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DC-BUS VOLTAGE CONTROL OF A GRID-CONNECTED PHOTOVOLTAIC INVERTER USING A PI–FUZZY CONTROLLER

Tran Minh Duc

Institute of Engineering and Technology **-** *Thu Dau Mot University, Ho Chi Minh City, Vietnam*

Email: *tmduc147@gmail.com*

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ABSTRACT

This paper presents an adaptive DC-bus voltage control scheme using a proportional-integral fuzzy (PI–Fuzzy) controller for a three-phase grid-tied photovoltaic (PV) inverter operating under varying solar irradiance conditions. The proposed control strategy is implemented in the outer DC-bus voltage control loop, where a fuzzy logic controller is employed to adaptively tune the PI controller gains based on the DC-bus voltage error and its variation, aiming to improve dynamic performance and robustness against power fluctuations. A mathematical model of the grid-connected PV inverter system is developed in the synchronous reference frame to analyze the DC-bus dynamics and control behavior. The effectiveness of the proposed PI Fuzzy controller is validated through MATLAB/Simulink simulations under different irradiance levels and compared with a conventional fixed-parameter PI controller. Simulation results demonstrate that the proposed approach significantly reduces DC-bus voltage overshoot, shortens the settling time, and suppresses steady-state voltage oscillations, confirming its suitability for DC-bus voltage stabilization in three-phase grid-tied PV inverter systems.

Keywords: DC-bus voltage, grid-tied photovoltaic inverter, PI–Fuzzy control, fuzzy logic controller, voltage stability.

1. INTRODUCTION

In recent years, grid-connected photovoltaic systems (PVS) have been increasingly integrated into distributed power systems to meet growing energy demands and reduce carbon emissions. In three-phase grid-connected PVS, the grid-connected inverter (GCI) plays a key role in converting DC power into AC power and injecting it into the utility grid. In this structure, the DC-bus voltage (Vdc) acts as an intermediate energy buffer, ensuring power balance between the PV array and the grid while maintaining stable operating conditions for the inverter.

However, due to the inherent intermittency of solar irradiance and temperature variations, the output power of the PV array frequently fluctuates, leading to DC-bus voltage oscillations. These fluctuations can degrade power quality, reduce inverter efficiency, and adversely affect the reliability of power electronic devices. Therefore, stabilizing the DC-bus voltage is a critical issue in the control of grid-connected PV systems.

Conventionally, proportional–integral (PI) controllers are widely used for DC-bus voltage regulation due to their simple structure and ease of implementation. Nevertheless, under rapid PV power variations and nonlinear operating conditions, fixed-gain PI controllers often exhibit poor dynamic performance, including large overshoot and long settling time. To overcome these limitations, intelligent control approaches such as PI–Fuzzy controllers have been proposed to enhance adaptability and improve DC-bus voltage stability. In this paper, a PI–

Fuzzy control strategy is developed for DC-bus voltage regulation in a three-phase grid-connected PV inverter and its effectiveness is evaluated through simulation studies. Based on the above discussion, this paper proposes the following approach.

Although conventional PI controllers are widely used for DC-bus voltage regulation, their performance strongly depends on properly tuned parameters and may degrade under rapidly changing irradiance conditions. To overcome these limitations, intelligent control methods such as fuzzy logic control have been investigated to enhance controller adaptability. In this paper, a PI–Fuzzy control strategy is proposed to improve DC-bus voltage stability in a three-phase grid-connected photovoltaic inverter, where the fuzzy logic controller dynamically adjusts the PI gains based on the DC-bus voltage error and its variation. The main contributions of this work include the development of a mathematical model of the grid-connected PV inverter in the synchronous reference frame, the design of a PI–Fuzzy controller for adaptive DC-bus voltage regulation, and the evaluation of the proposed method through MATLAB/Simulink simulations under different irradiance conditions.

1.1. Overview of the Research Problem

The DC-bus voltage is a key variable in grid-connected photovoltaic (PV) inverter systems, acting as an energy buffer between the inherently fluctuating PV source and the utility grid. Inadequate regulation of the DC-bus voltage may result in large voltage ripple, increased stress on power electronic components, and degradation of inverter performance and reliability. Several studies have emphasized the challenges associated with the integration of renewable energy sources into modern power systems. It is shown in [1] that advanced power electronic converters and robust control strategies are essential to ensure stable operation of smart grids with high renewable penetration. However, the DC-bus voltage dynamics of grid-connected PV inverters are not specifically addressed.

Grid interaction and protection issues have been investigated in [2], where anti-islanding methods for PV systems are reviewed. Although inverter behavior under grid disturbances is discussed, DC-bus voltage regulation under fast irradiance variations is not considered. The limitations of conventional PI control under abnormal grid conditions are further highlighted in [3], but without focusing on DC-bus voltage control. General control architectures for renewable energy systems are presented in [4], stressing the importance of power electronic converters and their control. Nevertheless, detailed modeling and control of DC-bus voltage in PV inverters are beyond the scope of that work.

