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S. Adiche, M. Larbi, D. Toumi

Optimizing voltage control in AC microgrid systems with fuzzy logic strategies and performance assessment

Introduction. *Microgrids (MGs) have garnered significant attention for their numerous advantages, providing a solution for powering remote and distant locations while enhancing system reliability. In MGs, distributed generation inverters generally operate in parallel with the droop control strategies. This study focuses on the approach based on the P-f/Q-V droop control technique with virtual impedance for AC MG management. Essentially, the virtual impedance loop aims to decouple reactive and active power control without the need for additional physical components.* ***Novelty****. This research proposes enhancing voltage control in AC MG systems by introducing new methods of various control strategies, including PI and Fuzzy Logic Controller (FLC), and evaluating the effectiveness of each approach. The mathematical model of a system is always an approximation of real systems, variations or errors between mathematical models and real systems are referred to as uncertainty. This concept of uncertainty is present in both signals and models. In our study, uncertainties may involve factors related to the filter LC components. By employing advanced control strategies like FLC, the* ***purpose*** *of this research aims to contribute to the optimization and reliability of AC MG systems through the improvement of voltage control, which leads to guaranteed equitable power-sharing.* ***Results****. The major advantages of the FLC are robustness for any variation on the system and fast response. MATLAB software is used to simulate and validate the suggested control.* ***Practical value****. The simulation results show that the suggested control performs better in precise tracking optimization and robustness for all disturbances on the system compared to a PI controller.* References 24, table 5, figures 11.

Key words: **microgrid, droop control technique, distributed generation inverters, PI control, voltage control, virtual impedance, fuzzy logic.**

Вступ*. Мікромережі привернули значну увагу своїми численними перевагами, надаючи рішення для живлення віддалених місць, одночасно підвищуючи надійність системи. У мікромережах інвертори розподіленої генерації зазвичай працюють паралельно зі стратегіями управління спадами. Це дослідження фокусується на підході, що ґрунтується на техніці управління спадами P-f/Q-V з віртуальним імпедансом для управління мікромережею змінного струму. По суті контур віртуального імпедансу спрямований на розв'язку управління реактивною та активною потужністю без необхідності додаткових фізичних компонентів.* ***Новизна****. Це дослідження пропонує покращити управління напругою в системах мікромережі змінного струму шляхом впровадження нових методів різних стратегій управління, включаючи ПІ та нечіткий логічний контролер (FLC), та оцінку ефективності кожного підходу. Математична модель системи завжди є наближенням реальних систем, зміни чи помилки між математичними моделями та реальними системами називаються невизначеністю. Ця концепція невизначеності присутня як у сигналах, так і у моделях. У нашому дослідженні невизначеності можуть включати фактори, пов'язані з компонентами LC фільтра. Використовуючи передові стратегії управління, такі як FLC,* ***мета*** *даного дослідження полягає у сприянні оптимізації та надійності систем змінного струму мікромережі за допомогою покращення управління напругою, що призводить до гарантованого коректного розподілу потужності.* ***Результати****. Основними перевагами FLC є надійність для будь-яких змін у системі та швидкий відгук. Програмне забезпечення MATLAB використовується для моделювання та перевірки запропонованого керування.* ***Практична цінність****. Результати моделювання показують, що пропоноване управління працює краще у точній оптимізації відстеження та надійності для всіх збурень у системі порівняно з ПІ-регулятором.* Бібл. 24, табл. 5, рис. 11.

Ключові слова: **мікромережа, метод керування спадом, інвертори розподіленої генерації, ПІ-регулювання, керування напругою, віртуальний імпеданс, нечітка логіка.**

Introduction. A microgrid (MG) refers to a compact and self-contained network comprising distributed generation (DG) [1, 2] to provide local loads with dependable and effective power [3] it can be categorized as AC, DC and hybrid MG [4, 5]. MGs are becoming increasingly popular due to their flexibility, capable of operating in two primary modes: stand alone and grid-connected mode to clarify, to guarantee seamless mode transition and to enable grid-connected and stand alone functions, MGs should be controlled [6, 7]. DG with smaller generating systems based on renewable energy resources, such as solar power and wind power, combined with loads and energy storage systems brings evolutionary changes to the traditional electric utilities and becomes a new pattern of power grid. In comparison to traditional generators, the concept of MG is emerging as an effective way to integrate renewable energy resources. Droop control is the recommended method for regulating many inverters in parallel because it does away with the need for external communication between them.

