

# A Fuzzy Control Based Coordinated Method for Isolated Power Utility Connected Clustered Photovoltaic Systems to Provide Frequency Control

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**Abstract**—A Photovoltaic system’s output power is not constant and fluctuates depending on weather conditions. Fluctuating power causes frequency deviations and reduction in reliability of the isolated power utility or micro grid when large output power from several Photovoltaic systems is penetrated in the utility. In this paper, to overcome this problem, a simple coordinated control method for clustered Photovoltaic systems is proposed to provide the frequency control. Here, output power command is generated in two steps: central and local. Fuzzy control is used to generate the central output power command considering average insolation, change of insolation, and frequency deviations. In the local step, a simple coordination is maintained between the central power command and the local power commands by producing a common tuning factor. The proposed method is compared with the method where extracted maximum power is supplied to the utility. Simulation results show that the proposed method is feasible to reduce the frequency deviations of the isolated power utility and delivers the power near maximum Photovoltaic power.

**Index Terms**—photovoltaic system, fuzzy control, coordinated method, frequency control.

## I. INTRODUCTION

Among various renewable energy systems, photovoltaic (PV) power systems are expected to play an important role as a clean electricity power source in meeting future electricity demands. However, the power output of PV systems fluctuates depending on weather conditions. In the future, when a significant number of PV systems will be connected to the grids of power utilities, combined power output fluctuations may cause problems like voltage fluctuation and large frequency deviation in electric power system operation [1]-[3]. To date it has not been necessary for PV generators to provide frequency regulation services to the power system. In the future, with an increasing penetration of PV generation, their impact upon the overall control of the power system will be significant [4]. This will lead a situation where the PV generators will be required to share some of the duties, such as frequency control. Therefore, for the penetration of multiple or clustered PV systems output power in the utility without reduction of the reliability of utility power systems, suitable measures must be applied to the PV systems side.

On the PV system side, storage devices like batteries can be used as smoothing devices for a PV system’s output [5]-[8]. However, the capital cost and maintenance cost of batteries is a barrier to the large scale installation of PV systems and used batteries must be disposed of without causing environmental problems [9], [10]. Besides, these methods can not control the PV output power considering the power utility condition like load variation. Power characteristics of PV arrays are presented in [11] where monitored data from 100 PV systems are used to study the effects of combined power generation of these systems, compared to the characteristics of an individual system. It is claimed that a significant amount of power fluctuations disappeared, however, large amount of short term power fluctuations remained. In addition, when the number of PV power generation systems are decreased, the power fluctuations increased. Smoothing of PV system output by tuning maximum power point tracking (MPPT) control is demonstrated in [12]. In this method, when the insolation increases rapidly, the operating MPPT point changes to a new point where the maximum power is not generated with the current insolation. However, the condition of power utilities like frequency deviation is not considered for tuning the MPPT and for limiting the new output voltage. All of these methods tried to smooth the fluctuating PV power. However, none of them gives emphasis on controlling the PV power according to the load variation. Therefore, these methods have no sharing of the duties like frequency control.

To improve the contribution of distributed generation significantly in the existing electrical networks, which poses new technical and economical challenges to power system control and management, coordinated control of distributed resources is necessary. A coordinated management of a diesel power plant and a PV array is suggested in [13] in order to fully exploit the PV renewable energy. However, this coordination is not for clustered PV systems and it did not deal with the problems introduced in the power utility by the output power fluctuations of PV generators.

In this paper, a new and simple coordinated method for clustered PV systems to provide the frequency control is proposed. In this approach, the PV systems output power control

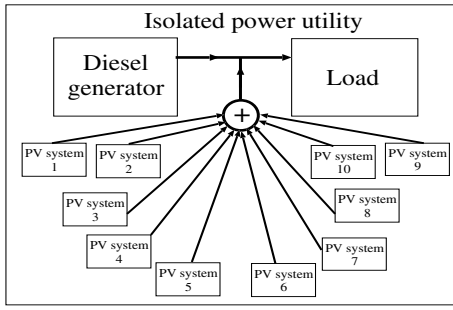


Fig. 1. Concept of isolated power utility.