Classical PI-based DC-link voltage control has been studied extensively. In [5], a PI controller is designed based on the mathematical model of a DC–DC boost converter–inverter system, showing satisfactory steady-state performance. A systematic approach for DC-bus control design is proposed in [6], while the influence of inverter control strategies on voltage stability in weak grids is analyzed in [7]. More recent studies have also focused on improving DC-bus voltage stability in renewable energy systems. In [8], a modified incremental conductance algorithm combined with inverter control is proposed to simultaneously achieve maximum power extraction and DC-bus voltage regulation in a grid-connected PV system. Despite their effectiveness, most of these approaches rely on fixed controller gains and exhibit limited robustness under rapidly changing operating conditions.

To enhance dynamic performance, intelligent control techniques have been introduced. A Fuzzy–PI controller for DC-link voltage stabilization is reported in [9], demonstrating smoother voltage response compared to conventional PI control. An adaptive PI–Fuzzy controller with an anti-windup mechanism is proposed in [10], achieving faster transient response and improved disturbance rejection. Fuzzy-based controllers have also been applied in MPPT-related studies. In [11], a fuzzy-PID controller significantly reduces DC-bus voltage overshoot during MPPT operation, while comparative investigations in [12] and [13] confirm that fuzzy logic improves robustness and dynamic behavior. In addition, the coordinated operation of DC microgrids with variable renewable generation and energy storage systems has been investigated in [14], highlighting the importance of stable DC-bus regulation for maintaining system reliability and power balance. Similar DC–AC boost inverter control strategies have also been reported in [15], where advanced inverter control techniques are employed to improve voltage conversion performance and dynamic response. However, these studies mainly focus on MPPT performance rather than DC-bus voltage regulation during grid-connected operation. Therefore, an adaptive and robust DC-bus voltage control strategy capable of improving transient response under varying irradiance conditions is still required. This work addresses this gap by proposing an adaptive PI–Fuzzy controller for DC-bus voltage regulation in a three-phase grid-connected PV inverter system

1.2. Contributions of the Paper

The main contribution of this paper is the development and evaluation of an adaptive DC-bus voltage control strategy for a three-phase grid-connected photovoltaic (PV) system. A complete mathematical model of the PV system, including the PV array, DC–DC boost converter, DC-bus capacitor, and grid-connected inverter, is established in the synchronous dq reference frame to analyze the DC-bus voltage dynamics. Based on this model, a PI–Fuzzy controller is proposed for DC-bus voltage regulation, in which the proportional gain is adaptively adjusted using fuzzy logic inference while the integral gain is kept constant, and an anti-windup mechanism is incorporated to enhance stability. The performance of the proposed controller is evaluated through MATLAB/Simulink simulations under varying irradiance conditions and compared with a conventional PI controller. Simulation results demonstrate that the proposed PI–Fuzzy controller effectively reduces voltage overshoot, shortens settling time, and improves DC-bus voltage stability, thereby enhancing the dynamic performance of the grid-connected PV system.

2. SYSTEM DESCRIPTION AND MODELLING

2.1. Block Diagram of the Grid-Connected PV System

The system investigated in this paper is a three-phase grid-connected photovoltaic (PV) inverter with a two-stage structure, consisting of a DC–DC conversion stage, a DC-bus capacitor, and a three-phase inverter on the AC side. The overall configuration of the system is illustrated in Fig. 1.

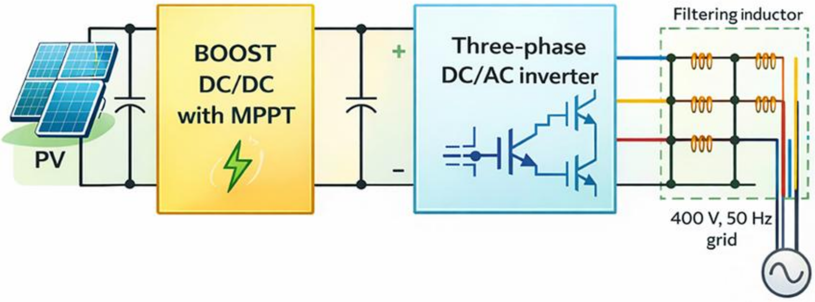

Fig. 1. Block diagram of a grid-tied PV system

The PV source supplies DC power to the system through the intermediate DC-bus. The three-phase inverter converts the DC power into AC power and injects synchronized current into the utility grid through an output filter. In this structure, the DC-bus acts as an energy storage and balancing stage, ensuring instantaneous power matching between the PV source and the power exchanged with the grid.

Due to the nonlinear characteristics of the PV source and the rapid variations in solar irradiance, the DC-bus voltage tends to exhibit significant fluctuations if it is not properly regulated. Therefore, stabilizing the DC-bus voltage is a key requirement to ensure reliable operation and high power quality of the grid-connected inverter system.

2.2. Overall Control Structure of the System

The overall control structure of the system is designed based on a cascade control scheme, consisting of an outer DC-bus voltage control loop and an inner current control loop implemented in the synchronous dq reference frame, as shown in Fig. 2.

