# Fuzzy PID Controller for Accurate Power Sharing in DC Microgrid

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## ABSTRACT

In this paper, an intelligent control scheme based on Fuzzy PID controller is proposed for accurate power sharing in DC Microgrid. The proposed Fuzzy PID controller is designed with the aid of a closed loop control based on per unit power of each distributed generator (DG), and accurate power sharing is successfully realized in proportional to each DG's power rating regardless of the line resistance difference or the load change. Thanks to Fuzzy PID controller, the dynamic response becomes faster and the stability of the microgrid system are improved in comparison to conventional PID controller. The superiority of the proposed method is analyzed and verified by simulation in Matlab and Simulink.

*Keyword: DC Microgrid, power sharing, droop control, fuzzy logic control.*

## 1. INTRODUCTION

In order to deal with the problems related to environmental pollution and exhausted fossil fuel supplies, renewable energy sources (RESs) such as solar cell, wind turbines, and hydrogen power have been widely utilized. To exploit these energy source with high efficiency and good performance, power electronic converters are commonly adopted with RESs and energy storage systems (ESSs) to form distributed generators (DGs) [1], and microgrid (MG) concept has been introduced as a promising solution to integrate DGs and loads, to supply the load power as well as support main grid effectively [2]. The MG is classified into DC MG and AC MG. In comparison with AC MGs, DC MGs have many advantages [3], so the researches on DC MG are increasing with many projects.

In order to achieve power sharing between each DG, droop control method has been generally used without communication network [1][3]. In this method, the voltage of each DG is regulated based on droop gain which is calculated from the rated capacity of the source, and determines the power sharing between DGs. However, because of the line impedance, this method is hard to achieve accurate power sharing.

To overcome these problems, a variety of researches based on a secondary controller have been conducted [1][4]. From the communication perspective, there are two types of secondary control scheme: centralized control and distributed control [1]. Although the centralized control provides a good technical solution to implement the advanced control functionalities, a single point of failure invokes serious problem to the control scheme [1]. This problem can be solved by means of the distributed control scheme [3][4].

In this paper, based on the distributed control scheme, we propose an enhanced fuzzy proportional-integral-derivative (Fuzzy PID) controller in order to achieve accurate power sharing between DGs in DC MG. The proposed Fuzzy PID controller is combined with the advantage of the nonlinear control fuzzy logic control and the zero steady state error of PID controller. Although the Fuzzy PID controller has already introduced in many literatures, the application of Fuzzy PID for accurate power sharing in DC MC has not been presented up to now. The proposed regulator provides outstanding performance, and guarantees system stability in spite of the load change. The effectiveness of the proposed FPID controller is verified by simulation in Matlab and Simulink.

## 2. DROOP AND DISTRIBUTED CONTROLS FOR POWER SHARING IN DC MG

### 2.1. Droop control

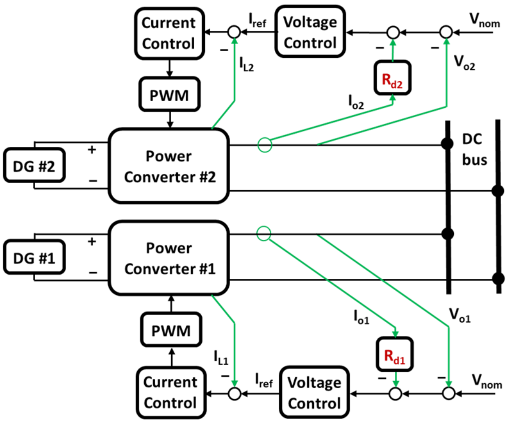


*Fig. 1. Droop control scheme for DC MG.*

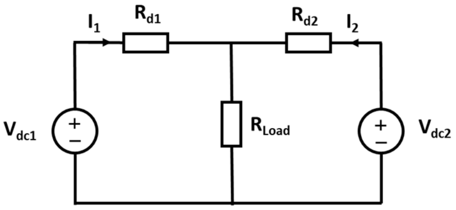


*Fig. 2. Simplified model of two DGs.*

Fig. 1 shows droop control scheme in DC MG, where only two DGs are considered for simple analysis. From Fig. 1, the equivalent circuit can be obtained simply without considering line resistance as shown in Fig. 2, where $R_{d1}$ and $R_{d2}$ are droop coefficient of DG1 and DG2, respectively.

From Fig. 2,

$$V_{dc1} - I_1 R_{d1} = V_{dc2} - I_2 R_{d2} \quad . \tag{1}$$

Without loss of generality, assume that two DGs have the same power rating $P_1 = P_2$ and the same output voltage $V_{dc1} = V_{dc2}$. From (1), $I_1 = I_2$, if $R_{d1} = R_{d2}$. Then, the load power is shared equivalently between two DGs. In droop control scheme, the condition $R_{d1} = R_{d2}$ can be achieved easily by adjusting the droop gain or virtual impedances in droop control scheme in Fig. 1. When the line resistance is considered, the equivalent circuit in Fig. 2 is modified by inserting the line resistance as shown in Fig. 3.