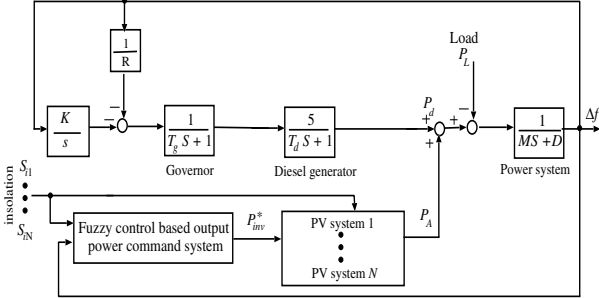


Fig. 2. Isolated power system model.

is achieved by two levels: central and local. In the central control, insulations from all PV systems are added together and an average insolation is formed. Based on this average insolation and power systems condition, the central output power command is derived. This method uses fuzzy control [14], [15] to produce the central output power command. The fuzzy control has three inputs and they are frequency deviation, average insolation, and change of insolation. Here, the central output power command decreases in time to respond to a low frequency deviation. On the other hand, the central output power command increases to respond to a high frequency deviation. In the local control, MPPT command is generated for each of the PV systems by Perturb and Observe (P&O) method [16]. All maximum power commands are summed up together and by dividing the central power command by this sum, a common tuning factor is generated. This tuning factor is multiplied with each of the individual maximum power command to produce new local power commands for each of the PV power generation systems. The proposed method is compared with the method where MPPT control is used for each of the PV systems without any coordination. Through simulation results, it is found that the proposed method is effective in achieving the following key features: reduction of the frequency deviations to maintain the reliability of power utility, and supplying the possible maximum amount of PV power to the utility.

## II. ISOLATED POWER UTILITY

The concept where clustered PV systems are connected to the isolated power utility is shown in Fig. 1. The isolated

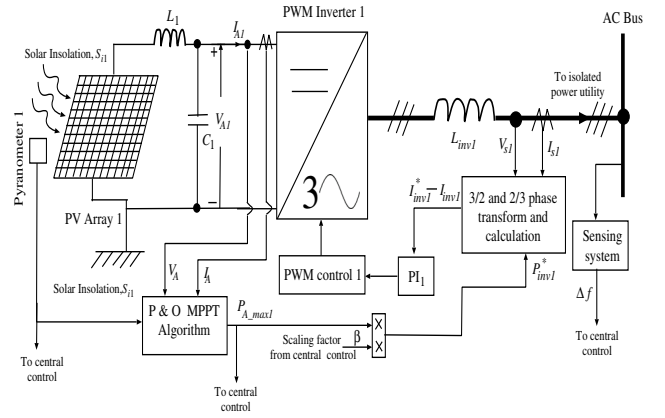


Fig. 3. Single PV power generation system.

power utility consists of the diesel generator and ten PV systems that generates power to supply the load. In addition, it is assumed that the isolated power utility is not connected to large power utility and it is always operated independently as a stand-alone system.

The isolated power system model consisted of a diesel generator, clustered PV systems and load is shown in Fig. 2, where  $S_i$  is the insolation,  $N$  is the total number of PV systems,  $P_{inv}^*$  is the central command power generated by the fuzzy based central output power command generation system,  $P_A$  is the combined power generated by  $N$  PV systems,  $P_d$  is the generated power by diesel generator,  $R$  is the speed regulation,  $T_g$  is the governor time constant,  $T_t$  and  $T_r$  are the time constants,  $P_L$  is the load,  $M$  is the inertia constant,  $D$  is the damping constant, and  $\Delta f$  is the frequency deviation of isolated power utility. The control of diesel generator described in [13] is also used in this paper to fully exploit the renewable energy.

In Fig. 3, single PV power system including a PV array, an inverter and a PI controller is shown where  $V_{A1}$  is the PV array voltage,  $I_{A1}$  is the PV array current,  $V_{s1}$  is the generated supply voltage and  $I_{s1}$  is the generated supply current by the inverter, and  $|I_{inv1}^* - I_{inv1}|$  is the error between the command current and the produced current. The control algorithm for the inverter [17] adopted here is very simple. The inverter output voltages and currents are sensed and transformed from 3-phase to synchronously rotating 2-phase. The command currents are generated by dividing the local output power command by sensed inverter voltage. Then the error between command inverter current and actual inverter current is processed through a PI controller to generate the PWM pulses.

