

Fuzzy Control of MW-class PV Generation to Reduce Frequency and Tie-line Power Fluctuations in Three Control Area Power System

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Abstract—This paper presents a fuzzy based frequency control strategy by grid-connected MW class PV generation. The frequency control is proposed from the view point of the frequency fluctuation problem produced by the large penetration of PV power. The fuzzy control has three inputs: average insolation, change of insolation and system frequency deviation. Following these three inputs, a frequency control system of the PV inverters is proposed. For the case of different insulations, a coordinated inverter and battery control method is presented. The proposed method is simulated in three control area power system by considering dual power and information flows between supply and demand sides and is found satisfactory to provide frequency control and to reduce tie-line power fluctuations.

Keywords—fuzzy control, frequency deviations, MW-class PV, tie-line power fluctuations

I. INTRODUCTION

PV systems are expected to play a vital role in the future energy efficient and zero emission society. Recently, along with the smart grid, large PV power generation is getting enormous attraction. The penetration of PV systems in Japan is rising. Two factors have been boosting this: improved generation efficiency of PV modules and governmental subsidies [1]. However, PV power fluctuates depending on the weather conditions, season, and geographic location and causes problems like voltage fluctuation and large frequency deviation in an electric power system operation [2]-[4].

The integration of a large number of embedded PV generators will have far reaching consequences not only on the distribution networks but also on the national transmission and generation system. If the PV generators are built on the roof and sides of buildings, most of them will be located in urban areas and will be electrically close to loads. On the other hand, these PV generating units may be liable to common mode failures that might cause the sudden or rapid disconnection of

a large proportion of operating PV capacity. However, considering the recent grid codes in Germany and Spain [5], PV generators should provide dynamic grid support e.g. voltage stability during voltage drops which is often referred to as Fault-Ride-Through (FRT) capability and frequency control.

Whether many studies are dedicated to the voltage control by PV inverters, this paper provides a strategy of frequency control by the grid-connected PV systems. The frequency control strategy is developed based on fuzzy logic [6] and is tested by simulation in a three control area power system and is compared with a conventional energy storage system (ESS) based smoothing method of PV output power fluctuations [1]. From the simulation results, it is found that the proposed frequency control method shows satisfactory performances and reduces the tie-line power fluctuations.

II. SYSTEM DESCRIPTION AND METHODOLOGY

To illustrate, frequency control performance by MW-class PV generation in a multi-area power system, three identical interconnected control areas are considered and is shown in Fig. 1. A generalized load frequency model in the presence of frequency control from PV generation is shown in Fig. 2[7]. The simulation parameters are given in Table I.

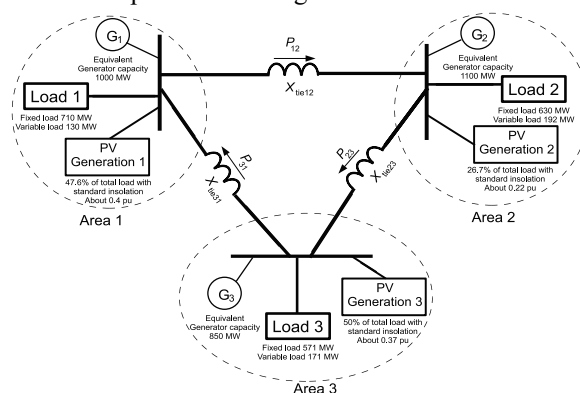


Fig 1. Three control area power system.

TABLE I. SIMULATION PARAMETERS FOR FIG. 2

Area	$K(s)$	D (pu/Hz)	$2H$ (pu s)	R (Hz/s)	T_g (s)	T_i (s)	β (pu/Hz)	T_{ij} (pu/Hz)	Generation Capacity	Load	PV Penetration
Area1	-0.3	0.015	0.1667	3.00	0.08	0.40	0.3483	$T_{12}=0.20$ $T_{13}=0.25$	1000 MW	Fixed 710 MW Variable 130 MW	47.60% of total load
Area 2	-0.2	0.016	0.2917	2.73	0.06	0.44	0.3827	$T_{21}=0.20$ $T_{23}=0.12$	1100 MW	Fixed 630 MW Variable 192 MW	26.70% of total load
Area 3	-0.4	0.015	0.1247	2.82	0.07	0.30	0.3692	$T_{31}=0.25$ $T_{32}=0.12$	850 MW	Fixed 571 MW Variable 171 MW	50.00% of total load

