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Fuzzy-IP Controller for Voltage Regulation in a Stand-Alone Microgrid System

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Abstract – *This paper presents a method that combines fuzzy inference system and Integral-Proportional named Fuzzy-IP controller to regulate an independent microgrid voltage with a distributed energy resource unit. The unit employed photovoltaic (PV) array with DC voltage converted to three-phase AC voltage. The control design was carried out through modeling and simulation using Matlab software environment. Transfer function with the 2×2 structure using system identification has estimated the non-linear plant model. Two controllers transformed the a-b-c to the d-q axis coordinates of voltage to simplify linear control design. An oscillator is applied to set frequency according to the recommendation. The results show that the compensated case-study system using Fuzzy-IP with disturbance tracked the setpoint excellently and it regulated the voltage properly including frequency control using internal oscillator. The paper presents performance superiority of the proposed method over PI control by comparing the transient response, the mean squared error, and the root mean squared error.* ***Copyright © 2018 The Authors.***
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Keywords: *Smart Grid, Microgrid, Energy Control, Distributed Generator, Distributed Energy Resource*

Nomenclature

V_{abc}	Three-phase Load Voltage
r_1 / r_2	Reference of *d*-axis / *q*-axis coordinates
y_1 / y_2	Output of *d*-axis / *q*-axis coordinates
u_1 / u_2	Input related to *d*-axis / *q*-axis coordinates
D_1 / D_2	Disturbance to *d*-axis / *y*-axis coordinates
Gp	Transfer function of the entire plant
Gp_{11}	Transfer function between y_1 and u_1
Gp_{12}	Transfer function of the coupling between y_2 and u_1
Gp_{21}	Transfer function of the coupling between y_1 and u_2
Gp_{22}	Transfer function between y_2 and u_2
e	Error which is the difference between reference input and actual output, e.g. e_1 (for *d*-axis) = y_1-r_1, e_2 (for *q*-axis) = y_2-r_2
de	Differential error or error change
$X_{i,1}$	fuzzy sets of *e* (input variable) where *i* is the rules number
$X_{i,2}$	fuzzy sets of *de* (input variable), where *i* is the rules number
$X_{i,3}$	Fuzzy set of K_{Ki} (output variable), where *i* is the rules number
$\mu_A(z)$	Aggregated output Membership Function (MF) a fuzzy set A
z_{COA}	Aggregation result on fuzzy inference system based on method Centroid of Area
K_i	Integral gain of PI controller where Ki_{min} and Ki_{max} are respectively the minimum and maximum value of K_i
K_{Ki}	Coefficient generated by the fuzzy system for Ki_{max} - Ki_{min}
Kp	Proportional gain of PI Controller
$Gc(s)$	Transfer function of the controller
pu	Per unit dimensionless value (maximum 1)

I. Introduction

Electrical engineering capacity from renewable sources is increasing steadily and it is bringing a new paradigm of a distribution system that faces new challenges in adopting new control mechanism and framework to integrate many kinds of available energy sources with different characteristics. The renewable sources offer the potential of a sustainable and an environmental-friendly power generation, but the technologies still present challenges due to their intermittent characteristics. Efforts to apply control engineering in the conversion, distribution process and conservation have been attracting much attention to recent researches due to the present and uprising energy and environmental problems. The new topology and design of generation and distribution systems from renewable sources develop continuously. It is essential to understand the distinctive characteristics of each element of the system and the interaction between them, in order

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to successfully incorporate and control a variety of plants [1]-[27]. Furthermore, microgrid systems have an important role in involving multiple energy sources. A microgrid is a power grid in a small size with two operation modes: independent (stand-alone) and grid-connected. It allows the implementation in wide range area even in the remote one, which represents an issue in developing countries. By implementing the microgrid concept, electrical supply and demand (grid-connected or stand-alone mode) can be flexible. Nowadays, control strategies in microgrid systems are still an open issue in accordance to power-sharing, stability, frequency, voltage, active, reactive power, synchronization, as well as connecting/ disconnecting detection and system recovery [1].