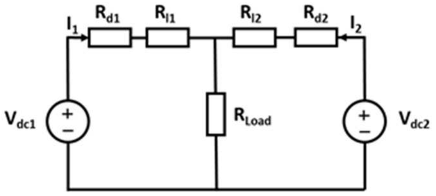


*Fig. 3. Equivalent model with two DGs by considering line resistance*

Then, (2) is obtained from Fig. 3:

$$V_{dc1} - I_1 (R_{d1} + R_{l1}) = V_{dc2} - I_2 (R_{d2} + R_{l2}) \quad , \tag{2}$$

In practical applications, the line resistances are different, i.e., $R_{l1} \neq R_{l2}$. Therefore, load currents are not equal ($I_1 \neq I_2$), and the load power is not equally shared between two DGs.

### 2.2. Distributed control scheme

Based on the conventional droop control, the distributed droop control for accurate power sharing is shown in Fig. 4.

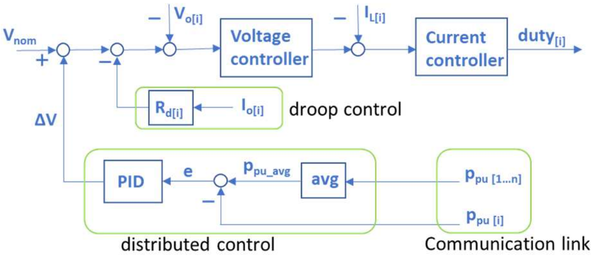


*Fig. 4. Distributed control scheme.*

In Fig. 4, PID controller is used to compensate the voltage magnitude to provide desired output power for accurate power sharing regardless line impedance. The conventional PID controller is defined as following:

$$\Delta V = (k_p + \frac{k_i}{s} + \mathrm{k}_d \mathrm{s})\ (\mathrm{p}_{pu\_avg} - p_{pu[i]})\ , \tag{3}$$

where, $p_{pu\_avg}$, $p_{pu[i]}$ are average per unit power and per unit power of ith DG, respectively.

Power per unit is calculated from voltage and current of DG:

$$p_{pu[i]} = \frac{V_{o[i]} I_{o[i]}}{\mathrm{P}_{rated[i]}}\ , \tag{4}$$

where $V_{o[i]}$, $I_{o[i]}$, $P_{rated[i]}$ are output voltage, output current, and rated power of ith DG, respectively. The measurement signals of voltage and current are obtained through low bandwidth communication link.

In the conventional PID controller, the gains of PID controller for power sharing can be tuned by following Ziegler Nichols procedure. However, the performance of the system highly depends on the load condition. This is simply because the PID gains are tuned under the given load condition such as the maximum load. When the load changes, the performance also changes. Meanwhile, fuzzy PID controller can overcome this problem, and show good system performance over the conventional PID controller. As we know, DC MG is basically nonlinear system with a lot of uncertainty and unpredictability due to noise and disturbance. Therefore, Fuzzy PID controller with nonlinear characteristic is suitable and useful to enhance DG performance to achieve accurate power sharing in DC MG.

## 3. PROPOSED CONTROL STRATEGY

In a period of thirty years, Fuzzy Logic controllers have been widely used for industrial applications. In comparison with the conventional PID controllers, the Fuzzy PID controllers have higher control gains when the system is away from equilibrium state, which enables better performance [5].

Up to now, many different types of Fuzzy PID controllers have been proposed [6], and they can be classified into two major categories according to their constructions [5]. One category of fuzzy PID controllers is composed of the traditional PID controller with a set of fuzzy rules and fuzzy logic mechanism. In this type, the PID gain is tuned according to the knowledge base and fuzzy inference, and the PID controller generates the control signal. Due to the nonlinearity of the fuzzy knowledge, it is hard to analyze the stability and performance of this structure.

In second category of fuzzy PID controllers, the control signal is directly derived from knowledge base, a set of control rules and the fuzzy inference with a typical fuzzy logic. This structure is analogous to that of the PID controller, so it is easy to analyze the performance. Moreover, it is easy to borrow the well known tuning method of the conventional PID controller to design the Fuzzy PID controller.

In this paper, a typical Fuzzy PID controller of second category is selected as shown in Fig. 5.