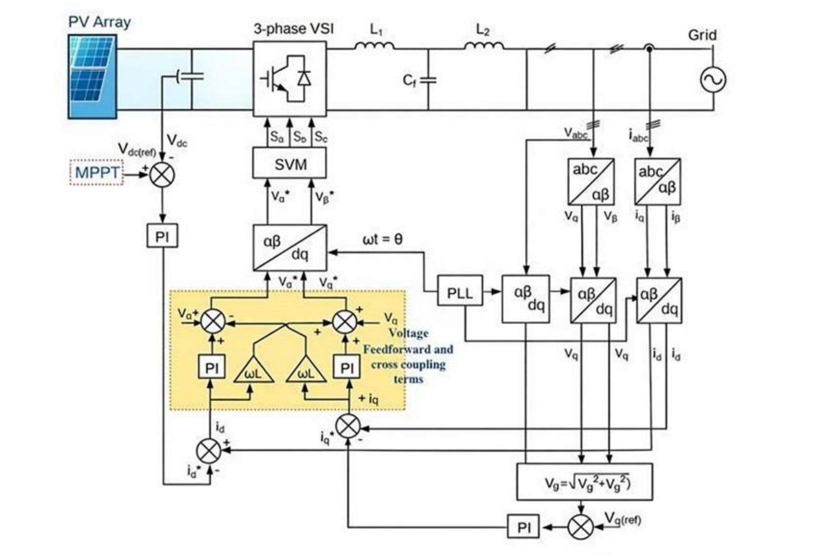

Fig. 2. Overall control structure of the three-phase grid-connected PV inverter

The outer DC-bus voltage control loop is responsible for maintaining the DC voltage at its reference value by regulating the active power exchanged between the inverter and the utility grid. The output of this control loop is the reference d-axis current i_d^* which is fed into the inner current control loop.

The inner dq current control loop ensures that the injected grid current has the appropriate magnitude and phase with respect to the grid voltage, while providing a fast dynamic response to the commands generated by the DC-bus voltage control loop. The separation of the voltage and current control loops enhances the overall stability and control performance of the system.

In this study, particular emphasis is placed on the DC-bus voltage control loop, as it plays a decisive role in determining the stability and dynamic response of the grid-connected PV inverter. The mathematical model and control strategies for DC-bus voltage regulation are presented in detail in the following section.

3. DC-BUS VOLTAGE CONTROL STRATEGY

3.1. Mathematical Model of the DC-Bus Voltage

The DC-bus voltage in a grid-connected PV inverter plays a crucial role in ensuring power balance between the PV source and the utility grid. In order to develop appropriate control strategies, it is necessary to establish a mathematical foundation that describes the dynamic behavior of the DC-bus voltage, which serves as the basis for the design of control schemes such as PI and PI–Fuzzy controllers [3]. This section presents the governing equations of power balance on the DC-bus capacitor, the expression of AC-side power in the synchronous dq reference frame, and the common assumptions adopted in the analysis. These results are directly utilized in the development of the mathematical model and in the parameter design of the control strategies discussed in the subsequent sections.

In this paper, the focus is placed on the DC-bus voltage control loop, whose block diagram is illustrated in Fig. 3. The capacitor C represents the DC-bus capacitor, which acts as an energy storage element to balance the power flow between the DC side and the AC side of the grid-connected inverter.

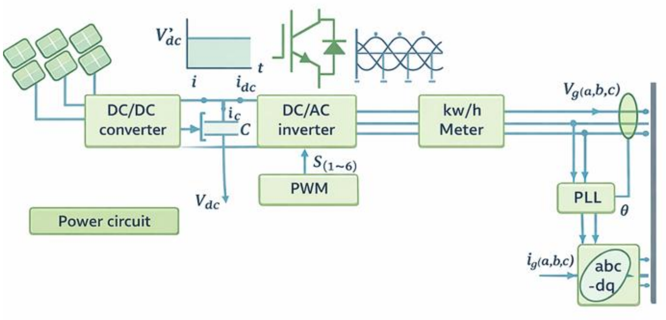

Fig. 3. Block diagram of the DC-bus voltage controller

The quantities in the block diagram are defined as follows:

$V_{g(a,b,c)}$: three-phase grid voltage in the natural reference frame.

$I_{g(a,b,c)}$: three-phase grid current in the natural reference frame.

V_{dc}: DC-bus voltage.

V_{dc}^{*}: reference value of the DC-bus voltage.

I_{dc}: current flowing from the DC-bus to supply the DC/AC converter.

I_c: current flowing through the DC-bus capacitor.

i: current drawn from or injected by the PV panels.

$i_{g(d,q)}^{*}$: reference grid current in the synchronous reference frame, including two components, i_{gd}^{*} and i_{gq}^{*}

The active power on the AC side in the dq reference frame is expressed as:

$$P_{AC} = \frac{3}{2}(V_d i_d + V_q i_q) \tag{1}$$

where V_d and V_q are the d-axis and q-axis components of the grid voltage,

i_d and i_q are the corresponding grid current components in the synchronous reference frame.

With the reference frame selected such that $V_q = 0$, we obtain:

$$P_{AC} = \frac{3}{2} V_{gm} i_{gd} \tag{2}$$

Where V_{gm} is the amplitude of the grid voltage, i_{gd} is the d-axis component of the grid current.