## III. COORDINATED OUTPUT POWER COMMAND GENERATION SYSTEM

To control the combined output power of clustered PV systems considering the power utility and insolation conditions, output power command is generated in two levels: central and local. Individual local output power commands are given to each of the PV systems by maintaining a coordination

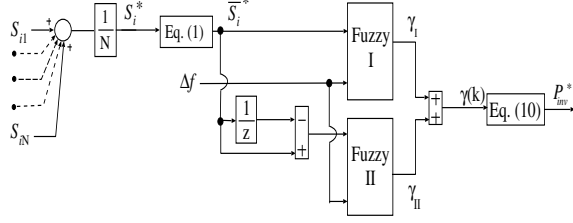


Fig. 4. Fuzzy based central output power command generation system.

TABLE I  
FUZZY RULES OF FUZZY CONTROL I

		$\Delta f$						
		NB	NM	NS	ZO	PS	PM	PB
$\bar{S}_i^*$	NB	NB	NB	NB	NB	NM	NS	ZO
	NB	NB	NB	NB	NM	NS	ZO	PS
	NS	NB	NB	NM	NS	ZO	PS	PM
	ZO	NB	NM	NS	ZO	PS	PM	PB
	PS	NM	NS	ZO	PS	PM	PB	PB
	PM	NS	ZO	PS	PM	PB	PB	PB
	PB	ZO	PS	PM	PB	PB	PB	PB

NB=Negative Big    NM=Negative Medium    NS=Negative Small  
 PB=Positive Big    PM=Positive Medium    PS=Positive Small  
 ZO=Zero

between central and local levels to produce combined PV output power same as central output power command. Central output power command  $P_{inv}^*$  is decided by the fuzzy based output power command generation system shown in Fig. 4. This central output power command system consists of two fuzzy reasonings. Fuzzy reasoning is described by a set of “if-then” based fuzzy rules.

First, fuzzy control I is explained. There are two inputs of fuzzy control I. One is frequency deviation  $\Delta f$ , and the other is average insolation  $\bar{S}_i^*$ . Average insolation  $\bar{S}_i^*$  is defined by

$$\bar{S}_i^* = \frac{1}{T} \int_{t-T}^t S_i^* dt \quad (1)$$

where

$$S_i^* = \frac{1}{N} \sum_{N=1}^N S_{iN} \quad (2)$$

where  $t$  is the present time,  $T$  is the integral interval,  $S_{iN}$  is the instantaneous insolation of each PV system,  $S_i^*$  is the summation of insolation of all PV systems divided by  $N$ . Fuzzy rules and membership functions of fuzzy control I are shown in TABLE I and Fig. 5, respectively. Fuzzy rules and membership functions that yield an output to decrease the frequency deviation are defined by trial-and-error. The  $i$ th fuzzy rule is expressed as

$$\text{Rule } i: \text{ if } \Delta f \text{ is } L_x \text{ and } \bar{S}_i^* \text{ is } M_y \text{ then } \gamma_I \text{ is } Z_l \quad (3)$$

$$x = 1, 2, \dots, 7, \quad y = 1, 2, \dots, 7, \quad l = 1, 2, \dots, 7$$

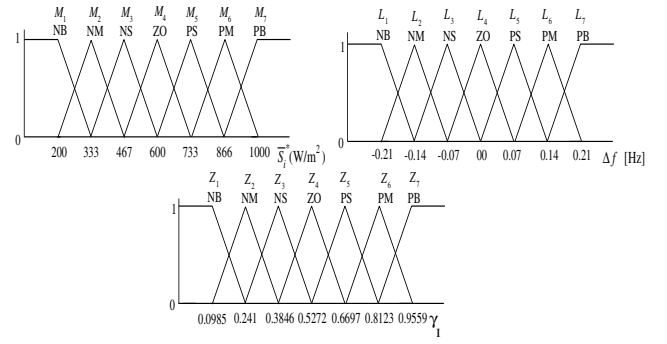


Fig. 5. Membership functions of fuzzy control I.

TABLE II  
FUZZY RULES OF FUZZY CONTROL II

		$\Delta f$						
		NB	NM	NS	ZO	PS	PM	PB
$\Delta \bar{S}_i^*$	NB	NB	NB	NB	NM	NM	NS	ZO
	NM	NB	NB	NM	NM	NS	ZO	PS
	NS	NB	NM	NM	NS	ZO	PS	PM
	ZO	NM	NM	NS	ZO	PS	PM	PM
	PS	NM	NS	ZO	PS	PM	PM	PB
	PM	NS	ZO	PS	PM	PM	PB	PB
	PB	ZO	PS	PM	PM	PB	PB	PB

NB=Negative Big    NM=Negative Medium    NS=Negative Small  
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 ZO=Zero

where  $L_x$ ,  $M_y$  denote the antecedents and  $Z_l$  are consequent part. Fuzzy control I output,  $\gamma_I$ , is calculated by

$$\gamma_I = \frac{\sum_{i=1}^{49} w_i Z_l}{\sum_{i=1}^{49} w_i} \quad (4)$$

where  $w_i$  denotes the grade for the antecedent and is obtained by

$$w_i = w_{\Delta f i} w_{\bar{S}_i^* i} \quad (5)$$

where  $w_{\Delta f i}$  and  $w_{\bar{S}_i^* i}$  are the grade of antecedents for each rule.