The microgrid system becomes more significantly complicated in facing some current technical and other challenges. Therefore, the use of the utility, non-renewable and renewable energy including the storage needs appropriate control techniques to be applied in a hybrid and a smart way to get the best performance. Control engineering has an important role to enhance the performance. Microgrid generally consists of three levels [1]-[2]. The primary level controls the energy sources and their interfaces to operate in a normal operation based on the local requirements that generally need no communication infrastructure. The secondary level mainly controls power quality once the system has several and different energy sources. The tertiary level relates to power interchange between microgrids and the utility.

The microgrid controller must secure the operation modes either grid-connected or stand-alone where the success of disconnection and reconnection processes mainly depend on microgrid control. It must guarantee the seamlessly processes in the system working in the specified operating points. The stand-alone operation mode requires an accurate load sharing mechanism since it must control frequency and voltage of the system independently. The power mismatch that may happen in the load sharing can cause high circulating current. The stand-alone electrical source and the dynamics of electrical load can reduce power quality due to the use of electrical equipment [3]-[4]. A converter can operate as a master unit for voltage regulation [5], and an internal oscillator can control the frequency. Some techniques in powers sharing control are presented in [6]-[10].

In the primary control level, the voltage control is quite challenging due to load dynamics and power transients. The transients may arise as a result of direct lightning strikes or inductions, switching loads on or off, switching of the power line or capacitor banks, and interruption of fault currents [5]. Some examples of the proposed techniques to solve these challenges are sliding mode [11], μ-synthesis [12], robust [13]-[15], robust servomechanism [16], and convex optimization [17]. However, most of these control methods are based on a mathematical model developed from the electrical components values such as resistance, inductance, and capacitance. Sometimes it is not easy to get the exact values for those components mainly in the real systems. Moreover, some of the presented systems are based on the fixed DC source and they are focused on the dynamic in the inverter to regulate the voltage. The control system design should consider the intermittent character of the DC source. Proportional-integral (PI) control scheme is commonly used for voltage regulation in power systems, but it has difficulties with the sensitivity of the various values of the parameters and also with non-linearity of the system. Another approach using Fuzzy adaptive [18] presents its superiority by comparing to the proportional-derivate control scheme. The fuzzy logic approach is also proposed in [19] using fix DC source. However, the system should be tested by the dynamics of DC source and disturbances regarding the load uncertainties to consider carefully to the real case in power systems especially microgrid.

This paper uses system identification to get the mathematical models (i.e., transfer functions) of the plant with minimum system order. These models are linear and they will reduce the burden with the unknown parameter values of the system such as resistance, inductance, and capacitance. A method, named Fuzzy-IP, is developed in this paper to regulate voltage magnitude in an independent microgrid. In this scheme, fuzzy inference system (FIS) is used to dynamically set the integral parameter that has integral-proportional (I-P) control scheme. The proportional gain is not connected to the error but it is directly connected to the feedback signal from the output to reduce the impact of system dynamics. Meanwhile, the dynamics of the error (*e*) and differential error (*de*) are set to be the FIS inputs. The output of the FIS is the K_{Ki} value, which is a dynamic integral value to compensate the system with the better tracking capability. The microgrid in the presented case has a DC source from a photovoltaic system and then it is converted to three-phase AC voltage. A phase-locked loop (PLL) controls the frequency to fulfill the requirement.

II. Research Method

The controller design goal is to have regulated voltage and frequency according to the setpoint in the microgrid system energized by the DC source by involving perturbation in the PV system and disturbances. The modeling and simulation of the system and its control have used Matlab software, especially Simulink and SimPowerSystems.

