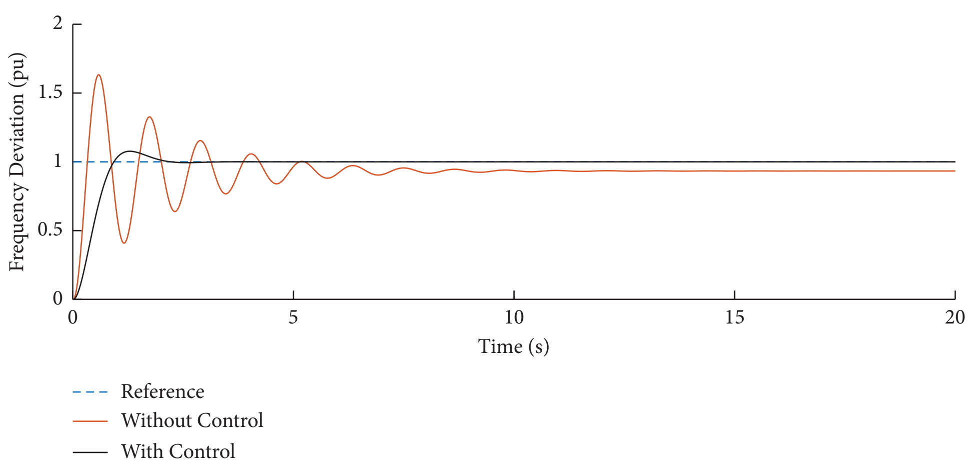

Figure 2: Comparison of AVR loop step response without controller and with controller.

abovementioned three cases are given in Table 8. The comparison trajectories of transient and permanent state parameters are shown in Figure 6.

Remark 1. To design the fuzzy sets for the inputs of the suggested PID, the range of inputs is divided into some parts, and for each part one fuzzy set is considered.

Remark 2. In this study, all possible rules are considered. For future studies, the number and format of rules can be tuned.

Remark 3. The designed PID can be developed using advanced type-3 fuzzy sets and systems. This type of FLSs provides more efficiency for control systems.

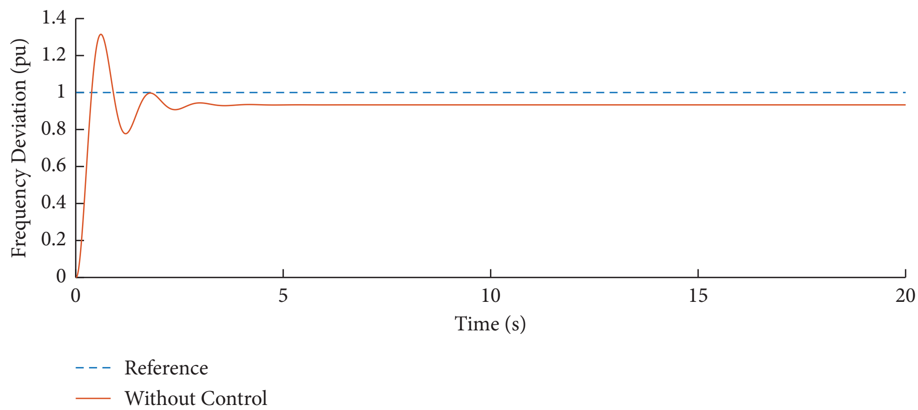

Figure 3: LFC and AVR step response without PID.

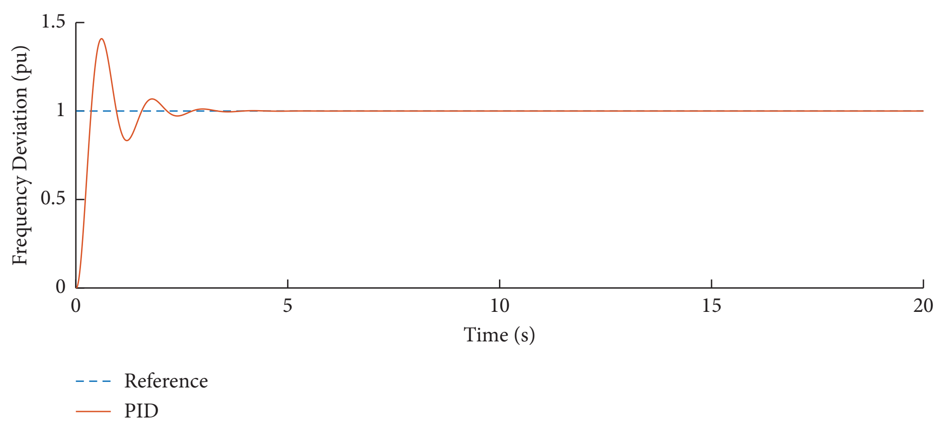

Figure 4: LFC and AVR step response with PID.