Second, fuzzy control II is explained. Frequency deviation  $\Delta f$  and change of average insolation  $\Delta \bar{S}_i^*$  are used as inputs of fuzzy control II, where  $\Delta \bar{S}_i^*$  is expressed as

$$\Delta \bar{S}_i^* = \bar{S}_i^*(t-1) - \bar{S}_i^*(t) \quad (6)$$

Fuzzy rules and membership functions of fuzzy control II are shown in TABLE II and Fig. 6, respectively. Setup of fuzzy rules and parameters of membership functions are determined to prevent boosting of frequency deviation. The fuzzy rules of fuzzy control II are same as fuzzy control I and will not be discussed any further.

The fuzzy rules and membership functions presented in fuzzy controls I and II are defined by trial-and-error. However, it is possible to tune the parameters of controllers and membership functions of fuzzy reasoning to achieve frequency

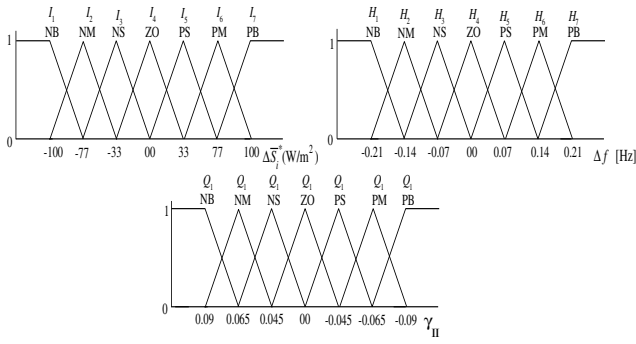


Fig. 6. Membership functions of fuzzy control II.

control and maximum capture of available PV power. A variety of methods have been proposed for tuning the fuzzy controller such as self-tuning algorithm based on an experimental planning method [18], in which the scaling factors of optimal parameters can be determined efficiently according to the desired performance indexes, Taguchi tuning method [19], and tuning the membership functions [20], [21]. Most of these methods need performance index. Two performance indexes can be made based on frequency deviation (tends to zero) and PV output power (tends to maximum). However, the main purpose of this research is show a simple approach of providing frequency control from PV system's side by using conventional fuzzy control. Therefore, no new development of fuzzy logic is presented in this paper.

The sum of outputs of fuzzy control I,  $\gamma_I$ , and fuzzy control II,  $\gamma_{II}$  become central output power command by using the following equation:

$$P_{inv}^* = NP_{rated} \left\{ \gamma(k) + \frac{\gamma(k+1) - \gamma(k)}{T_s} f(t) \right\} \quad (7)$$

where  $P_{rated}$  is the rated output power of one PV system,  $T_s$  is the sampling time,  $f(t)$  is a periodic function such that  $f(t) = t$  ( $0 < t < T_s$ ).

After generating the central output power command, local output power command for each of the PV systems is produced by a simple coordinated control. The  $N$  PV systems with coordinated control are shown in Fig. 7. Here the combined PV output power  $P_A$  is expressed as

$$P_A = \sum_{N=1}^N P_{AN} \quad (8)$$

where  $P_{AN}$  is the output power of each PV system. In order to achieve the combined output power,  $P_A$ , equal to the central output power command,  $P_{inv}^*$ , coordinated control method for each of the PV systems is employed. To generate coordination between the central power command and the individual local power commands, a common tuning factor  $\beta$  is formulated. The tuning factor  $\beta$  can be expressed as

$$\beta = \frac{P_{inv}^*}{\sum_{N=1}^N P_{AmaxN}} \quad (9)$$

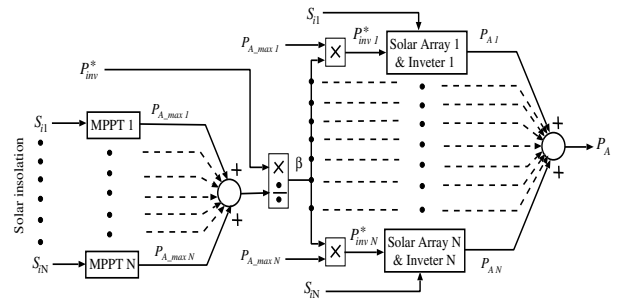


Fig. 7. Coordinated local output power command generation system.

