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A Novel Fuzzy Logic Controller Topology for Grid-Tied Photovoltaic Power Generation System with DC Voltage Droop Control

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ABSTRACT

This paper presents the implementation of Fuzzy Logic Controller based dc voltage droop control for grid-tied PV Power generation system to analyses the inertia and damping characteristics. The model is used to analyze the main parameters affecting the inertia, damping and synchronization characteristics of the system and their influence laws. The research results show that the energy storage effect of the capacitor on the medium time scale can also make the system exhibit certain inertia characteristics. From the point of view of control parameters, as the droop coefficient Dp decreases, the inertia characteristic exhibited by the system is stronger. The larger the DC voltage outer loop proportional coefficient Kp is, the stronger the damping effect of the system is. The larger the DC voltage outer loop integral coefficient Ki, the stronger the synchronization capability of the system. In addition, the MATLAB/Simulink simulation platform is used to verify the correctness of the theoretical analysis results.

Keywords: Grid-connected photovoltaic power generation system, DC voltage droop control, inertia characteristic, damping effect, synchronization ability, Fuzzy Logic Controller.

I. INTRODUCTION

The agreement among all nations is that clean energy should be aggressively developed as the global energy crisis and environmental degradation become a more significant problem. The development of electric cars, FACTS technology, and renewable energy sources has been substantial [1]–[3]. Because of its plentiful resources and advantages related to pollution-free operation, grid-tied photovoltaic power production, as a representative of renewable energy power generation technology, has seen spectacular expansion[4]–[6].

The rotating synchronous generator serves as the primary source of power generation in the conventional power system (RSG), Moreover, the

RSG has a high inertia and powerful dampening properties. The physical parameters of the grid-connected inverter in the grid-tied photovoltaic power generating system are noticeably different from RSG. The grid-tied inverter itself does not have physical inertia because it is a power electronic device. It has a large-scale connection to the grid and has low inertia and poor damping, which reduces the inertia of the power system and poses serious problems to the safe and stable functioning of the power grid. [6]–[8]. In addition, solar power generation has considerable volatility, significant unpredictability, and noticeable intermittent characteristics, all of which have a negative impact on the power grid's ability to operate steadily. As a result, in order to provide inertia when solar electricity is integrated into the power grid, they often need to include a specific level of energy storage [9].

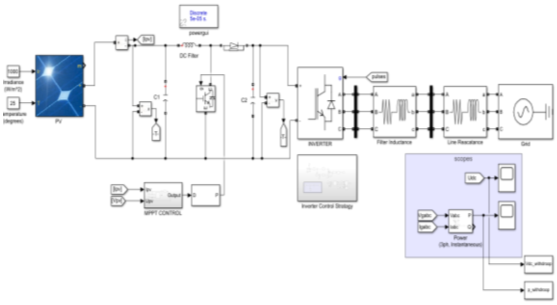

FIG 1. SIMULINK MODEL GRID-CONNECTED PHOTOVOLTAIC POWER GENERATION SYSTEM BASED ON DC VOLTAGE DROOP CONTROL.

To increase the system stability of the photovoltaic power production integrated into the grid, design and control strategy study are being undertaken in [10]–[12] on the integration of the solar generating and energy storage system.

Yet, the energy storage system is less cost-effective in the event of minor disruptions, and the primary energy and its converter have enormous potential for simulating inertia and damping characteristics, are not being completely used. The grid-tied inverter's DC side capacitor has traits of dynamic behaviour with the RSG rotor [13]. Although the DC side of the grid-tied inverter's capacitor voltage can fluctuate within a given range, offering some inertia support, but it did not examine the inertia, damping, and synchronisation characteristics of the entire system, including the capacitor dynamic. In [14], it is demonstrated that the grid-tied new energy power generation system corresponds to the traditional power generation system, and it is demonstrated that the grid-tied inverter in the new energy grid-tied power generation system and the RSG in the traditional power generation system have equivalent dynamic models and similar physical mechanisms.