Fig. 1 displays a high-level semantic of the microgrid with one DER unit. In this system, solar energy provides electricity for AC microgrid after voltage conversion using a voltage-sourced converter (VSC) or also called inverter. The three-phase voltage of the load (V_{abc}) will be controlled to have robust stability and small steady state error compared to the setpoint. The controller will face two uncertainties, which are the intermittent character of the photovoltaic (PV) source as the DC

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voltage input due to various temperature and the solar irradiance and disturbances that mainly due to the load dynamics that are affected by connection and disconnection of the load(s). Point common coupling (PCC) connects or disconnects microgrid to the leading network, where the exchange power becomes possible [18]. This point also connects the grid to the load. Therefore, V_{abc} is measured at PCC. In stand-alone mode, PCC disconnects from the primary network, so the microgrid works independently using the available DER. It means that the voltage and frequency control are switched from the centralized scheme of the main grid to the decentralized one in which microgrid has to own its independent authority. The control strategy will be challenging due to the power difference between DER and the loads caused by inappropriate control strategy at microgrid level. Therefore, the local controller in microgrid level must seamlessly capable to regulate the voltage and the frequency, especially in transition from connected grid-connected to stand-alone mode.

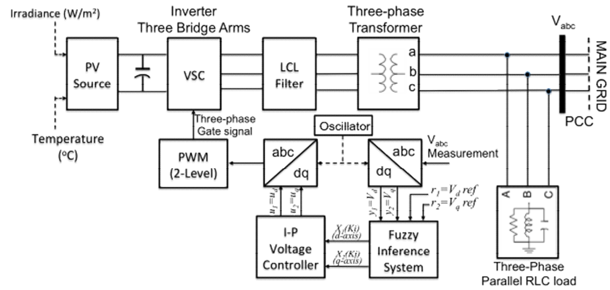

Fig. 1. High-level model semantic of the Stand-alone Microgrid System

Furthermore, a 2-level power width modulation (PWM) produces a gate signal for inverter after receiving a three-phase signal in *a-b-c* axis coordinates from the controller. This transformation is required since the system dynamics using *a-b-c* axis coordinates are nonlinear, so it will need a great effort to design a simple linear controller if there is no estimation. Therefore, the actual output (V_{abc}) which has *a-b-c* axis coordinates is transformed to *d-q* axis coordinates, in order to build the system dynamics model with a linear approximation. By doing this, the design and analysis of the linear controller are much more straightforward since it can use linear methods that are available in many design tools. This transformation, as an example, has been successfully applied to control voltage and current of a three-phase motor using anti-windup compensator [20]. The *d-q* axis coordinates of the actual output are then considered as two feedback signals and compared to the *d* and *q* references. The errors are then compensated by the controller and after transforming the signal back to the *a-b-c* axis coordinates. This signal controls the PWM reference input and subsequently becomes a gate signal for the VSC. Regarding the frequency, an internal oscillator (phase-locked loop, PLL) controls the frequency according to the standard. In this case, it is 50 Hz.

The PV source in this paper has a maximum DC voltage magnitude at 1,500 V (1 pu). An inverter, with three bridge arms controlled by three-phase gate signal produced by PWM as a subsequent process from the controller, will convert the DC voltage to AC. The output of the inverter is a three-phase bipolar square signal. This signal will be filtered by an LCL filter to reduce the harmonics produced by the inverter and smooth the waveform. Then, a step-up transformer will increase the voltage magnitude to track the voltage set-point magnitude for the three-phase local load. The microgrid is connected to 20 kW parallel RLC load at the beginning. Then at 2 s, connecting additional 10 kW in parallel increases the total RLC load value. In this load change, the controller must compensate the system to the steady state.

In this paper, the plant transfer functions are estimated using system identification. By using input (i.e., square signal) and output data of uncontrolled plant with perturbation from the various DC voltage from PV source, the transfer functions estimation using Matlab and the primary parameter is mean squared error (MSE). Numerator and denumerator can be selected considering those three parameters. Afterward, the controllers designed in this paper combine fuzzy inference system (FIS) and Proportional-Integral (PI) scheme. The *e* and *de* will be fuzzified, aggregated and defuzzified by the FIS and they generate K_{Ki} added to the calculation of integral parameter *Ki*. This process runs automatically depending upon the *e* and *de* magnitudes.