Traditional droop control employs reactive power/voltage (*Q*/*V*) control and active power/frequency (*P*/*f*) control to accomplish the decoupling of the regulation of active and reactive power [8]. The concept of virtual impedance has been introduced to uphold uniform primary inductive output impedance among paralleled inverters. It guarantees reactive power based on voltage amplitude and active power determined by power angle. Furthermore, virtual impedance aids in decoupling active and reactive powers [9]. To maintain the voltage regulation across the inverters, the internal control loop also identified as the low-level voltage and current controllers consists of 2 loops: an external voltage loop and an internal current loop, this level of control is elaborated in [10]. An efficient control mechanism is needed to regulate the voltage in the AC MG because voltage control is required to achieve power balance in the bus. This paper proposes an improvement of voltage control in AC MGs and a comparative study including PI and Fuzzy Logic Controllers (FLCs). The PI controller is frequently employed in MG. However, this controller necessitates precise mathematical models. The PI controller demonstrates satisfactory performance but it becomes difficult to control the voltage when variations in parameters and system operating conditions impact the performance of the PI controller potentially leading to system instability. The FLC, on the other hand, has been demonstrated advantage over conventional controllers. Recent years have seen the widespread use of FLC because of its less complex mathematical ideas and flexibility concerning input modifications. FLC differs from conventional controllers in that they rely on knowledge [11, 12]. However, the performance of the voltage and current controls in AC MG under various control strategies has not been investigated in previous research studies. PI controllers are frequently used by them to account for errors [13, 14]. FLC controller is given in this article as an error-compensation technique for voltage control for AC island MG. It has been demonstrated that employing FLC can effectively reduce output overshoot and decrease the time required for the system to reach its steady-state value. A comprehensive simulation study using the MATLAB/Simulink environment is used to determine the effectiveness of the suggested control under various system parameter variations. It includes several test cases that measure the performance of the system concerning maximum overshoot, rising time, and settling time.

The goal of the paper is to propose a robust and adaptive control technique using FLC systems stabilizing the voltage of islanded microgrids under both normal and variation operation modes. Additionally, it highlights the superiority and robustness of FLC systems compared to conventional PI controllers.

Configuration of the proposed microgrid. Figure 1 depicts the MG running in islanding mode. This MG comprises 2 decentralized generators that operate in a parallel configuration. The load is connected to each through output impedances and LC filters.

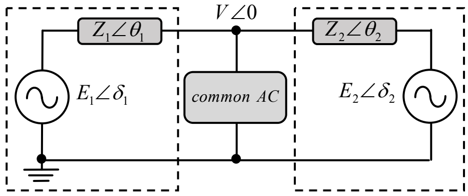


Fig. 1. Equivalent circuit for DG inverters in autonomous mode

The model consists of an ideal voltage source of amplitude E and internal angle δ in series with output impedance «Z». This output impedance encompasses both the filter impedance at the output and line impedance connecting each elementary DG to the point of common coupling (PCC), where $V\angle 0$ is the AC bus voltage amplitude.

Control of the microgrid system. The core components of an MG's DG system control structure are:

a) inner loops are the cascading voltage/current control loops that manage the 3-phase inverter's voltage;

b) primary loop, also known as the external power control loop, employs the droop technique to regulate the DG system's active and reactive power outputs.

Droop control technique and output impedance for DG systems. As seen in Fig. 2, while in islanding mode, operating DG units are interfaced to the MG utilizing voltage source converters in a grid-forming architecture, with the droop control handling the voltage and frequency set points.

The dq voltage and current outputs can be used to calculate the active power P and reactive power Q, which can then be averaged using a low-pass filter with a narrow bandwidth. The following equation describes the observed powers P and Q [15]:

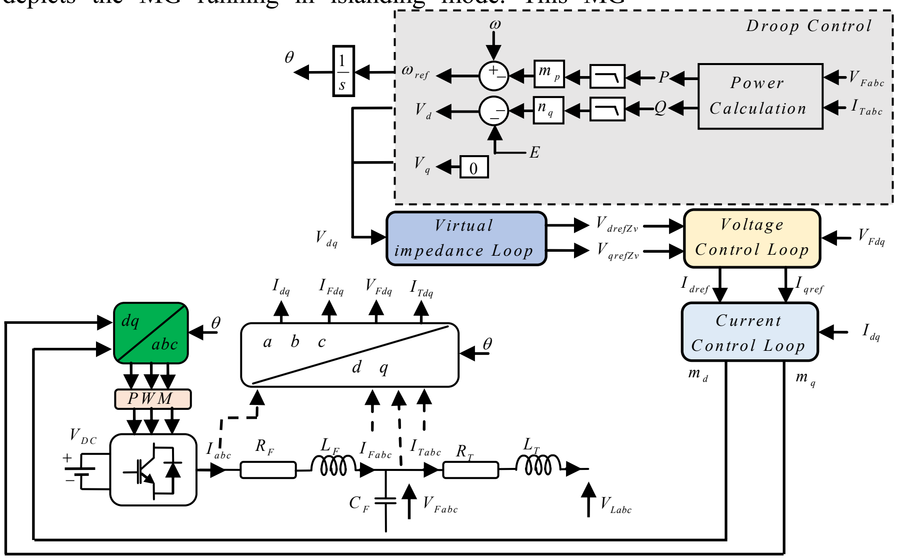


Fig. 2. DG control system block diagram

$$\begin{cases} P = \dfrac{\omega_c}{s+\omega_c} p \Rightarrow p = \dfrac{3}{2}\left(V_{Fd} I_{Td} + V_{Fq} I_{Tq}\right); \\ Q = \dfrac{\omega_c}{s+\omega_c} q \Rightarrow q = \dfrac{3}{2}\left(V_{Fd} I_{Tq} - V_{Fq} I_{Td}\right), \end{cases} \tag{1}$$

where $\omega_c/(s+\omega_c)$ is the low pass filter; V_{Fd}, V_{Fq} are the voltage command values of d-q axis components; I_{Td}, I_{Tq} are the d-q axis output currents flowing through the filter $R_T L_T$.

