

DC bus voltage control strategy of PV systems based on fuzzy logic

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Abstract. In a grid-connected photovoltaic (PV) power generation system, sudden changes in the output power of PV panels, caused by fluctuations in solar irradiation or shading, as well as real-time variations in system load, can lead to significant voltage fluctuations in the DC bus. If not properly managed, these voltage fluctuations can compromise the stability and efficiency of the entire system. To address this challenge and improve the performance of DC bus voltage regulation, this paper proposes a control method based on a fuzzy logic controller (FLC). The proposed method primarily relies on two key correctors: the first is an energy corrector, which regulates the energy stored in the DC bus capacitor, and the second is an FLC, which controls the current to maintain voltage stability. This dual-corrector system is designed to enhance the system's response to power fluctuations and maintain a stable DC bus voltage. The performance of this FLC-based control approach is compared to the traditional double closed-loop PI control method. Simulation results, carried out in the Matlab/Simulink environment, demonstrate that the proposed FLC method outperforms the traditional PI control in terms of both system stability and dynamic response. This improvement is especially evident in handling sudden disturbances and maintaining consistent voltage levels.

Keywords: Control strategy of DC bus voltage, Control strategy of micro grids, AC&DC, Micro grids, Photovoltaic Systems, Fuzzy Logic Control, DC-DC converter, Simulation, Matlab.

1 Introduction

In the context of the integration of distributed renewable energy production systems such as photovoltaic solar and wind, as well as energy storage systems, DC micro-grids compared to AC micro-grids present several benefits [1–3].

In a DC micro-grid, there is no need to address issues related to phase synchronization or frequency, which simplifies the overall control strategy and reduces system complexity [4,5]. In contrast, these are critical aspects of AC systems, which require complex control mechanisms to establish a stable operating point. Additionally, AC systems must manage reactive power, which necessitates additional infrastructure, such as capacitors, inductors, and transformers, further increasing the cost and complexity. The absence of reactive power management in a DC micro-grid eliminates these complications, contributing to a simpler and more efficient system [6–8].

In a DC micro-grid, the power balance of each module is primarily reflected in the DC bus voltage [9]. Significant fluctuations in the DC bus voltage may indicate an imbalance in the system, requiring adjustments in source or load management to restore

stability. Maintaining a stable DC bus voltage is crucial for the reliable and efficient operation of DC micro-grids [10]. This has led researchers to focus more attention on DC bus voltage regulation and power management methods to ensure optimal system performance [9–12].

Many studies have explored DC bus voltage stability and the development of power management controllers, each addressing the issue from different perspectives, particularly in systems integrating renewable energy sources and energy storage systems.

In [13], the study evaluates the role of mixed energy storage in maintaining the stability of DC bus voltage and ensuring the coordinated control of system energy. In [14], a control strategy was designed for hierarchical control of the DC bus voltage in a DC micro-grid, dividing the bus voltage into four levels for improved regulation. In [15], a new distributed control technique based on the direct Lyapunov method was proposed to regulate the DC bus voltage in a standalone DC micro-grid with diverse energy production and consumption sources.

In this paper, a DC bus voltage control method based on managing the energy stored in the bus capacitor is proposed for a photovoltaic system that can operate either connected to the grid or in isolation. The method combines two controllers: a PI controller and a fuzzy

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logic controller. The PI controller regulates the power sent to the accumulator by controlling the current flowing through the buck converter's coil, while the fuzzy logic controller manages the energy stored in the DC bus capacitor by regulating the voltage across its terminals.

The rest of the article is organized as follows: Section II provides the system description and the governing equations. Section III explains the proposed DC bus voltage control strategy and the method used for comparison. In Section IV, the main results are discussed and summarized.

2 Mathematical model

The block diagram of the system is shown in Figure 1. The system consists of PV panels connected to a DC voltage bus through DC-DC converters, which are also linked to a storage battery and a DC load.