The DC-side power of the inverter is determined as:

$$P_{DC} = V_{dc} i_{dc}^{mean} \tag{3}$$

By neglecting power losses, it can be assumed that

$V_{dc} \approx V_{dc}^{*}$. Therefore, by comparing (2) and (3) (i.e., $P_{AC} \approx P_{DC}$), we obtain:

$$i_{dc}^{mean} \approx \frac{3}{2}\frac{V_{gm}}{V_{dc}^{*}} i_{gd}^{*} \tag{4}$$

where, $G = \frac{i_{dc}^{mean}}{i_{gd}^{*}}$, is a pure gain coefficient.

Thus, the current control loop (inner loop) can be represented as a pure gain G inside the outer DC-bus voltage control loop, under the assumption that the current loop is much faster than the voltage loop. This assumption significantly simplifies the analysis and design of the PI controller. This forms the common mathematical foundation for developing DC-bus voltage control strategies based on PI or Fuzzy-PI controllers in the subsequent sections.

3.2. PI Controller for DC-Bus Voltage Stabilization

In a three-phase grid-connected inverter system, the DC-bus voltage must be maintained at a stable level to ensure power balance between the DC side and the AC side. A commonly used and simple approach is to employ a PI controller in the DC-bus voltage control loop.

Based on the mathematical model of the DC-bus presented in Section 3.1, the DC-bus voltage is regulated through the active power exchanged between the inverter and the grid. By neglecting power losses, the power balance equation at the DC-bus can be expressed as:

$$C_{DC}\frac{dV_{DC}}{dt} = \frac{P_{in} - P_{out}}{V_{DC}} \tag{5}$$

where P_{out} is indirectly controlled through the d-axis current i_d of the inverter in the dq reference frame. Therefore, the DC-bus voltage control loop essentially generates the reference value for the d-axis current i_d^{*}

The DC-bus voltage error is defined as follows:

$$e(t) = V_{dc}^{*} - V_{dc}(t), \tag{6}$$

where V_{dc}^{*} is the reference value of the DC-bus voltage.

The PI controller is used to process the voltage error and generate the control signal for the d-axis current:

$$i_d^{*}(t) = K_p e_{dc}(t) + K_i \int e_{dc}(t)dt \tag{7}$$

where:

K_p : proportional gain

K_i : integral gain

The obtained reference current i_d^{*} is then fed into the inner current control loop of the inverter to regulate the active power exchanged with the grid, thereby stabilizing the DC-bus voltage.

The block diagram of the DC-bus voltage control loop using the PI controller is illustrated in Fig. 4.

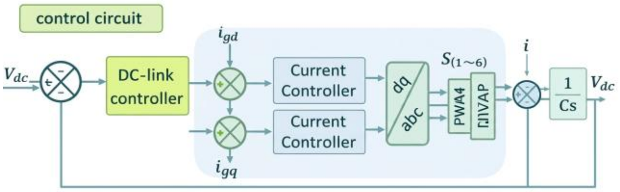

Fig. 4. Block diagram of the DC-bus voltage control loop using the PI controller

Remarks and limitations of the PI controller

Although the PI controller has a simple structure and is easy to implement, its control performance strongly depends on the proper selection of the gains K_p , K_i. In grid-connected PV inverter systems, the input voltage and power vary nonlinearly with solar irradiance and ambient temperature. Therefore, with fixed PI parameters, the system often encounters the following issues:

- DC-bus voltage oscillations under rapid changes in solar irradiance
- Long settling time
- Large overshoot
- Poor disturbance rejection and low adaptability

These limitations indicate that the conventional PI controller does not adequately meet the DC-bus voltage stabilization requirements under highly variable operating conditions of grid-connected PV systems. Consequently, in this study, an adaptive PI–Fuzzy controller is proposed to enhance control performance. The details of the proposed controller are presented in Section 3.3.

3.3. Proposed PI–Fuzzy Controller for DC-Bus Voltage Stabilization

As analyzed in Section 3.2, the conventional PI controller with fixed parameters has difficulty ensuring satisfactory DC-bus voltage control performance when the PV system operates under conditions of rapidly varying irradiance and input power. To overcome this limitation, an adaptive PI–Fuzzy controller is proposed in this study for the DC-bus voltage control loop.

The main idea of the PI–Fuzzy approach is to employ fuzzy logic to adjust the PI controller parameters K_p , K_i online based on the instantaneous state of the DC-bus voltage error. As a result, the controller exhibits improved adaptability to the nonlinear characteristics and parameter variations of the system.

3.3.1. Structure of the PI–Fuzzy Controller

The overall structure of the PI–Fuzzy controller for DC-bus voltage regulation is illustrated in Fig. 5.