The notion of droop control [16] is based on measuring active and reactive powers to adjust frequency and voltage. Through the use of the conventional droop technique, the different DGs in an MG may share the power required by the loads. By using a power theory-based method, DGs systems may simulate the actions of a synchronous generator [17]. Depending on the predominance of the output impedance of each DG, different variants of conventional droop controls can be used, for more details [18]. The basic droop P-f/Q-V technique equations are written as:

$$\begin{cases} \omega = \omega_{nom} - m_p P; \\ V = V_{nom} - n_q Q, \end{cases} \tag{2}$$

where ω_{nom}, V_{nom} are the respectively the frequency and the RMS values of the reference voltage; P, Q are the respectively the active and reactive power at the output of each inverter; m_p, n_q are the proportional droop coefficients for frequency and voltage, chosen according to the rated active and reactive powers.

Virtual impedance. It's added to the droop control as indicated by (3), Modifying the virtual impedance variable creates an inductive network, guaranteeing that the active and reactive power may be controlled using the droop (3) [19, 20]:

$$Z_v = \left(R_v + jL_v\omega\right), \tag{3}$$

where R_v, L_v, Z_v stand for virtual resistance, reactance and impedance droop, respectively.

The reference voltage obtained by droop control is modified as:

$$V_{zv} = V_{d\ droop} - R_v . I_{Fabc} - L_v \frac{dI_{Fabc}}{dt}, \qquad (4)$$

where V_{zv} is the voltage obtained by the virtual impedance; I_{Fabc} is the current flowing through the R_F, L_F filter.

Through transforming (4) to *d-q* reference frame:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix}_{Zv} = \begin{bmatrix} V_d \\ V_q \end{bmatrix}_{droop} - R_v \begin{bmatrix} I_{Fd} \\ I_{Fq} \end{bmatrix} - L_v \begin{bmatrix} -\omega I_{Fd} \\ +\omega I_{Fq} \end{bmatrix} = \begin{bmatrix} V_{d\ droop} \\ 0 \end{bmatrix} - \begin{bmatrix} R_v & -\omega L_v \\ \omega L_v & R_v \end{bmatrix} \begin{bmatrix} I_{Fd} \\ I_{Fq} \end{bmatrix}. \qquad (5)$$

The cascading voltage/current control loops. The inner control loop, including the current and voltage loops, regulates the 3-phase inverter voltage to assess the DG unit's operational condition. Using Kirchhoff's law, the following equations are:

$$\begin{cases} I_{Fabc} = I_{Cabc} + I_{Tabc}; \\ e_{abc} = R_F I_{Fabc} + L_F \, \mathrm{d}I_{Fabc}/\mathrm{d}t + V_{Fabc}; \\ \mathrm{d}V_{Fabc}/\mathrm{d}t = (1/C_F) I_{Cabc}; \\ V_{Fabc} = R_T I_{Tabc} + L_T \, \mathrm{d}I_{Tabc}/\mathrm{d}t + V_{Labc}, \end{cases} \qquad (6)$$

where I_{Cabc} is the current flowing through the filter capacitor; I_{Tabc} is the current flowing through the R_T and L_T filters; e_{abc} is the converter's output voltage; R_F is the equivalent series resistance; L_F is the inductance of the converter-side filter; C_F is the capacitance of the filter; V_{Fabc} is the voltage across the filter capacitor; R_T, L_T are respectively the equivalent series resistance and the inductance; V_{labc} is the voltage at the PCC point; ω is the frequency of MG.

Through the use of the Park transformation, the expressions obtained can be shown as:

$$\begin{cases} I_{Fd} = I_{Cd} + I_{Td}; \\ I_{Fq} = I_{Cq} + I_{Tq}; \end{cases} \qquad (7)$$

$$\begin{cases} e_d = R_F I_{Fd} + L_F \dfrac{\mathrm{d}I_{Fd}}{\mathrm{d}t} + V_{Fd} - \omega L_F I_{Fq}; \\ e_q = R_F I_{Fq} + L_F \dfrac{\mathrm{d}I_{Fq}}{\mathrm{d}t} + V_{Fq} + \omega L_F I_{Fd}; \end{cases} \qquad (8)$$

$$\begin{cases} V_{Fd} = R_T I_{Td} + L_T \dfrac{\mathrm{d}I_{Td}}{\mathrm{d}t} + V_{Ld} - \omega L_T I_{Tq}; \\ V_{Fq} = R_T I_{Tq} + L_T \dfrac{\mathrm{d}I_{Tq}}{\mathrm{d}t} + V_{Lq} + \omega L_T I_{Td}; \end{cases} \qquad (9)$$

$$\begin{cases} I_{Fd} = C_F \dfrac{\mathrm{d}V_{Fd}}{\mathrm{d}t} - \omega C_F V_{Fq} + I_{Td}; \\ I_{Fq} = C_F \dfrac{\mathrm{d}V_{Fq}}{\mathrm{d}t} + \omega C_F V_{Fd} + I_{Tq}. \end{cases} \qquad (10)$$

Current control loop. The current controller produces the PWM signal for the inverter in the *d-q* reference frame [21]. It minimizes the error between the measured and reference current using a PI regulator (Fig. 3).