The inertia, damping, and synchronisation characteristics of the grid-tied converter system under voltage and current double closed-loop control are analysed, and an SSG model suitable for the analysis of the DC voltage time scale dynamic characteristics of the grid-tied converter system is proposed. The mechanism of a static synchronous compensator for reducing the power oscillation of the power grid is investigated in [15] by developing the SSG model. In order to maximise the converter's capacity to make up for grid imbalance power, the rapid power compensation (RPC) based frequency control approach is developed in [16], this strategy completely utilises the converter's idle capacity.

The mathematical demonstration showed that the RPC technique outperformed droop control and inertia control while maintaining the same converter capacity limit for both frequency deviation suppression and RoCoF suppression. The inertia and damping properties of the grid-tied energy storage system are examined in [17], [18] using the SSG model-based analytical technique under two alternative control schemes.

The grid-tied photovoltaic power generation system that is controlled by DC voltage droop control is the research object of this paper. It establishes the SSG mathematical model, uses the electrical torque analysis method to study the inertia, damping, and synchronisation characteristics of the photovoltaic grid-tied inverter side DC voltage droop control system, derives the system equivalent parameter expression, and elaborates on the function law of the parameter from the level of mathematical analysis and physical mechanism. The study demonstrated that some modifications to the traditional control techniques can also alter the system's inertia and damping characteristics and provided a theoretical framework for the design of key parameters for grid-tied solar power generating systems.

II. SYSTEM DESCRIPTION

A. THE STRUCTURE OF GRID-TIED PHOTOVOLTAIC POWER GENERATION SYSTEM

Fig 1 depicts the physical layout of the grid-connected solar power generation system with DC voltage droop control. The solar module, the DC/DC converter, and the grid-tied inverter are the key components of the system. The maximum power point tracking (MPPT) control for the DC/DC converter is used, and the frequency deviation for the inverter side is based on the voltage outer loop and inner current loop to construct the DC voltage droop control [14].

In Figure 1, U_{pv} and I_{pv} are the photovoltaic module's output voltage and current, respectively; C_1 and C_2 are the DC/DC converter's low- and high-voltage side capacitance, respective converter; U_{sk} (k = a, b, c) stands for the inverter's three-phase output voltage, and i_k (k = a, b, c) for the inverter's three-phase output current; U_{gk} (k = a, b, c) indicates the three phase voltage on the grid side; Lg represents the equivalent inductance on the grid side; U_{dc} represents the measured voltage of the DC capacitor; L_f represents the filter inductance; The real-time grid frequency is collected via a phase-locked loop, or PLL, and is denoted by the symbols 0 and g, which stand for the grid's rated and actual angular velocities, respectively. In the dq coordinate system, I_d and I_q stand for the current in the d axis and the current component in the q axis; Iq is the reference value for the current in the q axis; and U_{dc0} is the reference value for the voltage across the DC capacitor.

B. DC/DC CONVERTER CONTROL STRATEGY

The grid-tied inverter is incorporated into the grid after a boost DC/DC converter is used to enhance the output voltage of solar modules since it is necessary to do so in order for the modules to fulfil the grid voltage class criteria.

The grid-tied photovoltaic inverter must give the power system adequate inertia support during grid frequency fluctuations in order to promptly restore the system's power balance. In fact, the maximum output power of the photovoltaic system is much lower than the demand of the power grid in the context of the application of photovoltaic power grids, so the photovoltaic power generation system frequently outputs the maximum power, and the DC/DC converter adopts the MPPT control. Figure 2 depicts the DC/DC converter's control block diagram in the following manner.