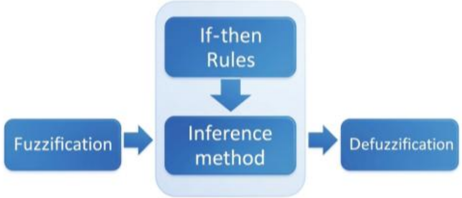

Fig. 5. Structure of Fuzzy logic control system

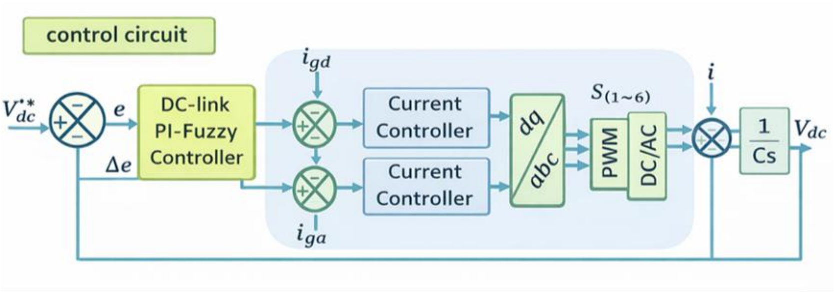

Fig. 6. Block diagram of the closed-loop DC-bus voltage control system using the PI–Fuzzy controller

The controller consists of two main components:

- Fuzzy Logic Controller – FLC
- Conventional PI controller

Unlike the standard PI controller, in the PI–Fuzzy controller the gains K_p, K_i are not constant but are dynamically adjusted through the outputs of the fuzzy inference system. The FLC generates two correction signals for ΔK_p and ΔK_i. These signals are added to the initial PI gains to form the adaptive control gains:

$$K_{p,new} = K_p + \Delta K_p \tag{8}$$

$$K_{i,new} = K_i + \Delta K_i \tag{9}$$

The final control signal is computed using the modified PI control law:

$$u(t) = K_{p,new}(t) \cdot e(t) + K_{i,new}(t) \cdot \sum_{\tau=0}^{t} e(\tau)T_s \tag{10}$$

$u(t)$: output control signal of the PI–Fuzzy controller (voltage or current reference supplied to the inverter/boost converter).

$K_{p,new}(t)$: proportional gain after fuzzy adjustment, which varies according to the error state to enhance the dynamic response speed.

$K_{i,new}(t)$: integral gain after fuzzy adjustment. It is adaptively varied to reduce the steady-state error and suppress oscillations.

$e(t) = V_{dc}^* - V_{dc}(t)$: DC-bus voltage error at time *t*.

$\sum_{\tau=0}^{t} e(\tau)T_s$: accumulated error over time (integral term), where T_s is the sampling period.

The control signal consists of two components:

- Proportional component $K_{p,new}(t) \cdot e(t)$: enables a fast system response when a voltage error occurs.
- Integral component $K_{i,new}(t) \cdot \sum_{\tau=0}^{t} e(\tau)T_s$: ensures that the DC-bus voltage reaches its reference value with zero steady-state error.

Since $K_{p,new}(t)$ and $K_{i,new}(t)$ are continuously adjusted by the fuzzy logic controller, the proposed PI–Fuzzy controller exhibits superior adaptability compared to the fixed-gain PI controller, particularly under conditions of PV power fluctuations or grid disturbances.

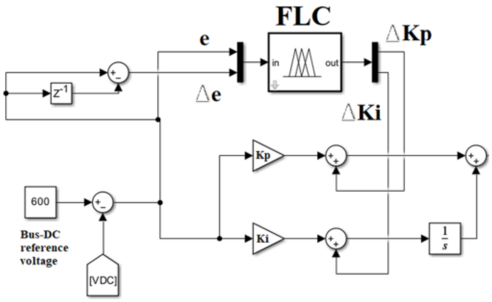

Fig. 7. Simulink model of the proposed PI–Fuzzy controller for DC-bus voltage regulation

3.3.2. Membership functions and fuzzy inference rules

The universe of discourse of the fuzzy variables is divided into seven fuzzy sets:

{NB, NM, NS, ZO, PS, PM, PB}

corresponding to:

NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZO (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big). The fuzzy inference rules are constructed based on the tuning experience of PI controllers and the dynamic characteristics of the DC-bus system. The main design principles of the fuzzy rules can be summarized as follows:

- When $|e|$ is large:
  - K_p should be increased to improve the dynamic response speed
  - K_i should be reduced or kept small to limit overshoot.
- When $|e|$ is small: Both K_p and K_i are increased to improve steady-state accuracy.
- When $|\Delta e|$ is large: The controller gains are adjusted cautiously to avoid oscillations.

The fuzzy rule tables for ΔK_p, ΔK_i are presented in Table 1.

Table 1. PI-fuzzy control rules for ΔK_p and ΔK_i

e(t)/Δe(t)	NB	NM	NS	ZO	PS	PM	PB
NB	NB,NM	NB,NS	NM,NS	NM,ZO	NS,ZO	NS,PS	ZO,PM
NM	NB,NS	NM,NS	NM,ZO	NS,ZO	NS,PS	ZO,PS	ZO,PM
NS	NM,NS	NM,ZO	NS,ZO	NS,PS	ZO,PS	ZO,PM	PM,PM
ZO	NM,ZO	NS,ZO	NS,PS	ZO,ZO	PS,PS	PM,ZO	PM,ZO
PS	NS,ZO	NS,PS	ZO,PS	PS,PS	PS,ZO	PM,ZO	PM,NS
PM	NS,PS	ZO,PS	ZO,PM	PM,ZO	PM,ZO	PM,NS	PB,NM
PB	ZO,PM	ZO,PM	PM,PM	PM,ZO	PM,NS	PB,NM	PB,NB

Notation:

Row = $e(t)$ (error)

Columns = $\Delta e(t)$ (change of error)

Each cell: $(\Delta K_p, \Delta K_i)$

The Mamdani fuzzy inference method is employed, combined with the centroid defuzzification method to determine the output values.