Fig. 2 shows the diagram that has a combination of FIS and PI. The combination means that the output of FIS sets the coefficient parameters of the PI. The two references are r_1 and r_2 respectively for *d*-axis and *q*-axis. Assuming that the microgrid has a balanced condition, r_1 represents PCC voltage magnitude setpoint regarding the active power, while r_2 that represents the voltage regarding the reactive power that always has a zero value. In this case, r_1 is a step function with magnitude 1 per unit (pu) at the beginning, reduced to 0.8 pu at 0.3 s, where pu is a dimensionless ratio based on its original value. For the voltage, 1 pu is representing 13.8 kV. The FIS combined with PI controller produces two outputs namely u_1 and u_2 that will be the inputs for the plant (G_p). In Fig. 1, the value of u_1 and u_2 that is in *d-q* axis coordinates will be transformed to *a-b-c* as the representation of the three-phase voltage lines. This signal is a reference for PWM to set a three-phase signal to the inverter gate. G_p is composed of four transfer functions with 2×2 structure namely Gp_{11}, Gp_{12}, Gp_{21}, and Gp_{22}. *Gp* represents the mathematical model estimation for the microgrid system in Fig. 1 consisting in *dq-abc* transformation, DER (PV-source and VSC), LCL filter, three-phase step-up transformer, three-phase parallel RLC load(s), three-phase PCC voltage (V_{abc}), and *abc-dq* transformation.

Fig. 3 shows FIS design for *d*-axis controller that uses the Mamdani method, in which the system has two variables for inputs and one output, which are similar for

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both controllers. The decomposition of the input variables *e* representing e_1 and e_2, and *de* (de_1 and de_2) are Negative (N), Zero (Z), and Positive (P). The output variable namely K_{Ki} is an additional amount to the minimum value of integral control gain (*Ki*) at *d*-axis and *q*-axis controller. This fuzzy variable is decomposed into Small (S), Medium (M), and Big (B), respectively.

Fig. 3 shows that the membership functions (MFs) represent the fuzzy sets. The i-th fuzzy rule in the rule base of FIS for *d*-axis and *q*-axis controller is generally designated by:

Rule i : IF *e* is $X_{i,1}$ AND *de* is $X_{i,2}$ THEN K_{Ki} is $X_{i,3}$, $i = 1, \ldots, 9$.

where *i* is the rules number, $X_{i,1}$, $X_{i,2}$, and $X_{i,3}$ are respectively the fuzzy sets defining the linguistics terms of the input variables *e* (e_1 or e_2), *de* (de_1 or de_2), and the output variable K_{Ki} (K_{Ki1} or K_{Ki2}). In this research, there are nine rules set for the FIS listed in Table I.

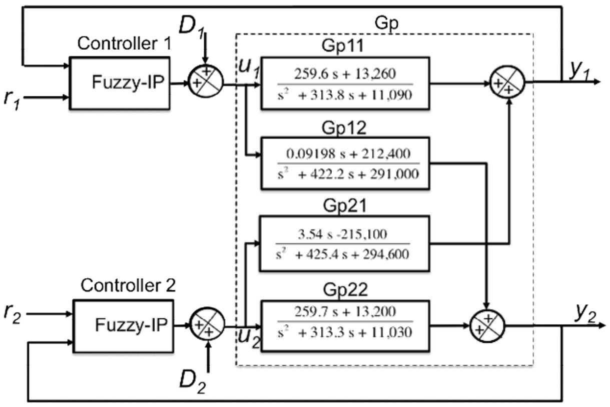

Fig. 2. Block diagram of the controlled system

Mamdani has a simple structure with a min-max operation and commonly used in many applications. This method is based on the fuzzy theory in [21] which was then developed to be a control combination [22]. The centroid of area (COA) defuzzification method is applied in this paper to get outputs (K_{Ki1} and K_{Ki2}) of the FIS. The outputs are obtained by taking the fuzzy area center point, generally formulated in (1):