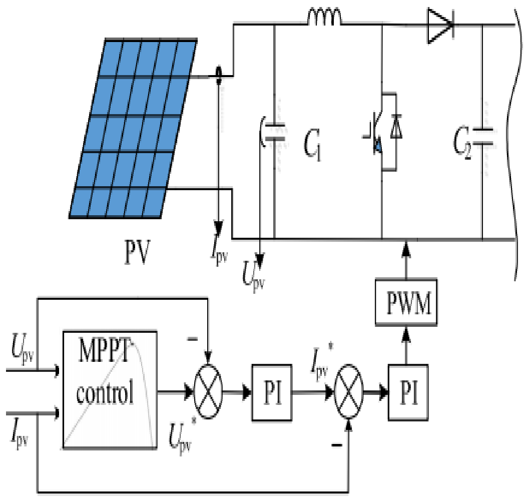

FIG 2. DC/DC CONVERTER CONTROL STRATEGY

In this diagram, PI stands for the proportional integral regulator, and U_{pv^*} and I_{pv^*} are the DC voltage and current reference signals that the photovoltaic module outputs, respectively. As seen in Figure 2, the boost DC/DC converter has a double closed-loop control system that consists of an inner current loop and an outer DC voltage loop. The dynamic behaviour of the inner current loop may be disregarded under the DC voltage time scale [14], allowing the solar module's output current to be represented as follows:

$$I^*_{pv} = I_{pv} = \left(K'_p + \frac{K'_i}{s}\right)\left(U^*_{pv} - U_{pv}\right) \qquad (1)$$

where K_p' and K_i' stand for the outer voltage loop's proportional and integral coefficients, respectively.

The most electricity is produced by photovoltaic modules. The output power of solar modules and DC/DC converters remains constant under the conditions of constant temperature and constant light intensity, allowing us to calculate:

$$\Delta P_{in} = 0 \qquad (2)$$

Where ΔP_{in} stands for the change in input power intensity.

C. THE INVERTER CONTROL STRATEGY

To achieve capacitor voltage stability, the grid-tied inverter uses a twin closed-loop control system with an outer DC voltage loop and an inner current loop. And rather, because the DC/DC converter produces the maximum power when a little disturbance occurs, the grid-connected inverter may still work with it. The frequency deviation is added to the standard double closed loops to provide the DC voltage droop control since the decoupling relationship is unable to adapt to variations in the grid frequency. The control block is displayed as follows in Fig 3.

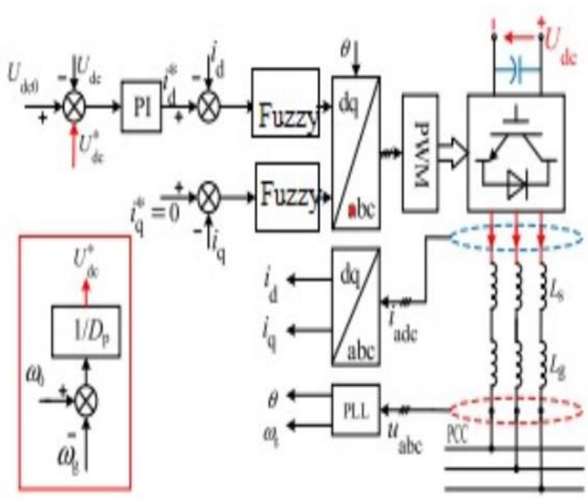

FIGURE 3. GRID-CONNECTED INVERTER CONTROL STRATEGY

By eliminating the dynamic behaviour of the inner current control loop and defining the control process in terms of the DC voltage control time scale as follows:

$$I^*_d = I_d = -\left(U^*_{dc} + U_{dc0} - U_{dc}\right)\left(K_p + \frac{K_i}{s}\right) \qquad (3)$$

Where U_{dc} denotes the DC voltage deviation and K_p and K_i the proportional and integral coefficients of the outer DC voltage loop, respectively.

The DC voltage deviation can be characterised as follows:

$$U^*_{dc} = \frac{1}{D_p}(\omega_g - \omega_0) \qquad (4)$$

Where D_p is the droop coefficient for DC voltage.