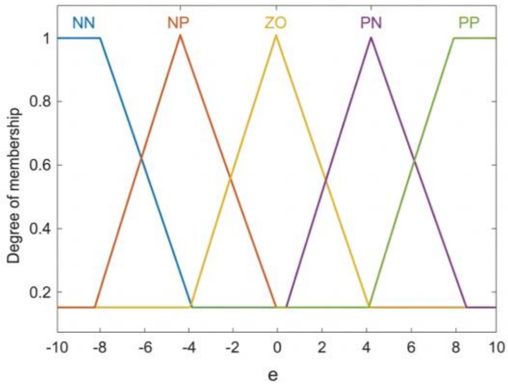

Fig. 8. e membership function

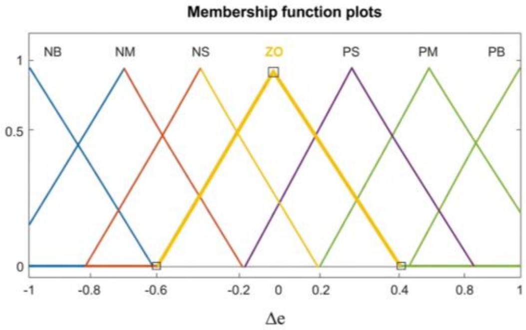

Fig. 9. Δe membership function

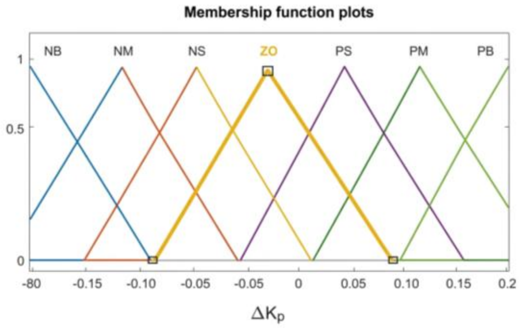

Fig. 10. ΔK_p membership function

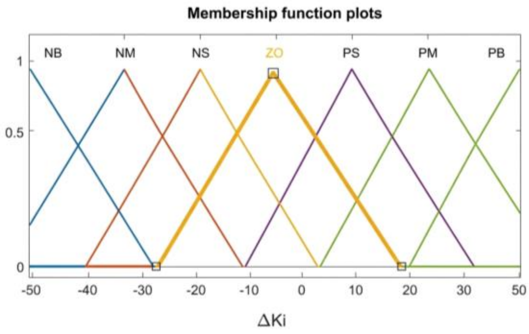

Fig. 11. ΔK_i membership function

4. SIMULATION RESULTS

4.1. Simulation Model Description

To evaluate the dynamic performance of the proposed PI-Fuzzy controller for the DC-Bus voltage control loop, simulation studies are carried out to compare its performance with that of the conventional PI controller used in the thesis. The simulations are conducted in the MATLAB/Simulink environment for the three-phase grid-connected PV inverter system modeled in the previous sections.

The simulation scenarios are designed based on variations in solar irradiance, reflecting realistic operating conditions of the PV system. Specifically, the irradiance is changed in a step manner from its rated value to a lower level, while the ambient temperature is kept constant. The change in the input power from the PV source causes a temporary power imbalance at the DC-Bus, which leads to DC-Bus voltage fluctuations and enables the evaluation of the dynamic response of the controllers.

In this study, two control strategies are compared, namely the conventional PI controller with fixed parameters and the proposed PI-Fuzzy controller. The main simulation parameters of the system, including the PV source, DC-Bus capacitor, inverter, and grid parameters, are summarized in Table 2.

Table 2. Grid-connected PV system parameters

Component	*Parameter*	*Value*
Grid	Line voltage	380 V
	Grid frequency	50 Hz
PV Module	Module type	Bosch NA42117
	Rated power	250 W per module
	Number of modules	470 modules (117.5 kW)
	Open-circuit voltage	Voc = 37.9 V
	Voltage at maximum power point	Vmp = 30.31 V
	Short-circuit current	Isc = 8.72 A
	Current at maximum power point	Imp = 8.25 A
Boost DC/DC	Input voltage	Vin = 250 – 350 V
	Output voltage	Vout = 600 V
	Inductance	C = 3227 μF
	Capacitance	L = 1.45 mH
	Switching frequency	f_s = 5 kHz
Inverter	Inverter topology	Two-Stage VSI with Boost Converter
LCL filter	DC output voltage	V_{DC} = 400 V
	DC-bus capacitor	$C_b = 6.577 \times 10^{-3}$ F
	Maximum current	Imax = 642.824 A
	Inverter-side inductor	$L_1 = 5{,}1 \times 10^{-4}$ H
	Filter capacitor	$C_f = 3{,}289 \times 10^{-4}$ F
	Grid-side inductor	$L2 = 1.244 \times 10^{-4}$ H
	Resonant frequency	f_{res} = 995.203 Hz