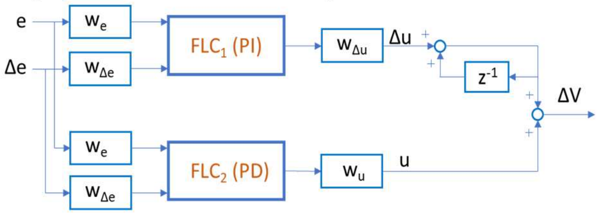


*Fig. 5. Distributed control scheme.*

In Fig. 5, e is the error between average power per unit of all DGs and power per unit of ith DG, Δe is the change of error:

$$\begin{aligned} e(k) &= p_{pu\_avg}(k) - p_{pu[i]}(k) \\ \Delta e(k) &= e(k) - e(k-1) \end{aligned}\ , \tag{2}$$

and $w_e$, $w_{\Delta e}$ are weighting factors, while $w_{\Delta u}$ and $w_u$ are gains of output. The membership function is given simply for easy analysis, and in addition, the nonlinearity of the simplest fuzzy controller is the strongest [7]. It is shown in Fig. 6.

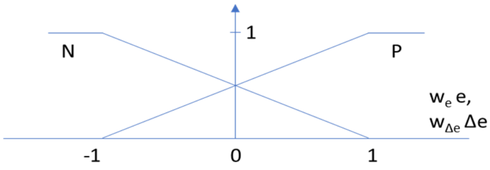


*Fig. 6. Membership functions of $w_e\ e$ & $w_{\Delta e}\ \Delta e$.*

The fuzzy outputs are singletons defined as P=1, Z=0, N=-1. While, the fuzzy control rules are defined :

- If error is N and change of error is N, change in control action is N.
- If error is N and change of error is P, change in control action is Z.
- If error is P and change of error is N, change in control action is Z.
- If error is P and change of error is P, change in control action is P.

The control outputs of each fuzzy logic controller are calculated as following [5]:

$$\begin{aligned} \Delta u &= \frac{w_{\Delta u}}{4 - 2\max(w_e |e|, w_{\Delta e} |\Delta e|)} (w_e e + w_{\Delta e} \Delta e) \\ \Delta u &= \frac{w_{\Delta u}}{4 - 2\alpha} (w_e e + w_{\Delta e} \Delta e) \end{aligned}\ , \tag{6}$$

$$\begin{aligned} u &= \frac{w_u}{4 - 2\max(w_e |e|, w_{\Delta e} |\Delta e|)} (w_e e + w_{\Delta e} \Delta e) \\ u &= \frac{w_u}{4 - 2\alpha} (w_e e + w_{\Delta e} \Delta e) \end{aligned}\ , \tag{7}$$

where $\alpha = \max(w_e |e|, w_{\Delta e} |\Delta e|)$.

The total fuzzy control output becomes

$$\begin{aligned} \Delta V &= \sum_0^k \Delta u + u \\ &= \sum_0^k \frac{w_{\Delta u} w_{\Delta e}}{4 - 2\alpha} (\Delta e + \frac{\Delta t}{\frac{w_{\Delta e}}{w_e} \Delta t} e) + \frac{w_u w_e}{4 - 2\alpha} (e + \frac{w_{\Delta e} \Delta t}{w_e} \frac{\Delta e}{\Delta t}) \end{aligned}\ . \tag{8}$$

If we define the parameters in (8) as following:

$$K_c^{(F)} = \frac{w_{\Delta u} w_{\Delta e}}{4-2\alpha}; \quad \mathrm{T}_i^{(F)} = \frac{w_{\Delta e}}{w_e}\Delta t; \quad \mathrm{K}_c^{(F)}\frac{T_d^{(F)}}{T_i^{(F)}} = \frac{w_u w_e}{4-2\alpha}, \qquad (9)$$

the proposed Fuzzy PID control output is finally given in (10) from (8):

$$\Delta V = \sum_0^k K_c^{(F)}\left(\Delta e + \frac{\Delta t}{T_i^{(F)}} e\right) + K_c^{(F)}\frac{T_d^{(F)}}{T_i^{(F)}}\left(e + T_i^{(F)}\frac{\Delta e}{\Delta t}\right), \qquad (10)$$

In order to verify the proposed Fuzzy PID controller relevance to the conventional PID controller, the Fuzzy PID controller in (10) is investigated by analogy with the conventional PID controller. By substituting $\frac{\Delta e}{\Delta t}$ with $\frac{de}{dt}$ into (10), the total control output of fuzzy controller becomes

$$\Delta V \approx \int_0^{k.\Delta t} K_c^{(F)}\dot{e}\,dt + \int_0^{k.\Delta t}\frac{K_c^{(F)}}{T_i^{(F)}} e\ \mathrm{d}t + \frac{K_c^{(F)}T_d^{(F)}}{T_i^{(F)}}(e + \mathrm{T}_i^{(F)}\dot{e}) \ ,(11)$$