III. DYNAMIC CHARACTERISTICS ANALYSIS OF GRID-TIED PHOTOVOLTAIC POWER GENERATION SYSTEM

A. THE ORETICAL BASIS OF SYSTEM DYNAMIC CHARACTERISTIC ANALYSIS

The dynamic process of the grid-tied inverter under the DC voltage control time scale is represented as follows in [14], using the approach for analysing the static stability and instability mechanism of the RSG system:

$$\begin{cases} \frac{d\Delta\delta}{dt} = \Delta\omega \\ 2H\frac{d\Delta U_{dc}}{dt} = \Delta P_{in} - \Delta P_e \end{cases} \qquad (5)$$

Where δ is the power angle; ω is the angular frequency of the grid; Udc is the DC side capacitor voltage; Pin is the input

P_e is the output power; $H = CU^2_{dc}/S_B$ is the system's inertial time constant; and Pt is the power of the energy transfer medium [14].

$$\begin{cases} \frac{d\Delta\delta}{dt} = \Delta\omega \\ T_J\frac{d\Delta\omega}{dt} = -T_D\Delta\omega - T_S\Delta\delta \end{cases} \qquad (6)$$

Where TJ, TD and TS represent the equivalent inertia coefficient, damping coefficient and synchronization coefficient of the SSG model, respectively.

The aforementioned three factors are crucial physical ideas that describe an SSG system's dynamic properties according to classical stability theory. T_J, T_D, and T_S stand for the grid-tied inertia level, damping, and synchronisation capabilities of the inverter system, respectively. The electrical torque analysis approach based on the aforementioned principles may examine the stability of the system from the physical mechanism level [14].

B. SSG MODEL OF THE GENERATION SYSTEM

Before establishing the SSG model of the generation system, the transient process of the grid-tied inverter is simplified and analysed. This article simplifies the grid-tied inverter to a single-phase equivalent circuit shown in figure 4. Among them, we represent the amplitude of the grid-tied inverter excitation potential; δ represents the phase angle difference between the grid-tied inverter and the grid voltage; ug represents the terminal voltage amplitude of the grid-tied inverter.

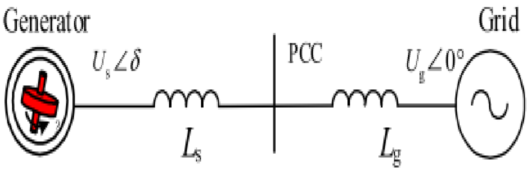

FIGURE 4. SINGLE-PHASE SIMPLIFIED CIRCUIT DIAGRAM OF THE INVERTER.

They are frequently orientated in accordance with the grid voltage for designing and assessing the grid-tied inverter system. Figure 5 illustrates the vector diagram of the grid-tied inverter in the dq coordinate system based on the grid voltage orientation under the assumption that the line impedance is neglected.

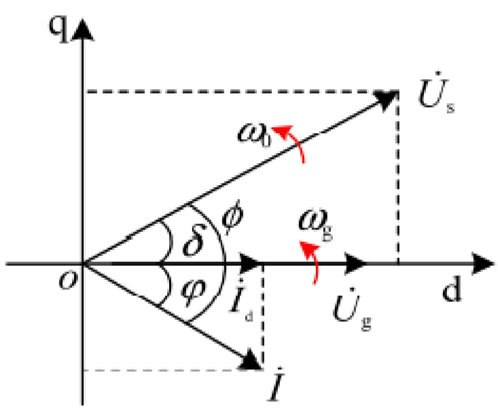

FIG 5. VECTOR ILLUSTRATION IN dq SYSTEM.

The expressions of the active power and active current produced by the three-phase grid-connected inverter may be computed from the phasor diagram of the grid-tied inverter system depicted in Figure 5.

$$P_e = \frac{3}{2}\frac{U_s U_g}{X}\sin\delta \tag{7}$$

$$I_d = \frac{U_s}{X}\sin\delta \tag{8}$$

Where X = ω_0L and X is the corresponding inductance attached to the grid.