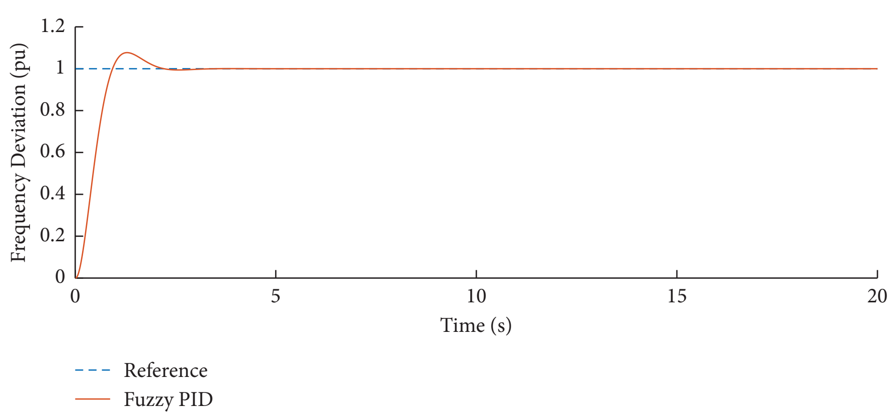

Figure 5: LFC and AVR step response with fuzzy PID.

Table 8: Numerical comparison.

Fuzzy PID	PID-Zigler	No. of controller	Parameters	Description
0.39	0.53	0.74	t_r	Rising time
0.7	0.88	0.94	t_p	Peak time
1.57	2.88	19.0812	t_s	Settling time
32.72%	61%	21.44%	M_p	Overshoot
0	0	0.1585	E_{ss}	Steady-state error

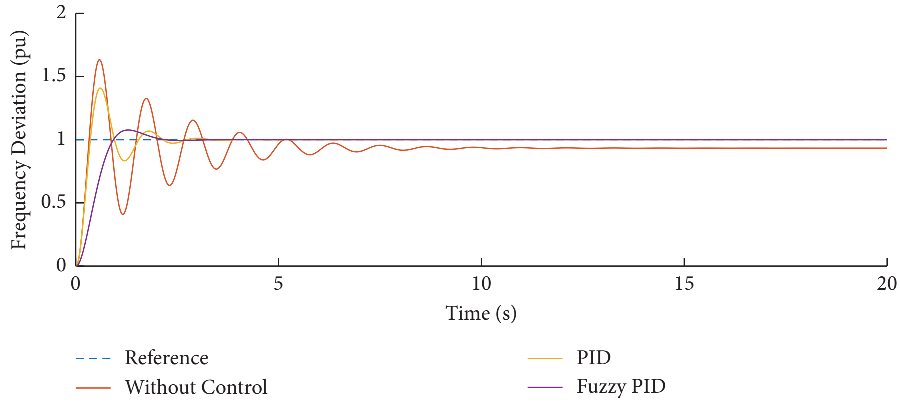

Figure 6: Comparison of transient and permanent state parameters.

Remark 4. The designed PID in this paper can be easily extended to the other problems. The main difference is the range of input changes in various problem that should considered.

Remark 5. The suggested method can be developed by using new fuzzy systems, and combining with new control systems [27], new optimization techniques [26], and new decision making methods [28].

6. Conclusion

This paper introduces a new optimal and robust PID controller with a combination of different control methods such as the Ziegler–Nichols method and fuzzy logic. Fuzzy logic is used to create the property of the control system's resistance to system uncertainties and modeling and external disturbances. Several simulations demonstrate that the suggested fuzzy LFC is more robust against solar and wind perturbations. Also, numerical and graphical comparisons are presented to better examine the introduced LFC's superiority. The main disadvantage of the suggested method is that the structure of used fuzzy sets are simple and can not handle more uncertainties. For future studies, the developed type-3 fuzzy sets can be used.

Abbreviations

MG: Microgrid
LFC: Load frequency control
AC: Automatic control
AVR: Automatic voltage regulator
ECCs: Modern energy control centers
FLS: Fuzzy logic system
E_{ss}: Steady-state error.

Data Availability

No underlying data were collected or produced in this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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