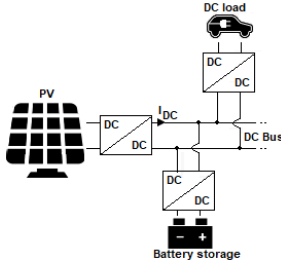


Fig. 1. Synoptic diagram of the overall system.

The circuit topology of the studied system is illustrated in Figure 2. The PV generator is controlled by a boost converter, which operates under a Maximum Power Point Tracking (MPPT) algorithm to continuously extract the maximum available power. A buck converter is employed to maintain the power balance between the first stage and the subsequent stages of the system. It plays a crucial role in stabilizing the DC bus voltage by regulating the DC bus power (P_{DC}). This ensures efficient power transfer while maintaining system stability, even in the presence of fluctuations in input power or load demand.

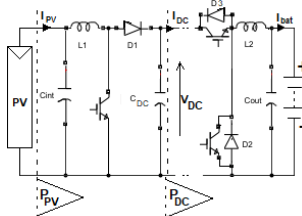


Fig. 2. The circuit topology of the PV system studied.

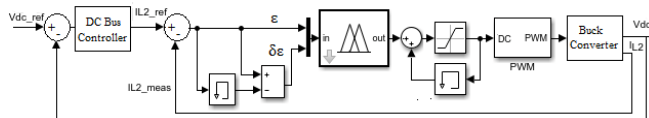


Fig. 4. Structure of the DC bus voltage control system based on Fuzzy Logic.

The state equations of the buck converter stage variables, i_{L2} and V_{DC} , are as follows:

$$\begin{cases} L_2 \frac{di_{L2}}{dt} = u V_{DC} - V_{bat} \\ C_{DC} \frac{dV_{DC}}{dt} = i_{D1} - i_{L2} - i_{DC_Load} \end{cases} \quad (1)$$

3 DC bus voltage control

The MPPT algorithm tracks the maximum power point by adjusting the V_{pv} voltage when one or more external environmental factors change suddenly [16]. This adjustment affects the DC bus voltage, leading to transient fluctuations in the power at the DC bus input. Consequently, regulating the DC bus voltage enhances MPPT performance, as the tracking of the maximum power point and V_{DC} variations are interdependent. Proper regulation also helps avoid triggering protection devices and prevents energy from flowing back from the electrical load to the DC side. Therefore, it is essential to regulate the voltage across the DC bus capacitor using a reliable controller.

3.1 Double closed loop PI control (DCL PI)

Figure 3 shows the structure of the control system, which consists of two closed loops. The external loop provides a reference current by comparing the DC bus voltage to a set point. This reference current serves as the input to the internal loop, known as the current loop. Both loops use a PI controller. The transfer function of the PI controller is:

$$C(s) = k_p + k_i \cdot \frac{1}{s} \quad (2)$$

By utilizing equations (1) and (2), the transfer functions for both the current loop and the voltage loop can be derived.

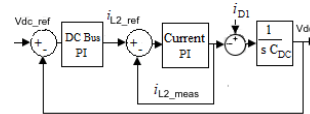


Fig. 3. structure of double closed loop PI control.

This control strategy is simple and effectively achieves the primary objectives of DC bus voltage control. However, it has limitations in terms of speed and stability and is sensitive to variations in the output power of the PV generator. To address these weaknesses and enhance control performance, this article proposes an alternative DC bus voltage control strategy based on fuzzy logic.

3.2 Fuzzy-PI dual-loops controller

As shown in Figure 4, the regulation of the DC bus voltage is achieved using two loops: an external energy loop and an internal current loop. The V_{DC} voltage is measured and compared to a reference value, after which the voltage controller generates a current reference (I_{L2_ref}). This reference is then quickly reached by the current controller, which is a fuzzy logic controller (FLC). In this way, the power transferred to or from the battery is regulated to maintain a constant voltage across the capacitor C_{DC} .