In order to study the inertia, damping, and synchronisation characteristics of the grid-tied photovoltaic power generation systems, an SSG model of the grid-tied photovoltaic power generation system based on the DC voltage droop control is developed using the aforementioned research techniques as the theoretical basis. Incorporating (4) into (3), we have:

$$I_d = -\left[\frac{1}{D_p}(\omega_g - \omega_0) + U_{dc0} - U_{dc}\right]\left(K_p + \frac{K_i}{s}\right) \tag{9}$$

Combining (8) and (9), we have:

$$\frac{U_s}{X}\sin\delta = -\left[\frac{1}{D_p}(\omega_g - \omega_0) + U_{dc0} - U_{dc}\right]\left(K_p + \frac{K_i}{s}\right) \tag{10}$$

The incremental link between variables is often taken into account for the stability analysis in the case of the tiny disturbance, and (10) may be linearized to provide the following equation, i.e.

$$sK\Delta\delta = -(sK_p + K_i)\left(\frac{1}{D_p}\Delta\omega - \Delta U_{dc}\right) \tag{11}$$

Where δ0 is the power angle of the grid-tied inverter system in the steady state. And K is defined as:

$$K = \frac{3}{2}\frac{U_s}{X}\cos\delta_0$$

The linearization of (7) is:

$$\Delta P_e = \frac{3}{2}\frac{U_s U_g}{X}\cos\delta_0 \Delta\delta \tag{12}$$

When (2) and (12) are included into (5), the voltage increment equation is derived as follows:

$$\Delta U_{dc} = -\frac{3KU_g}{4Hs}\Delta\delta \tag{13}$$

Here may examine the inertia, damping, and grid-tied photovoltaic power generating system's properties using the conventional electrical torque approach. Eliminating the voltage increment by including (13) into the incremental equation (11) allows us to obtain the conventional electric torque equation in (6).

It is possible to obtain the SSG model of the grid-connected solar power generating system based on the DC voltage droop management as follows:

$$\begin{cases} \frac{d\Delta\delta}{dt} = \Delta\omega \\ 2H\frac{K_p}{D_p}\frac{d^2\Delta\omega}{dt^2} + \left(2HK + 2H\frac{K_i}{D_p}\right)\frac{d\Delta\omega}{dt} \\ = -\frac{3}{2}KU_gK_p\Delta\omega - \frac{3}{2}KU_gK_i\Delta\delta \end{cases} \quad (14)$$

The rate of change of frequency (RoCoF) and the grid frequency do not fluctuate much while the power grid is really in use. As a result, the quadratic component in (14) for the frequency change rate is a high-order infinitesimal quantity and may be disregarded, i.e.:

$$2H\left(K + \frac{K_i}{D_p}\right)\frac{d\Delta\omega}{dt} = -\frac{3}{2}KU_gK_p\Delta\omega - \frac{3}{2}KU_gK_i\Delta\delta \quad (15)$$

By comparing (14) and (6), it is simple to determine the system's equivalent inertia parameter T_J, equivalent damping parameter T_D, and equivalent synchronisation parameter T_S, i.e.:

$$\begin{cases} T_J = 2HK + 2\frac{HK_i}{D_p} \\ T_D = \frac{3}{2}KU_gK_p \\ T_S = \frac{3}{2}KU_gK_i \end{cases} \quad (16)$$

Inertia level, damping capacity, and synchronisation characteristics of the grid-tied photovoltaic power generation system operating under DC voltage droop control are shown in Figure 16 and are determined by the system's control parameters, structural parameters, and steady-state operating point parameters. The grid voltage level U_g, the DC capacitance C, and the equivalent inductance X make up the majority of the structure's parameters. The steady-state power angle 0, the DC side capacitance voltage U_{DC}, and the inverter equivalent internal potential U_s are the major steady-state operating point parameters.

The easiest and most adaptable way to get the solar power generating system to participate in the grid frequency adjustment when there is no energy storage device is to alter the inverter control settings. Here is an analysis of how control settings affect certain traits. The equivalent inertia coefficient T_J of the system is jointly influenced by the proportional integral coefficient K_i of the outer DC voltage control loop and the droop coefficient D_P of the system, as can be seen from equation (16). The larger the $1/D_P$ and K_i, the larger the T_J, and the stronger the inertia level of the system; equation illustrates how the system's equivalent inertia coefficient T_J is simultaneously controlled by the proportional integral coefficient Ki of the outer DC voltage control loop and the system's droop coefficient D_P (16), The system's inertia level is higher and the T_J is bigger with larger $1/D_P$ and K_i; and the higher the effect of synchronisation. It should be noticed that from (16), the system has its own inertia impact since the grid-tied photovoltaic power generating system's inertia coefficient has nothing to do with the control parameters.