TABLE III  
SIMULATION PARAMETERS

Parameters of small power system	
Inertia constant, $M$	0.150 puMW·s/Hz
Damping constant, $D$	0.008 puMW/Hz
Governor time constant, $T_g$	0.10 s
Time constant, $T_t$	0.25 s
Time constant, $T_r$	8.0 s
Speed regulation, $R$	2.5 Hz/puMW
Parameters of PV array	
Rated output power	225 kW
Open circuit voltage, $V_{oc}$	584 V
Short circuit current $I_{sc}$	526.50
Number of module in series	16
Number of module in parallel	65
Total no. of cells	62,400
Parameters for power conditioning system	
Inverter power rating	225 kW
Nominal ac output voltage	480 V (3-phase)
Nominal ac output frequency	50 Hz
Maximum ac line current	271 A rms
Maximum dc input voltage	600 V
Maximum dc input current	781 A
Efficiency	94.5%
Parameters for PI controller	
Proportional constant, $K_P$	0.1
Integral constant, $K_I$	10

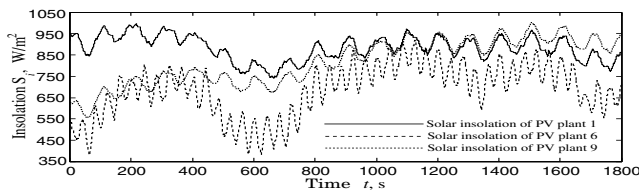
where  $P_{AmaxN}$  is the MPPT output power command of each PV system.

The individual local output power command for each of the PV systems can be obtained by the following equation

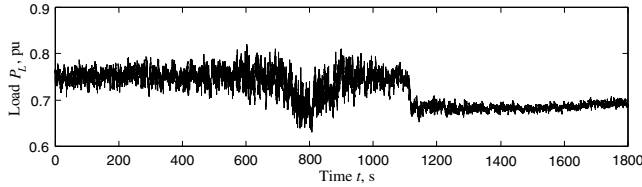
$$P_{invN}^* = P_{AmaxN} \times \beta \quad (10)$$

#### IV. SIMULATION RESULTS

In this paper, effectiveness of the proposed coordinated method is examined by simulation with the system model and parameters mentioned in [22]-[25]. In order to use parameters of the real systems given in [24], [25], the rated output power of each PV array is 225kW. The total number of PV system used in this paper is 10 and the combined rated output power of ten PV systems is 2.25 MW. Simulation parameters for power system, PV array, and power conversion system are shown in TABLE III. Integral time  $T$  is 100s, and sampling



(a) Insolations of PV plant 1, 6, and 9.



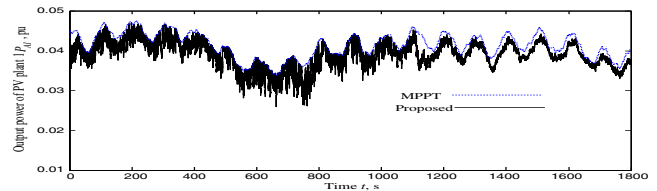
(b) Load,  $P_L$ .

Fig. 8. Insolation patterns and load.

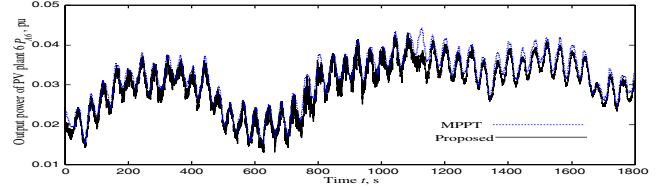
time  $T_s$  to obtain discrete value of output power command is 10s. Simulation time is 30 minutes.