Voltage control loop. PI approach. This voltage control loop uses a regulator PI. To compensate for output current disturbances and give the *d-q* current reference components, a feed-forward gain is added to the signal created by comparing the sampled output voltage to the power controller's reference value (Fig. 4).

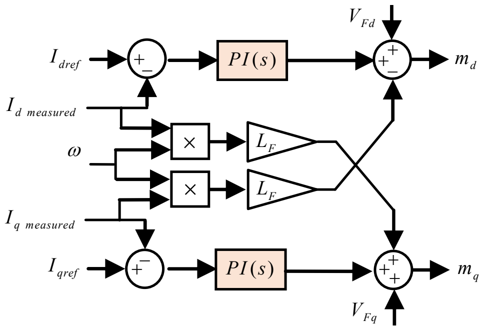


Fig. 3. Detailed diagram of the current control

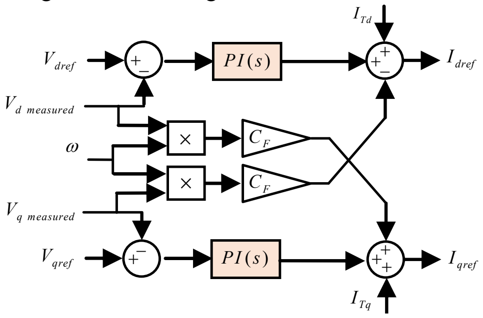


Fig. 4. Detailed diagram of the voltage control

Proposed voltage controller using fuzzy logic. Fuzzy logic is an AI technology that quickly creates nonlinear controllers from heuristic data [22]. Unlike traditional PI controllers, it relies on experiential control methods. A key advantage of FLC systems is their ability to manage complex controlled systems without requiring mathematical modeling. The fuzzy controller has 2 inputs and 1 output. The error signal between the specified reference voltage and the measured voltage is the first input; its derivative is the second; and the reference current is the output. The linguistic variables *N*, *Z*, and *P* where *N* stands for negative, *P* for positive, and *Z* for zero. Most of the controllers that have been built make use of the basic approach proposed by outlined Mamdani (Fig. 5–7).

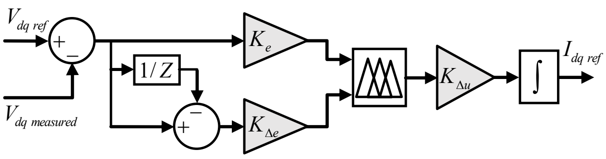


Fig. 5. Block diagram of a proposed FLC

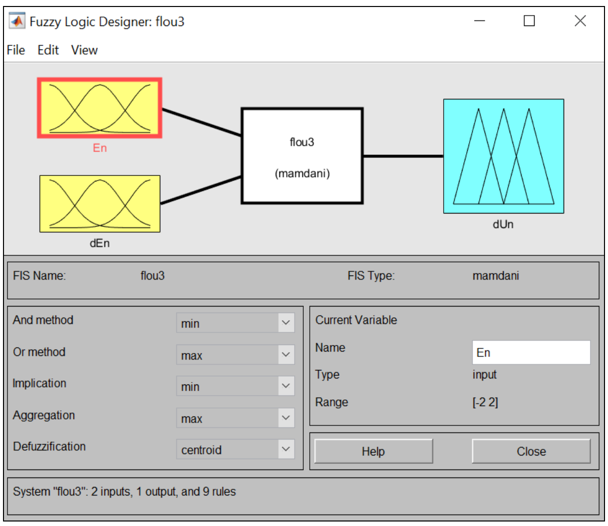


Fig. 6. MATLAB's fuzzy inference system editor window

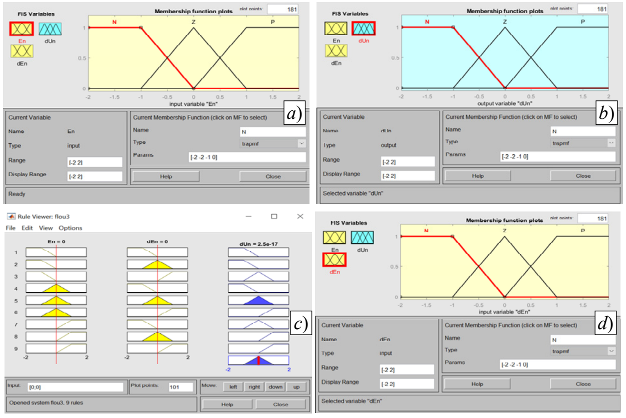


Fig. 7. Different structures of FLC: *a* – membership functions generated error; *b* – derivative of error; *c* – derivative of command of the proposed FLC; *d* – FLC rule viewer

Inference method. The inference engine comprises 2 key components: the fuzzy rule base and the fuzzy implication subblocks. The fuzzified inputs are fed into the inference engine, where the rule base is applied. This process results in the determination of the output fuzzy set (Table 1).