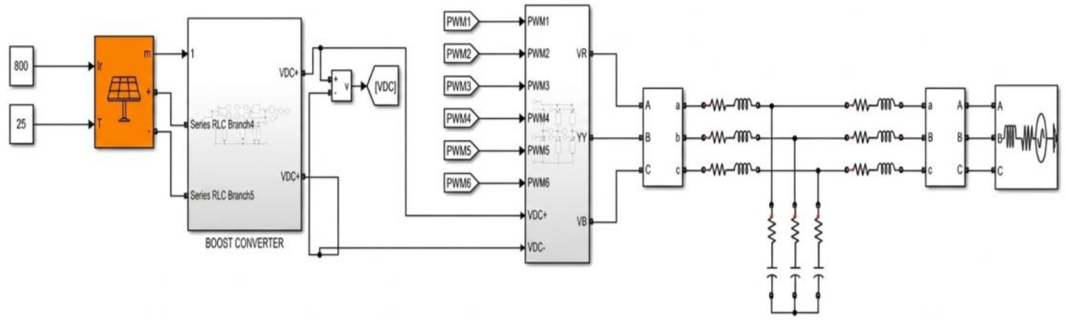

Fig. 12. Overall simulation model of the grid-connected photovoltaic (PV) system

4.2. Simulation results

The initial value of solar irradiance is set to 800 W/m².

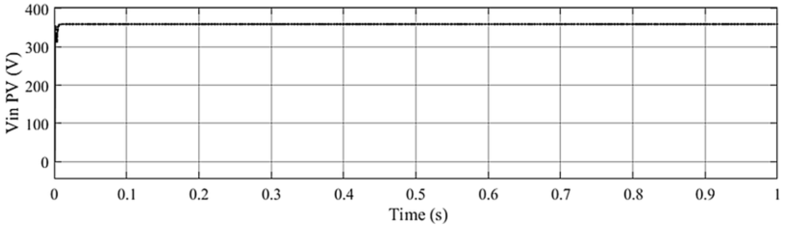

Fig. 13. Input voltage of the photovoltaic (PV) array at an irradiance level of 800 W/m²

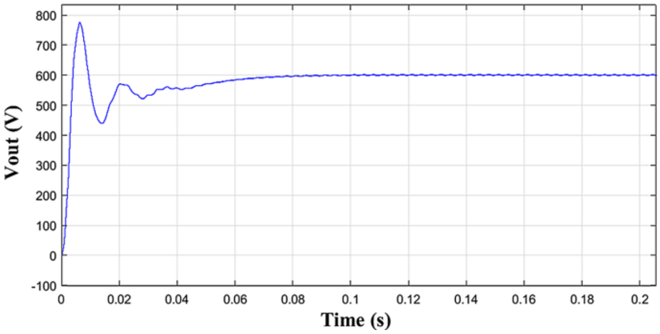

Fig. 14. DC-Bus voltage at an irradiance level of 800 W/m² using the PI controller

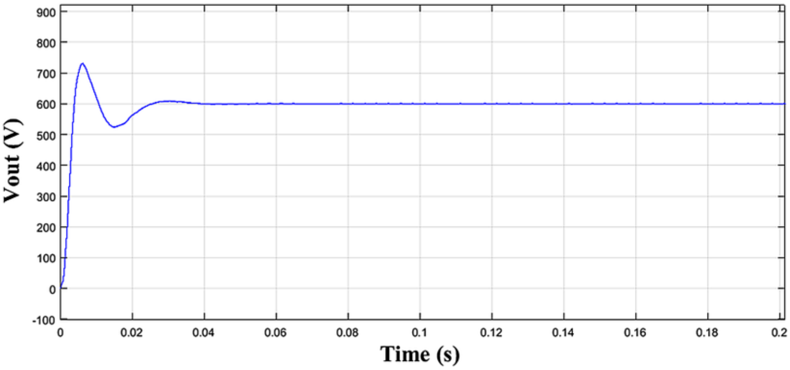

Fig. 15. DC-Bus voltage at an irradiance level of 800 W/m² using the PI-Fuzzy controller

Dynamic Response of DC-Bus Voltage at 800 W/m²

Figures 14 and 15 illustrate the DC-bus voltage responses of the grid-connected PV system at an irradiance level of 800 W/m² using the conventional PI controller and the proposed PI-Fuzzy controller, respectively.

With the PI controller, the DC-bus voltage exhibits a relatively large overshoot, reaching approximately 770–790 V, which corresponds to an overshoot of about 30% compared to the reference value of 600 V. In addition, noticeable oscillations appear during the transient period, and the voltage settles to its steady-state value after approximately 0.03 s.

In contrast, when the PI-Fuzzy controller is applied, the DC-bus voltage response is significantly improved. The peak overshoot is reduced to around 740–760 V, and the oscillation amplitude during the transient state is noticeably smaller. Moreover, the settling time is shortened to approximately 0.02 s, indicating a faster and smoother dynamic response.

These results demonstrate that the PI-Fuzzy controller provides better damping characteristics and improved transient performance compared to the conventional PI controller under medium irradiance conditions.

The initial value of solar irradiance is set to 1000 W/m².