(11) has similar shape as that of the conventional PID controller in (12):

$$u_{PID} = \int_0^t K_c\dot{e}\,dt + \int_0^t \frac{K_c}{T_i} e\,dt + \frac{K_c T_d}{T_i}(e + T_i\dot{e}), \qquad (12)$$

Therefore, we can say the Fuzzy PID controller in (10) is designed reasonably, and its design process is summarized as following: firstly, tune the parameter of PID controller: $K_c$, $T_i$, $T_d$ by means of well known method such as the Ziegler - Nichol rules, secondly, weighting factors and gains of control output: $w_e$, $w_{\Delta e}$, $w_u$, $w_{\Delta u}$ are calculated from (9) based on the selected control parameters $K_c$, $T_i$ and $T_d$. The overall block diagram for distributed control with Fuzzy PID controller is shown in Fig. 7 respect to Fig. 4.

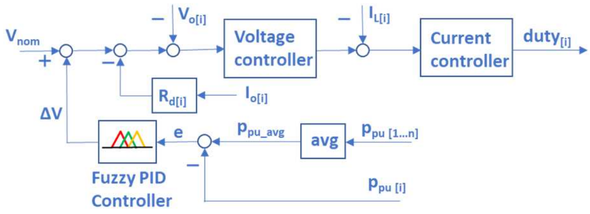


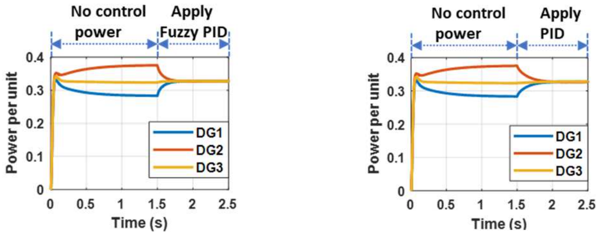
*Fig. 7. Overall block diagram with Fuzzy PID controller.*

## 4. SIMULATION RESULTS

To verify the effectiveness of the proposed Fuzzy PID controller, DC MG with 3 DGs is simulated by means of Matlab and Simulink. Each DG consists of a buck converter with the parameters given as: $V_{in}$ = 200V; $V_{nom}$ = 100V; $L_1$ = $L_2$ = $L_3$ = 0.5mH; $C_{in}$ = $C_{out}$ = 2200uF; $R_{line1}$ = 0.1Ω; $R_{line2}$ = 0.2Ω; $R_{line3}$ = 0.15Ω; $P_{rated1}$ = $P_{rated2}$ = $P_{rated3}$ = 1kW; $f_{sw}$ = 20kHz; $T_{sample}$ = 50μs; $K_c$ = 9.965; $T_i$ = 0.285; $T_d$ = 0.0001; $w_e$ = 0.2; $w_{\Delta e}$ = 1140; $w_u$ = 0.07; $w_{\Delta u}$ = 0.035.

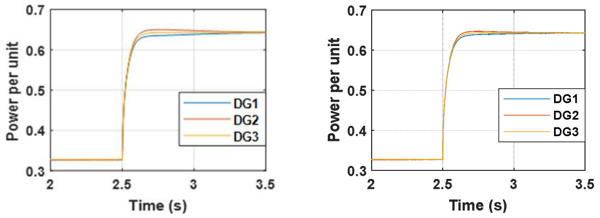
Fig. 8 shows the dynamic performance of the system with the conventional PID and Fuzzy PID controllers. From 0 to 1.5s, because the power sharing controller is not active, the per unit power of each DG is different due to the different line resistance. At 1.5s, accurate power sharing scheme becomes active, and the Fuzzy PID has better performance with faster response and shorter settling time comparing to the conventional PID controller.

Fig. 9 shows the dynamic response of system when the load changes from 1kW to 2kW at 2.5s. In comparison with the conventional PID controller, the Fuzzy PID controller has smaller overshoot, and faster response. As a result, it is clear that the proposed Fuzzy PID shows very good dynamic performance compared with the conventional PID controller.



*(a)* *(b)*

*Fig. 8. Dynamic respone of system with*
*(a) conventional PID controller (b) Fuzzy PID controller.*



*(a)* *(b)*

*Fig. 9. Dynamic performance of system under load change*
*(a) conventional PID controller (b) Fuzzy PID controller.*

## 5. CONCLUSION

This paper has presented an intelligent control approach based on the fuzzy logic controller to achieve accurate power sharing in DC microgrids. The nonlinear properties of Fuzzy PID controller with variable control gains brings enhanced control performance in comparison with the traditional PID. The validity of the proposed Fuzzy PID controller is confirmed through simulation in Matlab & Simulink, and simulation results have shown the effectiveness of the method.

## 6. ACKNOWLEDGMENTS

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