$$z_{COA} = \frac{\int_z \mu_A(z) z \, dz}{\int_z \mu_A(z) \, dz} \qquad (1)$$

where *A* is a fuzzy set of a universe of discourse *Z*, $\mu_A(z)$ is the aggregated output MF. Figs. 4 show the surface of a relation between *e*, *de*, and K_{Ki}. K_{Ki1} and K_{Ki2} represent the coefficient of *Ki* with variation from 0 to 1, and each of them in the FIS will be connected to an integral gain (*Ki*). *Ki* applies first Zieger-Nichols method [23] to determine its values. The difference with conventional PI control design is that *Ki* can vary due to the coefficient K_{Ki} where it is a fixed value in the original method. The FIS will accelerate the response during the significant error to reach a steady state quickly, and then slightly response after reaching that state.

The calculation of *Ki* values is shown in Equation (2):

$$Ki = Ki_{min} + K_{Ki}\left(Ki_{max} - Ki_{min}\right) \qquad (2)$$

The PI controller has the following ideal form:

$$Gc(s) = Kp + \left(1 + Ki\frac{1}{s}\right) \qquad (3)$$

TABLE I
LIST OF FUZZY RULES FOR K_{Ki1} AND K_{Ki2}

e \ *de*	P	Z	N
P	B	M	S
Z	S	S	S
N	S	M	B

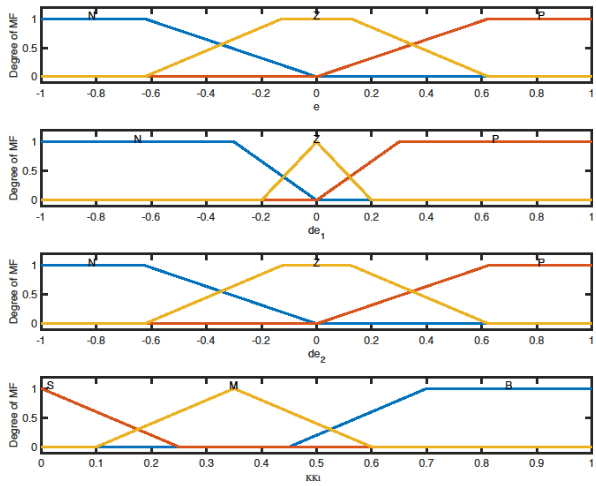

Fig. 3. MFs of inputs (*e* and *de*) and output K_{Ki}

III. Results and Analysis

This section will present the superiority of the proposed controller named Fuzzy-IP over the PI control scheme to regulate the microgrid voltage during the disturbances. Some simulation results show both *d*-*q* and *a*-*b*-*c* (three-phase) axis coordinates of voltage, as well as their power and current waveforms.

III.1. DER Characteristics without Controller

The DER unit presented in this paper is a PV-array source with characteristics Current-Voltage (I-V) and Power-Voltage (P-V). The PV-array consists of PV modules type SunPower-SPR-305-WHT with 24 series-connected modules per string and 150 parallel strings. Each module has 96 PV cells with 64.2 V open circuit voltage, 5.96 A short-circuit current, and 54.7 V voltage at the maximum power point.

Fig. 5(a) describes the characteristics of I-V and P-V and the various irradiation values. The current and the