3.2.1 External loop

To maintain a constant DC bus voltage, we regulate the energy stored in the C_{DC} capacitor. The energy regulator operates according to the following equations:

$$\dot{e}_s = P_C = K_{pe} \cdot (e_{ref} - e_s) + K_{ie} \cdot \int (e_{ref} - e_s) dt \quad (3)$$

Where e_s represents the energy stored in the C_{DC} capacitor, and e_{ref} is the reference energy. They are calculated using the following equations:

$$e_{ref} = \frac{1}{2} C_{DC} \cdot V_{DC_ref}^2 = f(u) \cdot V_{DC_ref}^2 \quad (4)$$

$$e_s = \frac{1}{2} C_{DC} \cdot V_{DC_mes}^2 = f(u) \cdot V_{DC_mes}^2 \quad (5)$$

After calculating the power to be delivered to the DC bus, the current reference I_{L2} is determined using the notations shown in Figure 2. The structure of the energy loop is illustrated in Figure 5.

$$P_{DC} = P_{PV} - P_{lo1} - P_C \quad (6)$$

$$I_{L2_ref} \cdot V_{bat} = P_{PV} - P_{lo1} - P_{lo2} - P_C - P_{dc_Load} \quad (7)$$

Where P_{lo1} and P_{lo2} represent the powers lost due to the Joule's effect at the first and second stages respectively.

This current will be the input to the internal loop.

3.2.2 Internal loop

The current of the inductor L2 is controlled by a corrector, based on fuzzy logic, in order to control the power emitted or received by the battery.

FLC can be used to regulate the current in L2 to control the power sent to the battery, even with an imprecise model. It is quite simple to develop such approach without exact knowledge of the mathematical model of the system.

In this work, the two inputs used are the error $e = I_{L2_ref} - I_{L2_mes}$, between the reference and the measured value of the current I_{L2} , and the variation of this error δe , using the Mamdani approach [17].

Figure 6, shows the input and output membership function of the FLC.

The selected inference rules were derived from general principles applicable to any controllable system.

The defuzzification process converts the linguistic variables into digital values to regulate the DC bus voltage, achieved by adjusting the duty cycle of the buck converter. In this article, the centroid method is used for defuzzification.

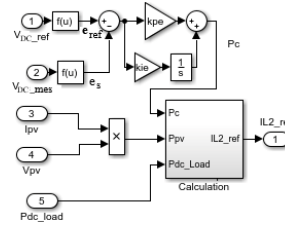


Fig. 5. Structure of energy loop.

4 Simulation and discussion results

The Simulink model used to validate the results of the proposed control structure is shown in Figure 7. To compare the performance of the proposed strategy with the double closed-loop PI strategy, a specific case with variable irradiation at constant temperature was considered. The specification parameters of the PV system are provided in Table 1.

In this simulation, the solar irradiation will vary while maintaining a constant temperature of 25°C, allowing us to demonstrate the advantages of the proposed DC bus voltage regulation strategy. This approach will be compared to the double closed-loop PI control strategy, which relies on a PI controller. By

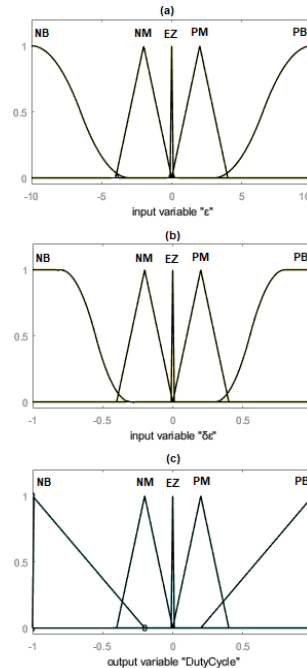


Fig. 6. Membership functions for inputs and output of fuzzy logic controller.

Table 1. The parameters values of the system.