Different insolation patterns are used for PV systems. Insolation patterns for PV plants 1, 6, and 9 are shown in Fig. 8(a). Load is shown in Fig. 8(b). The comparative simulation results using the MPPT control [16] and the proposed coordinated control are shown in Fig. 9. Figs. 9 (a) and (b) show the output power produced by the coordinated method and MPPT control for PV plants 1 and 6 respectively. From these figures, it is seen that the individual output power of each PV plant fluctuates more than the MPPT power to reduce the frequency deviations. Fig. 9(c) shows the combined PV output power for the MPPT control and for the proposed coordinated control. From Fig. 9(c), it is observed that the proposed method produces power near the MPPT power as the power delivered by the proposed method touches the maximum power curve at many points. Besides, the power produced by proposed method is controlled according to the frequency deviations. Therefore, it is more fluctuating than the MPPT power. However, the proposed method costs some PV power loss. This power loss can be avoided by using a small capacity energy storage system (ESS) with each of the PV systems.

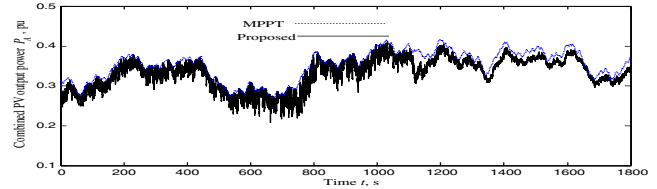
Output power of diesel generator is shown in Fig. 9(d). From Fig. 9(d), it is observed that the diesel generator output produced with the MPPT control fluctuates more in order to minimize the frequency deviations introduced by the MPPT generated PV power and the load. On the other hand, diesel generator power produced with the proposed method fluctuates less as the combined PV output power produced by the proposed method is controlled considering the frequency deviations. As the diesel generator's response is slow, less fluctuating diesel power is good for the practical operation. Fig. 9(e) shows the frequency deviation. From Fig. 9(e), it is observed that frequency deviation produced with the MPPT control deviates more than  $\pm 0.3$  Hz frequently. This is a severe problem for maintaining the power system reliability. Therefore, the combined output power of ten PV



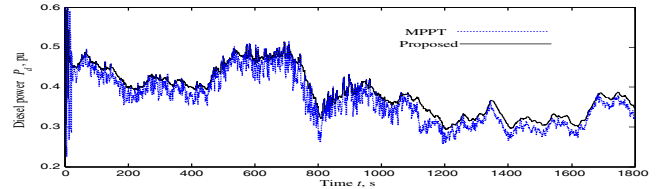
(a) Output power of PV plant 1,  $P_{A1}$ .



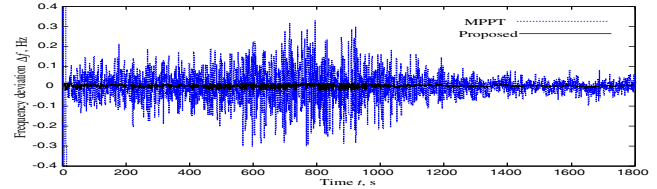
(b) Output power of PV plant 6,  $P_{A6}$ .



(c) Combined output power of ten PV plants,  $P_A$ .



(d) Output of diesel generator,  $P_d$ .



(e) Frequency deviation of power utility,  $\Delta f$ .

Fig. 9. Comparative simulation results of the proposed method and the MPPT control [16].

plant produced by the MPPT control has harmful effects on the power system. However, the frequency deviation produced with the proposed method is almost zero. Therefore, the proposed method is effective in maintaining power system reliability and in providing frequency control.

## V. CONCLUSION

This paper presents a simple coordinated control method for the isolated power utility connected multiple PV plants to introduce the frequency control. Here the output power command is generated in two steps. In the central step, output power command is defined by the fuzzy control, which has three inputs of frequency deviation, average insolation, and

change of insolation. Setup of fuzzy rules and parameters of membership functions are determined to prevent the increase of frequency deviations. Local output power command for each of the PV plants is generated by coordination between the central power command and the MPPT command. The proposed coordinated method increases or decreases the PV output power to respond to a high frequency or to a low frequency. From the simulation results, it can be said that the PV systems with the proposed coordinated method achieve flexible output power control, is effective in reducing the frequency deviations significantly in comparison with the MPPT control, and delivers the PV power near the maximum PV power. However, it produces some PV power loss which can be avoided by using small capacity ESS (for example, an electric double layer capacitor which is suitable for quick charge/discharge action). The current practice to reduce frequency deviations is the smoothing of PV output power fluctuations. However, the proposed method shows a new and simple coordinated control for isolated utility connected clustered PV systems to reduce the frequency deviations without smoothing the PV output power fluctuations. Therefore, it can be said that proposed method can be used to share some of the duties like frequency control.

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