Table 1

Fuzzy inference

The order		Derivative of error		
		N	*Z*	*P*
Error	*N*	*N*	*N*	*Z*
	Z	*N*	*Z*	*P*
	P	*Z*	*P*	*P*

Mathematical modeling of uncertainty. Term «*uncertainty*» refers to discrepancies between mathematical models and real systems. This study focuses on component uncertainty in DG power converters using an LC filter. This approach is vital for creating a robust control system. The system's 2 cascading loops (voltage and current) add complexity due to the LC filter and parametric uncertainty, with model transfer functions treated as uncertain. In our case study, uncertainties in the DG model may include uncertainties in the LC filter components. The following is a representation of the unknown filter parameters [23]:

$$\begin{cases} R_{lF} = R_F\left(1+\rho_R \Delta_R\right); \\ L_{lF} = L_F\left(1+\rho_L \Delta_L\right); \\ C_{lF} = C_F\left(1+\rho_C \Delta_C\right), \end{cases} \quad (11)$$

where R_F, L_F, C_F are the nominal values of R_{lF}, L_{lF}, C_{lF} respectively; Δ_R, Δ_L, Δ_C are the possible disturbances on these parameters; ρ_R, ρ_L, $\rho_C \in [-1, 1]$ are the maximum deviation between the real system and the mathematical model.

Simulation results. In this section, a simulation study based in AC MG was created by using MATLAB/Simulink software to validate the proposed controller. Several cases were done to examine and analyze the voltage controller's reaction. The main objective here is to design a robust FLC that stabilizes the MG, while comparing FLC and conventional PI controllers under load and system parameter fluctuations. Table 2 represents the parameters for the controller and power stage used in this study.

Proposed droop control with load variation. The proposed droop control principle with virtual impedance was validated against established standards, allowing for a 5 % voltage variation and a frequency variation below 1.4 % [24]. Power sharing among parallel inverters was tested

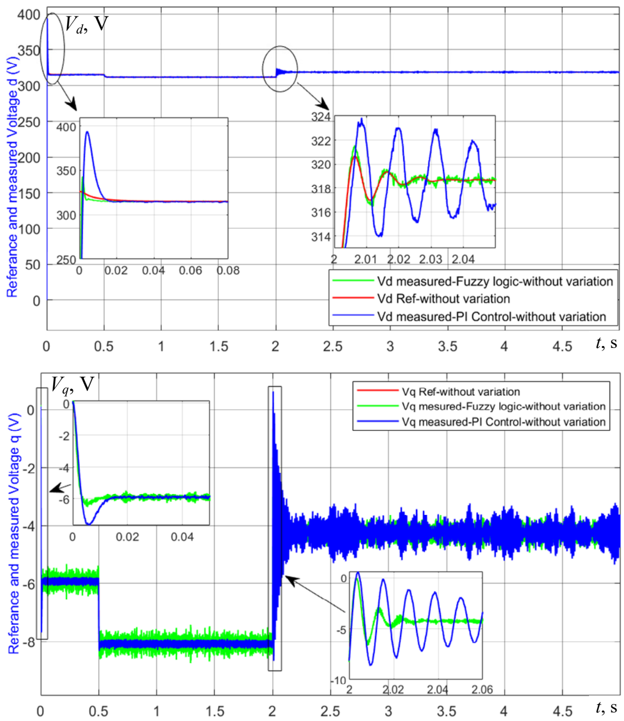
Table 2

Parameters for the controller and power stage

DC bus voltage	850 V		
Max active power	8 kW		
Max reactive power	6 kVAr		
Switching frequency	5 kHz		
RMS	400 V		
Filter	R_F = 0.1 Ω, L_F = 1.35 mH, C_F = 50 μF		
Line	R_T = 0.35 Ω, L_T = 0.03 mH		
Virtual inductance	L_v = 2 mH		
Sample time	$t_s = 2\cdot10^{-6}$ s		
Voltage PI control			
d axis control parameters	Proportional term	K_{pv_d} = 0.3142	
	Integral term	K_{iv_d} = 10.071	
q axis control parameters	Proportional term	K_{pv_q} = 0.5944	
	Integral term	K_{iv_q} = 36.0467	
Current control			
d axis control parameters	Proportional term	K_{pi_d} = 21.1057	
	Integral term	K_{ii_d} = 1699	
q axis control parameters	Proportional term	K_{pi_q} = 42.3115	
	Integral term	K_{ii_q} = 6798	
Proportional frequency droop		$m_p = 8.75\cdot10^{-5}$	
Proportional voltage droop		n_q = 0.0025	

with a common load P_{load} = 5 kW, Q_{load} = 3 kVAr, and a sudden change at 0.5 s to evaluate the dynamic response. The droop control technique enabled all DG units to meet the maximum active and reactive power requirements for islanding at full load, effectively sharing the total load demand.