Parameter	Symbol	Value
Power at MPP	P_{mp}	570.01 W
Battery voltage range	V_{bat}	25 ± 1 V
Load voltage range	V_{DC}	60 ± 0.6 V
DC Capacitor	C_{DC}	300 μ F
Input Capacitor	C_{in}	300 μ F
Output Capacitor	C_{out}	1 μ F
Boost Inductor	L1	1 mH
Buck-Boost Inductor	L2	0.97 mH

varying the irradiation, we can assess the system's performance in adapting to changes in solar input and maintaining stable bus voltage. Additionally, during the simulation, the power absorbed by the DC load will be considered zero, focusing the analysis entirely on the voltage regulation capabilities of the system under varying irradiation conditions.

The classic Disturb and Observe (P&O) approach was used to continuously extract the maximum power produced by the photovoltaic generator, even as environmental conditions change. The P&O technique works by repeatedly perturbing the operating point of the PV system and observing the resulting change in

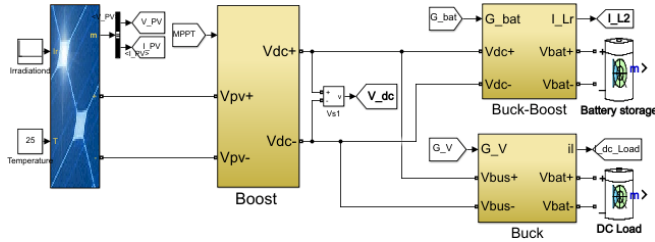


Fig 7. The Simulink model adopted to simulate the system.

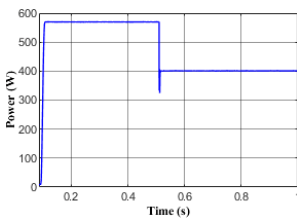


Fig 8. Evolution of the power generated by PV generator.

power to determine the direction toward the MPP [16,18].

The evolution of the power generated by the PV generator is illustrated in Figure 8. Figure 9 displays the simulation results when the double closed-loop control strategy based on a PI controller is used to regulate the DC bus voltage, while Figure 10 presents the simulation results using the proposed strategy for DC bus voltage regulation.

As seen in Figures 9 and 10, the proposed method effectively reduces the overshoot of the current passing through the buck converter inductor. Figure 11 further demonstrates that the proposed control method significantly outperforms the PI-based approach. The proposed method offers faster response times and ensures remarkable stability for the DC bus voltage. In contrast, the double closed-loop PI method takes longer to reach the voltage set point and exhibits more noticeable voltage ripples. Therefore, the proposed method clearly minimizes these voltage ripples and enhances overall system performance.

5 Conclusion

The simulation results demonstrate the effectiveness of the proposed method, even when utilizing a basic form of FLC, in terms of dynamic response, stability, and robustness, particularly under dynamic environmental conditions.

The insights from this study can guide the selection of the most suitable DC bus voltage control strategy, ultimately improving the overall performance and efficiency of DC microgrids across various operational scenarios, including enhanced energy management.

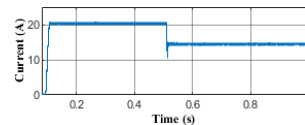


Fig 9. Evolution of the current IL2 in the case where the proposed method is used.

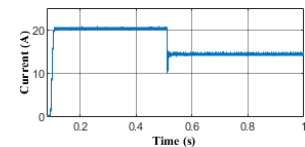


Fig 10. Evolution of the current IL2 in the case where the traditional method is used.

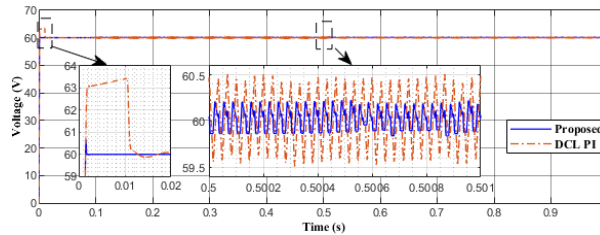


Fig 11. Comparison of the performances of the two methods used in this paper.

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