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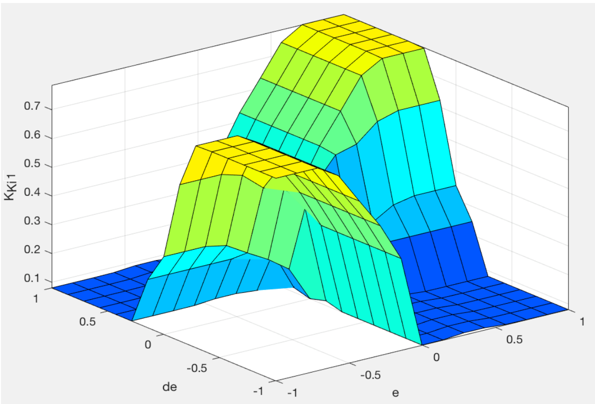
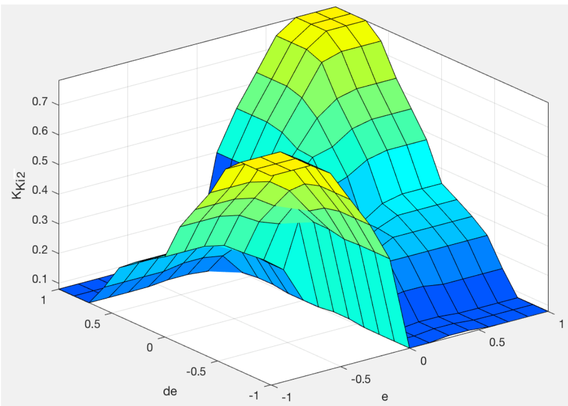
power in a PV-array reach the maximum values when the voltage is about 1,3 kV.

Fig. 5(b) shows the characteristics of the PV source for the uncompensated system regarding the PV voltage (v_{PV}), the PV current (i_{PV}), the diode current (i_{diode}), the irradiation (*irr*) and the temperature (*T*). It confirms that solar irradiation and temperature influence the PV voltage and PV current values. At 25°C, the PV produces electricity proportionally with the irradiation, but when the temperature increases to 75°C, the electric generation decreases slightly. These characteristics reveal the input description to the VSC that converts the voltage to the three-phase type with ***a-b-c*** axis coordinates.



(a) d-axis coordinate

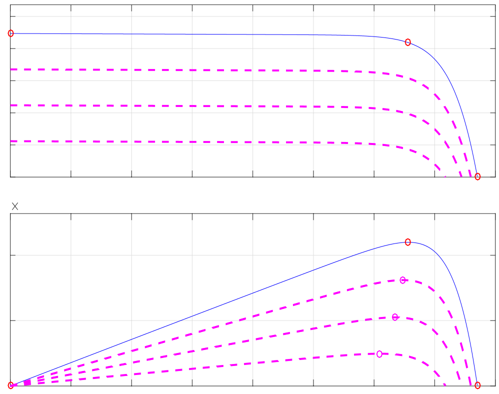


(b) *q*-axis coordinate

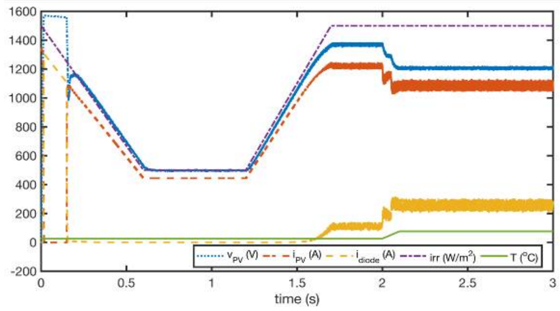
Figs. 4. Surface view of designed rules for *d-q* axis coordinates

III.2. Uncompensated Microgrid System Performance

The performance of the uncompensated or uncontrolled system response to the unit-step input in Fig. 6 shows that it lacks the capability of tracking the setpoint since the voltage is influenced by the intermittent character of the PV source and load uncertainties. The *d*-voltage value (y_1) reveals a more substantial error compared to the reference, which is a unit-step (u_1). Meanwhile, the *q*-axis voltage (y_2) is being a negation of the *q*-axis voltage. Its input (u_2) is zero while another input from the *d*-axis (y_1) gives a coupling effect with a negative number to the *q*-axis due to the 2×2 multiple-input-multiple-output (MIMO) structure of the system. It makes the *q*-axis voltage value affecting the *d*-axis coordinates of voltage. Then, the ***d-q*** axis coordinates that represent V_{abc} magnitude confirm that the system needs to be controlled to improve its voltage regulation. The system has to face the disturbances that are generated by the load uncertainties or others. The disturbances can affect both active and reactive parts of the power quality.