Objectively speaking, the higher the coupling between the DC voltage and grid frequency is, the more the DC voltage drops, the more energy is released, and the more the system's inertia effect is, the lower the droop coefficient D_P, or the higher the $1/D_P$. The voltage deviation increases as the proportional coefficient K_p of the outer DC voltage control loop increases, and the damping varies in accordance with the deviation law. The damping increases in proportion to the deviation, increasing the damping effect of the system. To eliminate the deviation and achieve no static error control, the integral regulator is employed. Thus, the system's ability to synchronise is inversely proportional to the size of the proportional integral coefficient K_i of the DC voltage outer loop.

IV. RESULTS & DISCUSION

In order to validate the theoretical study of the inertia and damping properties of the grid-tied photovoltaic power generating system, this research used the MATLAB/Simulink simulation platform. Figure 1 depicts the simulation system's structure, and Table 1 lists the key simulation circuit parameters. The grid frequency decreases by 0.2 Hz when the simulation operating condition is set at t = 1 s.

TABLE 1. The parameters of the system.

parameter	value	parameter	value
PV side bus capacitance /μF	100	AC grid line-to-line voltage/V	380
DC bus capacitance /mF	5	*L* filter inductance /mH	3
DC filter inductance /mH	24	Grid frequency/Hz	50
DC side voltage /V	750	Line reactance /mH	0.5

A. ANALYSIS OF THE DROOP MECHANISM

The grid-tied solar power generating system with or without droop loop was simulated in order to represent the impact of adding the frequency variation to create the DC voltage droop on the system, as shown in Fig 6.

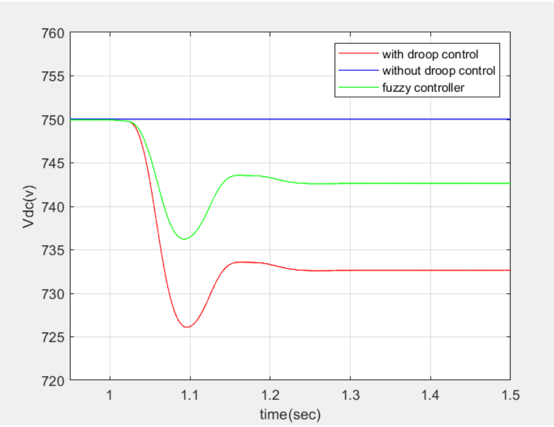

Fig 6: Vdc, INERTIA OF THE SYSTEM AS A RESULT OF DIFFERENT PARAMETER CHANGES.

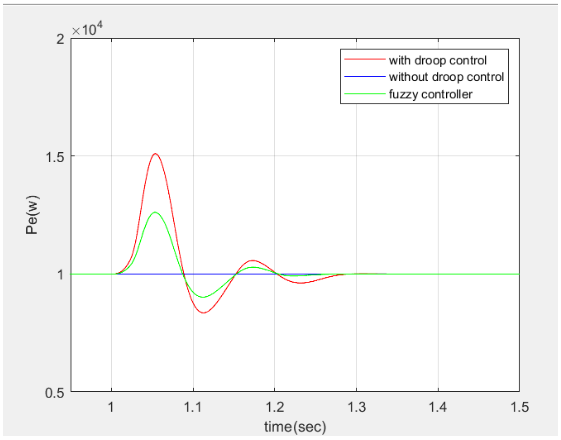

Fig 7: Pe, EFFECTS OF VARIOUS PARAMETER MODIFICATIONS ON THE SYSTEM'S INERTIA.

Grid-tied solar power generating systems with or without droop loops were simulated in order to represent the impact of adding the frequency variation to create the DC voltage droop on the system, as shown in Fig 7.