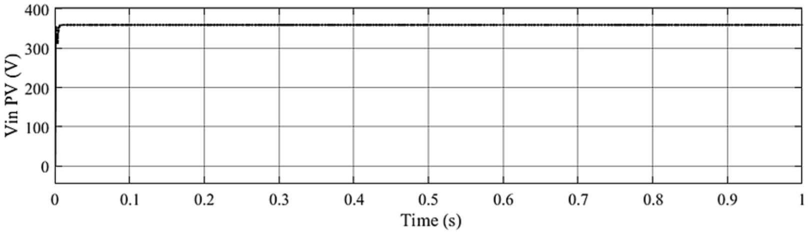

Fig. 16. Input voltage of the photovoltaic (PV) array at an irradiance level of 1000 W/m²

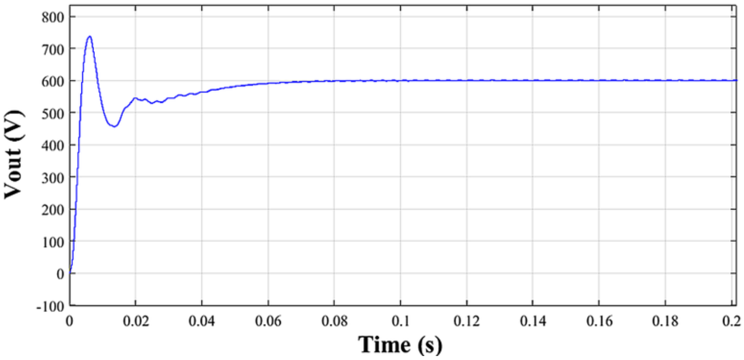

Fig. 17. DC-Bus voltage at an irradiance level of 1000 W/m² using the PI controller

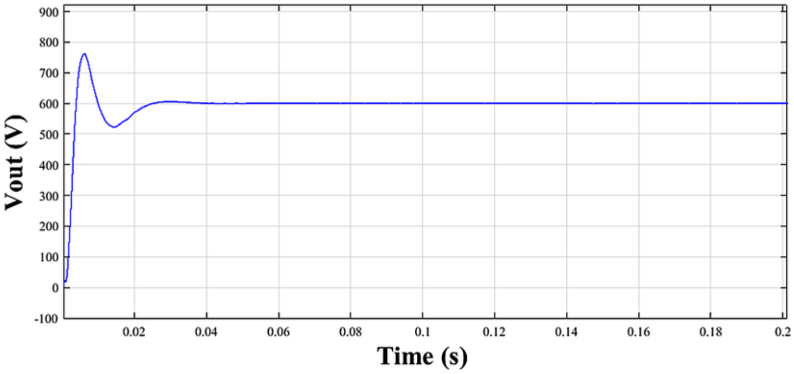

Fig. 18. DC-Bus voltage at an irradiance level of 1000 W/m² using the PI-Fuzzy controller

Dynamic Response of DC-Bus Voltage at 1000 W/m²

Figures 17 and 18 show the DC-bus voltage responses at a higher irradiance level of 1000 W/m² using the PI controller and the PI-Fuzzy controller, respectively.

Under this operating condition, the PI controller still exhibits a high overshoot, with the DC-bus voltage peaking at approximately 800–820 V, followed by oscillatory behavior before reaching steady state. Although the increased PV power slightly reduces the settling time, the response remains highly sensitive to operating conditions, indicating limited robustness of the fixed-parameter PI controller.

On the other hand, the PI-Fuzzy controller maintains a stable and well-damped response at 1000 W/m². The DC-bus voltage quickly converges to the reference value of 600 V, with the overshoot limited to below 25% and minimal residual oscillations. The settling time remains short, around 0.02 s, demonstrating good adaptability to increased input power.

From the simulation results at both irradiance levels, it can be observed that the proposed PI-Fuzzy controller effectively reduces voltage overshoot and improves the settling time of the DC-bus voltage compared to the conventional PI controller. This indicates a superior dynamic performance and enhanced robustness against irradiance variations.

5. CONCLUSION

In this paper, a detailed mathematical model of a three-phase grid-connected photovoltaic (PV) inverter and the DC-bus voltage dynamics is developed in the synchronous dq reference frame. Based on this model, an adaptive PI–Fuzzy control strategy is proposed to enhance DC-bus voltage regulation under varying irradiance and PV power conditions. In the proposed approach, the proportional and integral gains of the PI controller are dynamically adjusted using fuzzy logic inference, allowing the controller to adapt to the nonlinear and time-varying characteristics of the PV system.

The effectiveness of the proposed PI–Fuzzy controller is validated through MATLAB/Simulink simulations and compared with a conventional PI controller at irradiance levels of 800 W/m² and 1000 W/m². Simulation results show that the PI–Fuzzy controller consistently achieves lower DC-bus voltage overshoot, faster settling time, and reduced steady-state oscillations across different operating conditions. In contrast, the conventional PI controller exhibits larger overshoot and longer transient responses, highlighting its sensitivity to irradiance variations.

Overall, the obtained results confirm that the proposed PI–Fuzzy control strategy provides improved dynamic performance and enhanced robustness for DC-bus voltage regulation in grid-connected PV inverter systems. Future work will focus on experimental validation using a practical PV inverter prototype and further refinement of the fuzzy adaptation mechanism to improve controller performance under severe grid disturbances and rapidly changing environmental conditions.

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