(a)



(b)

Figs. 5. Characteristics of the PV: (a) I-V and P-V of the PV-array, (b) PV-Source

III.3. Compensated Microgrid System Performance

The system involves the disturbances at 0.2 s for both d- and q- axis coordinates as shown in Figs. 7. These disturbances are represented respectively as D1 and D2 in Fig. 2. In the simulation, the voltage disturbances will be multiplied by 20% as the maximum value. Therefore, in total, the disturbances are in range 0–0.2 pu. The controller has to face the disturbances and it has to keep the tracking capability to have less error, especially in a steady state. The responses in d-q axis coordinates will show the performance of the compensated system.

Fig. 8 shows the tracking capability between Fuzzy-IP and PI method to control the system under disturbances. In this case, r_1 (*d*-axis setpoint) is a unit-step reference and r_2 (*q*-axis setpoint) is a zero value reference while y_1 and y_2 are the output signals respectively. The unit-step responses of d-q axis show that Fuzzy-IP is superior to PI, based on transient characteristics, MSE and root mean squared error (RMSE). As the representation of V_{abc}, y_{dq} characteristics using Fuzzy-IP controller are the following: 0.008 s rise time, 5% maximum overshoot, and 0.030 settling time, while using PI rise time and

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settling time are respectively 0.029 s and 0.045 s without overshoot. The transient response shows that system compensates using Fuzzy-IP can react faster. Furthermore, MSE and RMSE using Fuzzy-IP are also better than PI control as listed in Table II.

TABLE II
MSE AND RMSE VALUES: FUZZY-IP VS PI CONTROLLER

Parameters		Response with Fuzzy-IP		PI Controller	
Signal	Ref.	MSE	RMSE	MSE	RMSE
y_1	r_1	0.0014	0.0379	0.0017	0.0411
y_2	r_2	0.29932	0.0173	0.37001	0.0192
y_{dq}	r_{dq}	0.0013	0.0360	0.0015	0.0383

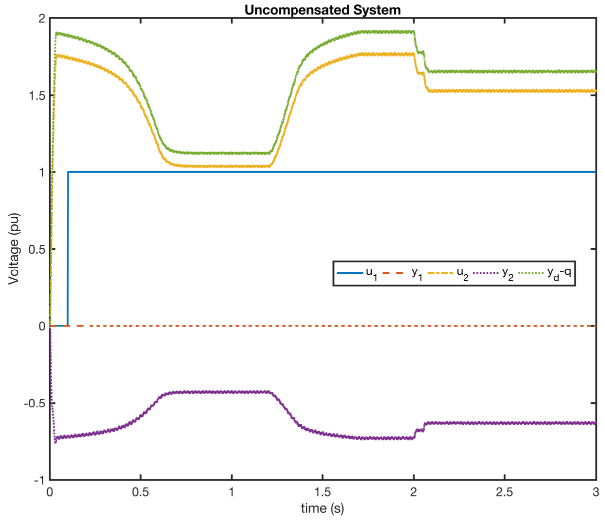
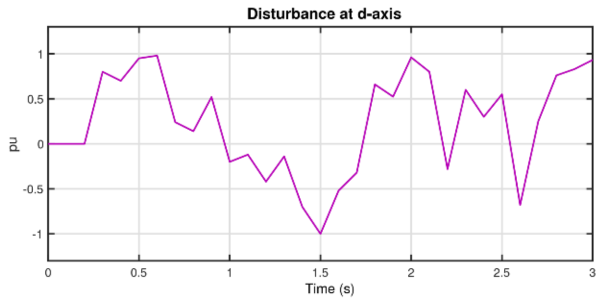
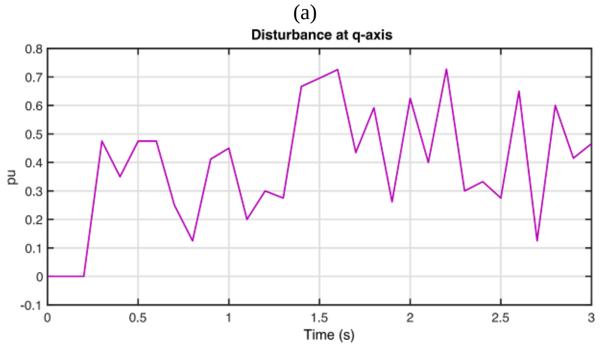