When the system doesn't have droop loop, the converter doesn't respond to change in grid frequency and it keeps the constant power output and DC side voltage. But when droop loop is considered, the converter responds to change in grid frequency. So, the capacitor voltage drops to release the energy, in order to produce the system power.

B. ANALYSIS OF INERTIA CHARACTERISTICS

In this, the grid-tied photovoltaic power generation system is controlled by DC voltage droop control, where K_P and K_i remains unchanged and the D_P changes which gives influence on inertia characteristics, which is shown in Fig 8 and Fig 9

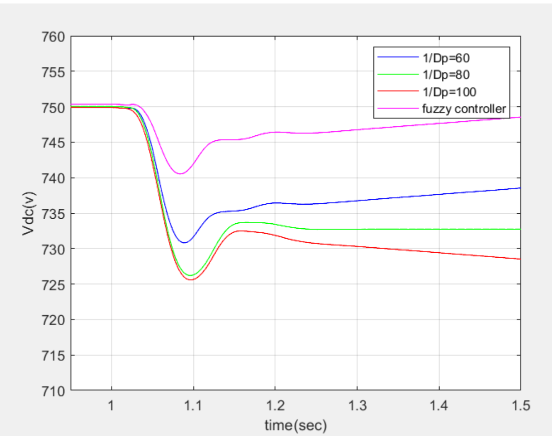

FIGURE 8. INFLUENCE OF DROOP COEFFICIENT D_P ON DC VOLTAGE.

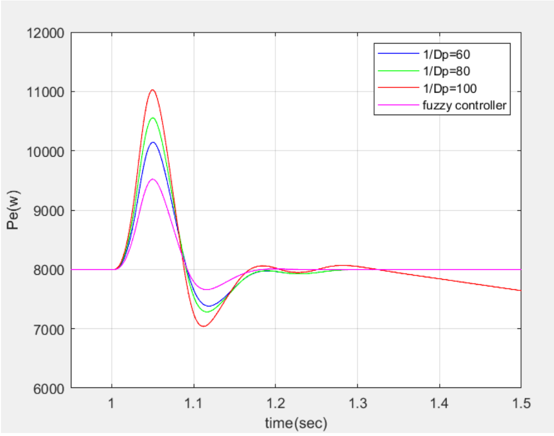

FIGURE 9. INFLUENCE OF DROOP COEFFICIENT D_P ON SYSTEM POWER.

From simulation results we can see that, as the D_P decreases, $\frac{1}{D_P}$ increases and the system exhibits the stronger inertia characteristics, which is consistent with the conclusion drawn by (16) and (19)

C. ANALYSIS OF DAMPING CHARACTERISTICS

In this, the grid-tied photovoltaic power generation system is controlled by DC voltage droop control, where D_P and K_i remains unchanged and the K_P changes which give influence on damping characteristics, which is shown in Fig 10 and Fig 11
From simulation results we can see that, as the K_P increases, the system exhibits the stronger damping characteristics, which is consistent with the conclusion drawn by (16) and (19)

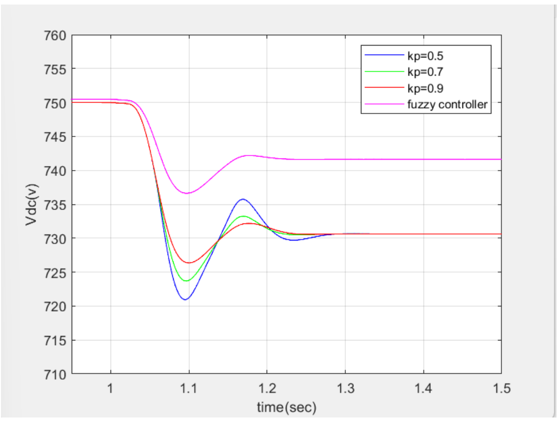

FIGURE 10. THE INFLUENCE OF P CONTROLLER ON DC VOLTAGE.