Figure 8 shows the performance evaluation of MG controllers using FLC without uncertainty. The comparative study reveals that FLC outperforms PI control by delivering a faster transient response and improved performance in reaching steady-state, as evidenced by the simulation results.



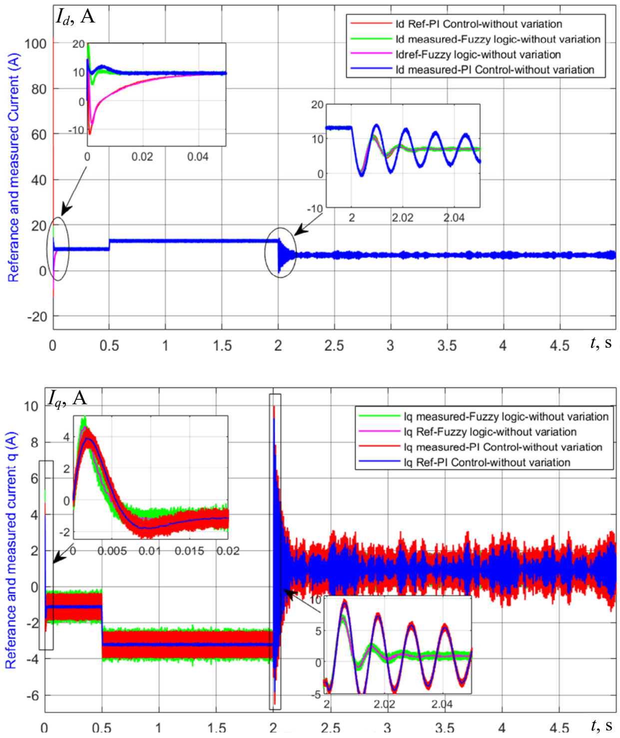
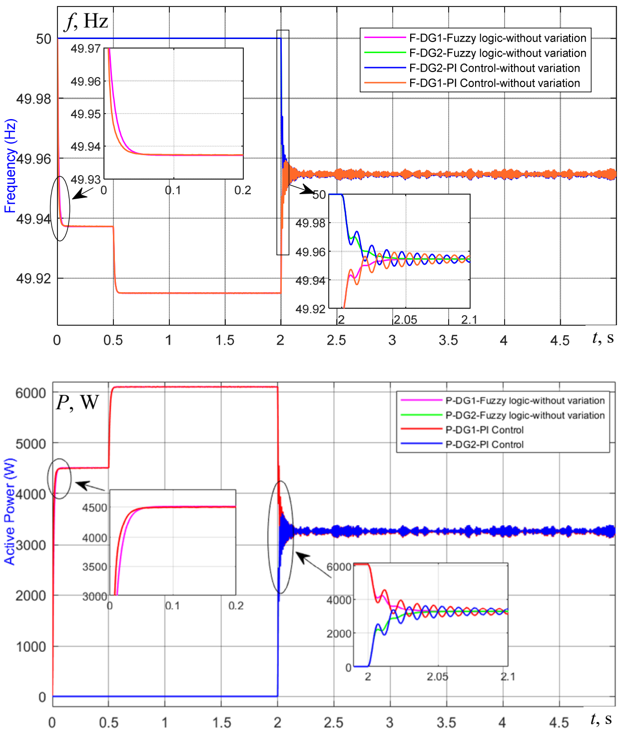


Fig. 8. Performance evaluation of MG controllers using FLC and PI controllers *without* uncertainty model

Figure 9 illustrates the study state value of the frequency and voltage amplitude in the MG as well as the active and reactive power delivered by the DG1 and DG2 for load variation at 0.5 s. Therefore, the *P-f*/*Q-V* droop control with virtual impedance ensures that the voltage fluctuations do not exceed 5 % and frequency deviations remain below 1.4 %. This established that better accuracy and effectiveness are achieved in the MG system.



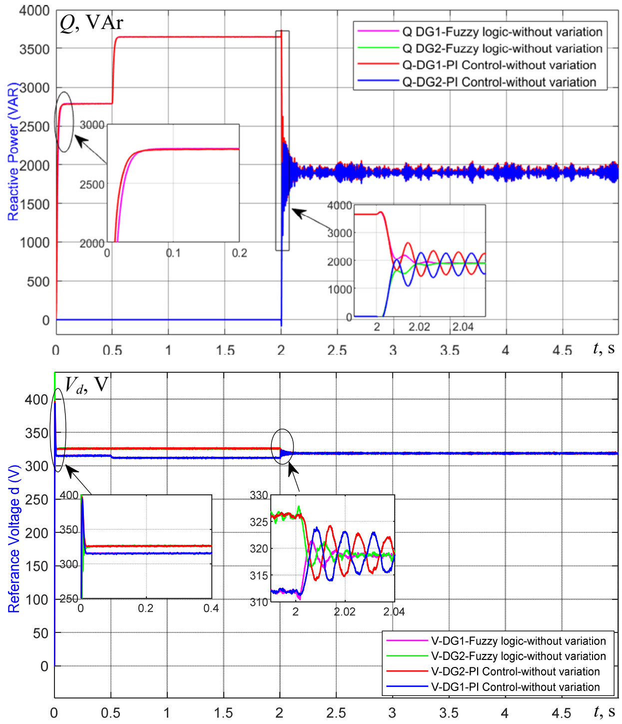


Fig. 9. Comparative study of FLC and PI controllers using *P-f*/*Q-V* droop with virtual impedance *without* uncertainty model