Fig. 6. Unit-step Response of the uncompensated Microgrid System



(a)



(b)

Figs. 7. Disturbance at the Control System Model: (a) D_1 and (b) D_2

Figs. 9 depict the three-phase signal representation that transformed from the *d-q* axis coordinates. It confirms that the system has an excellent response according to the set point during the transient and disturbances either at active (*d*-axis) or reactive (*q*-axis) voltage.

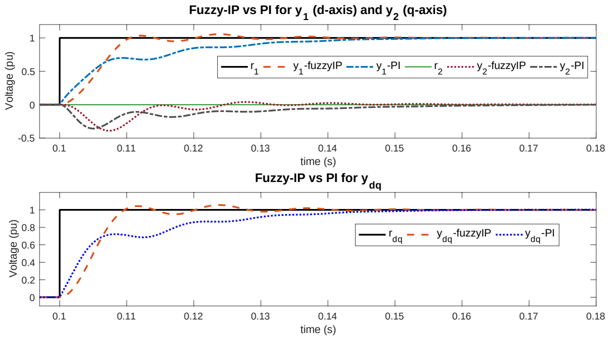
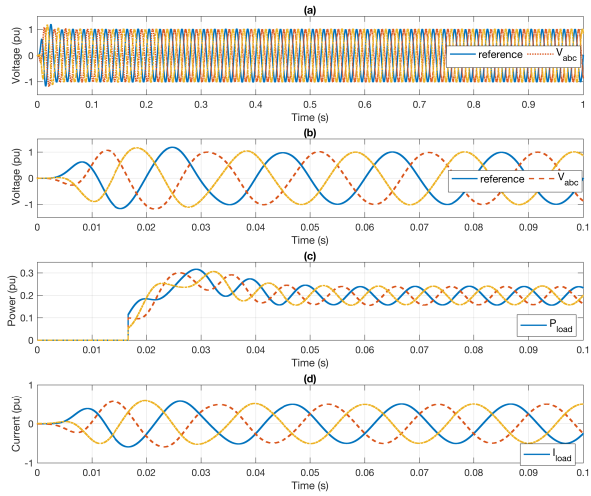


Fig. 8. The unit-step response of the compensated system: Fuzzy-IP vs. PI



Figs. 9. Three-phase Signal Responses of the Compensated System using Fuzzy-IP Controller: (a) Voltage (V_{abc}), (b) V_{abc} at transition, (c) Power, (d) Current

IV. Conclusion

The paper has elucidated the superiority of Fuzzy-IP controller to regulate voltage in a microgrid system during stand-alone mode. In this mode, a microgrid must control the voltage magnitude and frequency independently. The superiority of Fuzzy-IP control has been presented over the conventional voltage control method using PI. It combines fuzzy inference system to set the integral parameters, while the proportional gain is directly connected to the output instead of to the error like in PI. In the recent non-linear technique, the model used to have a complex mathematical and it needed great efforts to handle the dynamics of the system in the simulation. In this paper, transfer functions of the system were modeled using estimation from system identification technique to result in a linear plant model. It makes an effort to find the plant model easier. The *abc-dq* transformation or vice versa has emphasized the appeal of the method being used to ease linear control design from a non-linear plant. Based on the simulation results in Matlab environment, voltage control using Fuzzy-IP in a microgrid system with PV source as DER unit shows an excellent performance confirmed by the reference tracking and the system robustness. Meanwhile, the frequency set by the PLL presented a very less error regarding the standard (i.e., 50Hz). The future work will be to set the controller in a distributed way for the power-sharing using the distribution and scheduling technique that presented in [24].

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