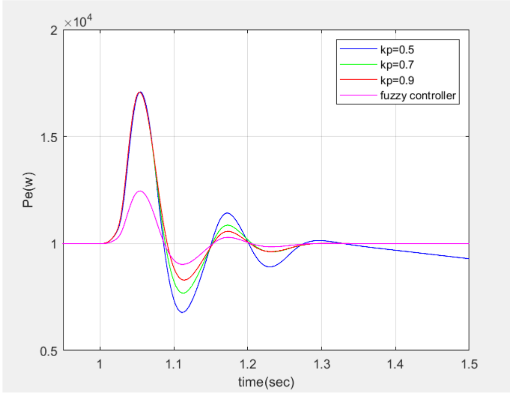

FIGURE 11. THE INFLUENCE OF P CONTROLLER ON SYSTEM POWER.

D. ANALYSIS OF SYNCHRONIZATION CHARACTERISTICS

In this, the grid-tied photovoltaic power generation system is controlled by DC voltage droop control, where D_P and K_P remains unchanged and the K_i changes which give influence on damping characteristics, which is shown in Fig 12 and Fig 13

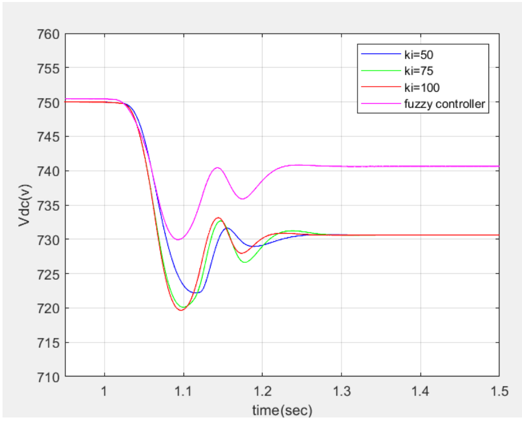

FIGURE 12. THE INFLUENCE OF I CONTROLLER ON DC VOLTAGE.

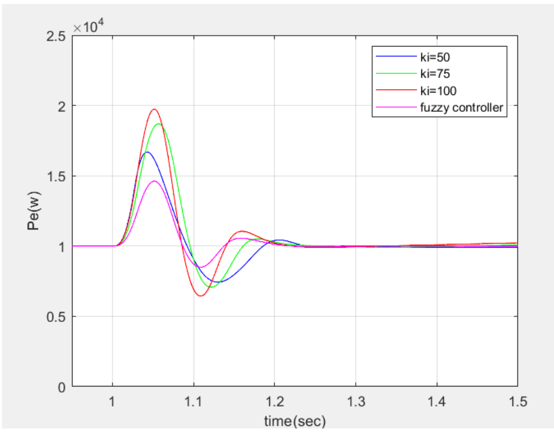

FIGURE 13. THE INFLUENCE OF I CONTROLLER ON SYSTEM POWER.

From simulation results we can see that, as the K_i increases, the system exhibits the stronger synchronization characteristics and which also shows some effect on inertia characteristics, which is consistent with the conclusion drawn by (16) and (19) According to the above all simulation results, fuzzy logic controllers provide better system inertia. When changing damping coefficients, fuzzy logic controllers give better performance than existing PI controllers.

V. CONCLUSION

The novel fuzzy logic controller topology proposed for grid-tied photovoltaic power generation system with DC voltage droop control is a promising approach for efficient and stable operation of the system. The controller design takes into account the dynamic behaviour of the system and effectively balances the power between the photovoltaic array and the grid. The use of fuzzy logic enables the controller to adapt to different operating conditions and effectively track the maximum power point of the photovoltaic array. The inclusion of DC voltage droop control further enhances the stability of the system, ensuring smooth power transfer and avoiding potential instability issues. Overall, the proposed fuzzy logic controller topology offers a robust and efficient solution for grid-tied photovoltaic power generation systems, contributing to the development of renewable energy sources and reducing our dependence on fossil fuels. Further research can be done to validate the proposed approach and explore its potential for other applications.

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