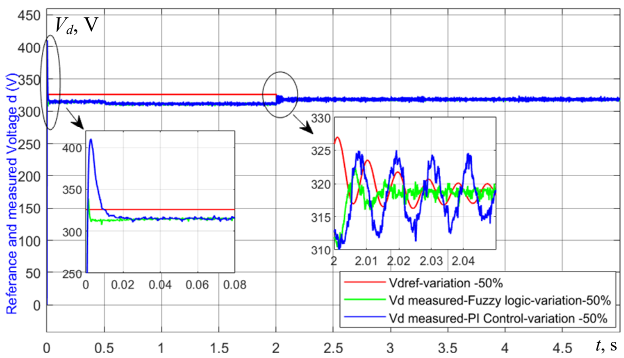
Sequence of DG connection/disconnection. As illustrated in Table 3, a test sequence was employed in this study, involving the activation and deactivation of the second unit at various times. This setup was used to evaluate the performance of inverters connected in parallel and their ability to share power effectively.

Table 3

Reconnection and disconnection sequence of DGs

Time, s	0	1	$2+t_s$	3	4	5
First DG	connected					
Second DG	disconnected			connected		

Figure 10 shows the performance evaluation of various controllers using an uncertainty model for the *d*-axis regulator voltage. The results indicate that the performance is affected by the PI controller as the parameters change. From 0 to 0.15 s the measured voltage rises to 388 V due to a 50 % reduction in the LC filter parameter. By using the FLC, the measured voltage converges seamlessly into the desired value with less impact compared to PI control where the measurement voltage increases to 335.8 V with variation of the LC filter parameters and the contrast is most pronounced when DG2 is connected at ($2+t_s$) s (Fig. 11). For *q*-axis the results obtained prove that the FLC is robust and better than the PI controller for all disturbances on the system.



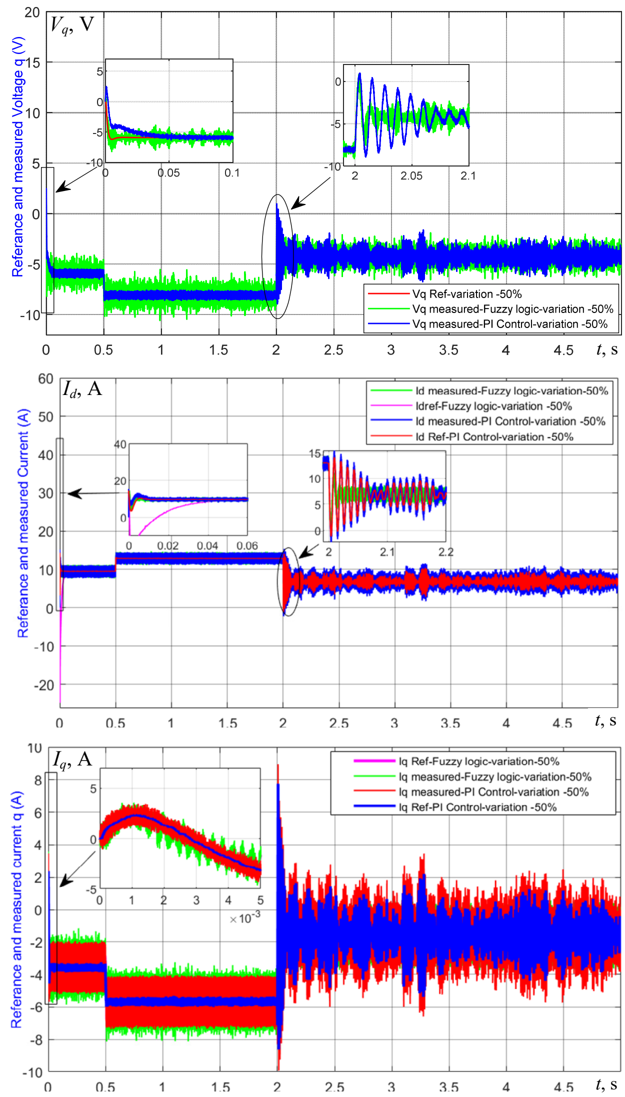
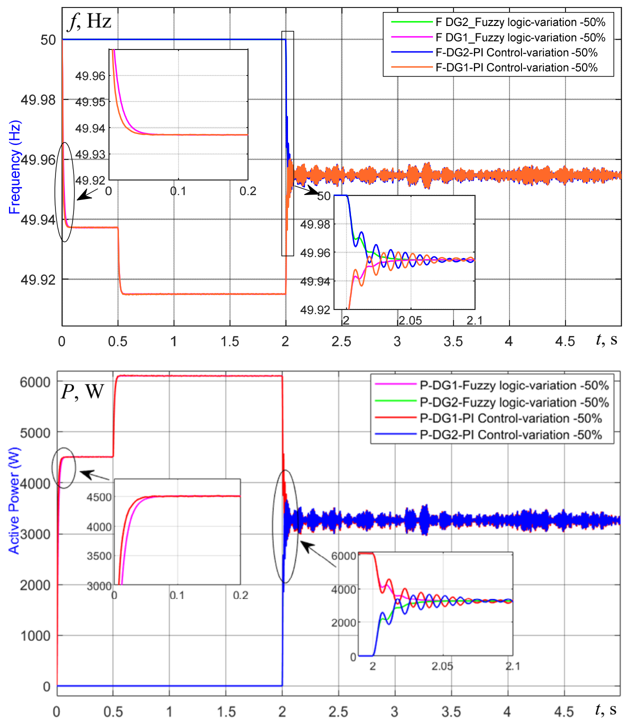


Fig. 10. Performance evaluation of MG controllers using FLC and PI controllers *with* uncertainty model



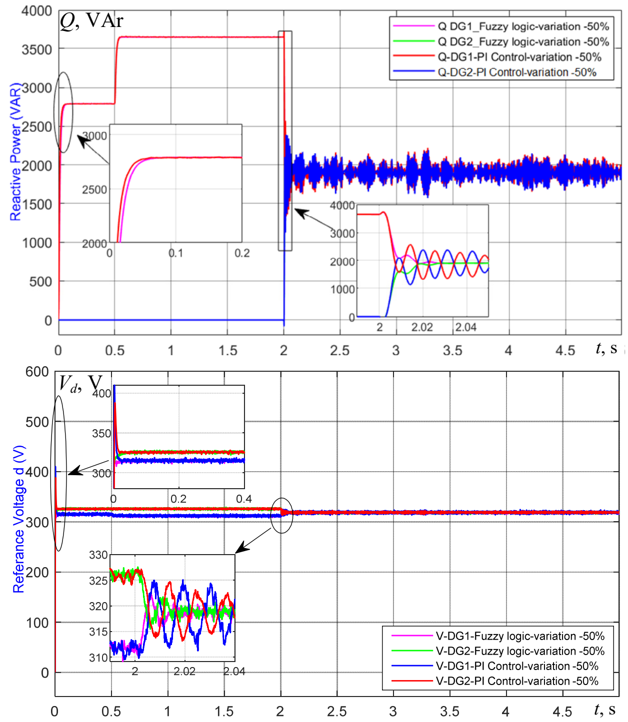


Fig. 11. Comparative study of FLC and PI controllers using *P-f*/*Q-V* droop with virtual impedance *with* uncertainty model

Tables 4, 5 show the assessing the performance of PI and FLC controllers. The voltage stabilization time was notably faster when using FLC. This indicates that FLC outperforms PI control in terms of dynamic performances. The voltage variance is greater with PI control as compared to FLC because it diminishes rapidly due to the effective response of the fuzzy controller.

Table 4

Performance comparison between different controllers *without* uncertainty model

Parameter	PI control		Fuzzy logic	
	d-axis	*q*-axis	*d*-axis	*q*-axis
Overshoot, %	63.962	2.245	10.556	1.992
Undershoot, %	14.955	10.918	1.962	3.125
Rise time, ms	1.84	1.311	0.76476	0.914

Table 5

Performance comparison between different controllers *with* uncertainty model

Parameter	PI control		Fuzzy logic	
	d-axis	*q*-axis	*d*-axis	*q*-axis
Overshoot, %	71.296	75.545	1.531	1.993
Undershoot, %	8.239	13.274	1.985	5.851
Rise time, ms	1.789	1.565	0.82689	0.9716

Conclusions. This paper offers a comparative analysis of voltage control enhancement in microgrids, utilizing both conventional PI controllers and fuzzy logic controllers. The performance evaluation shows that the proposed control, even with changes in the load or system characteristics, the voltage control can be efficiently regulated to the appropriate level. Furthermore, the fuzzy logic controller employed in this study exhibits excellent performance in various transient conditions, offering rapid voltage reference tracking, adaptability to load fluctuations, and superior robustness against system disturbances as compared to the PI controller. These advantages position fuzzy logic controllers as a more effective solution for voltage control in microgrid applications, highlighting their potential for enhancing the reliability and efficiency of future energy systems.

Conflict of interest. The authors declare that they have no conflicts of interest.

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S. Adiche [1]*, Phd Student,*
M. Larbi [1]*, Full Professor,*
D. Toumi [1]*, Senior Lecturer,*
[1] Department of Electrical Engineering, L2GEGI Laboratory, University of Tiaret, Algeria,
e-mail: sarra.adiche@univ-tiaret.dz (Corresponding Author); djilali.toumi@univ-tiaret.dz; mhamed.larbi@univ-tiaret.dz

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