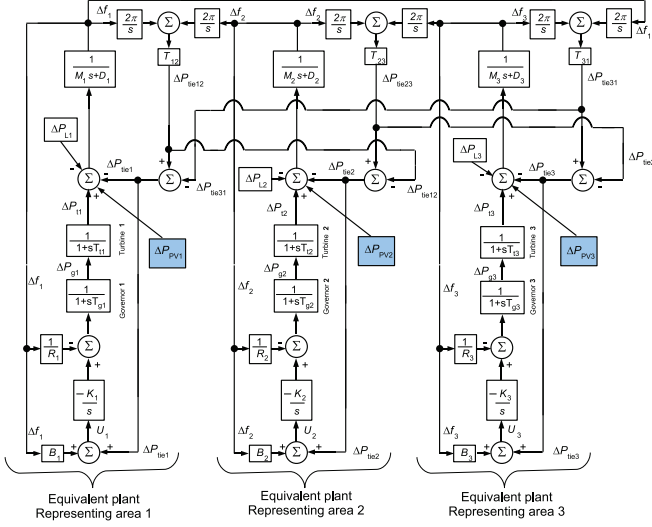


Fig. 2. Frequency control model with considering frequency control from PV generation.

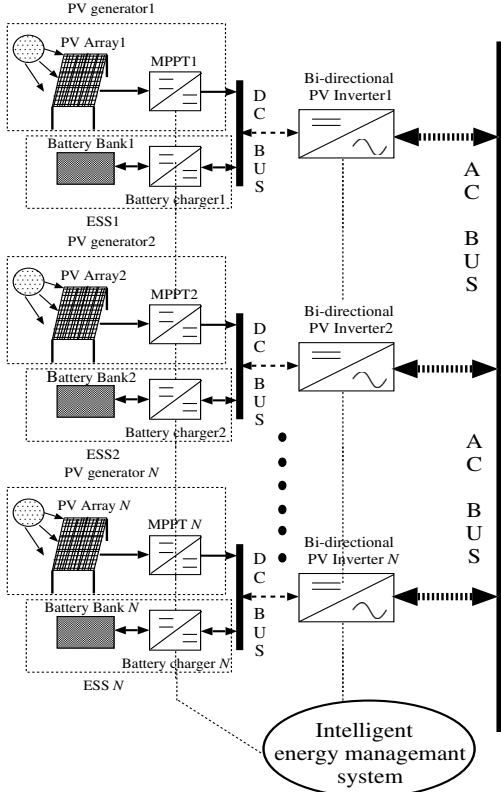


Fig. 3. Multiple PV generators are connected in coordinated control mode.

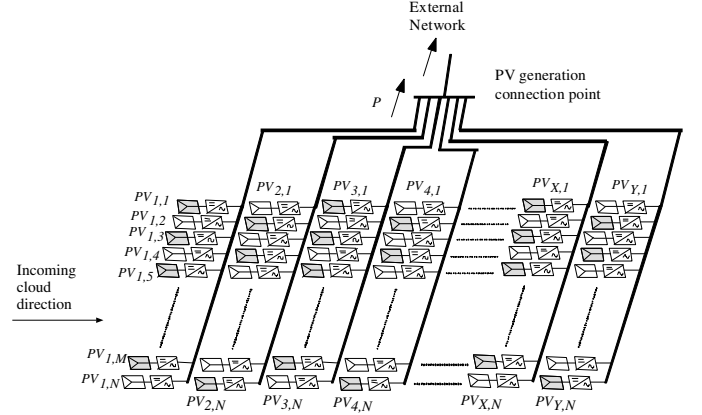


Fig. 4. The aggregate model of large PV plant connected to the power grid.

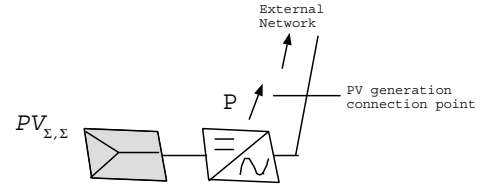


Fig. 5. One-PV generator equivalent.

A. Simplification of aggregate model of grid-connected PV generation

Commonly, grid-connected PV generation consist of a large number of relatively small PV units. This distributed generation can be represented by an equivalent PV generation plant whose rating is equal to the sum of the ratings of the individual PV generating units. A distributed PV generation systems with multiple PV generators is show in Fig. 3. An individual PV generator is consisted of a large PV array, a MPPT controller, and an ESS. The operational points of the individual PV generating units are determined by the insolation value and the frequency control algorithm. The aggregate model of the large-scale PV plant thus comprises $N \times Y$ PV generating units of G MW power capacity each where N is the number of PV generating unit in row and Y is the number of PV generating unit in column. The installed capacity of the equivalent PV plant is thus $N \times Y \times G$ MW. The model is shown in Fig. 4. However, the MPPT module and battery module of each PV system are not shown.

Uniform Insolation Distribution

In this case the PV generating units within the plant are assumed to have the same operating points. When reducing the

aggregate model of the large PV plant, the following assumptions are made:

- The MVA rating of the large PV plant equivalent, $S_{\Sigma,\Sigma}$ is the sum of the MVA ratings of the PV generating units:

$$S_{\Sigma,\Sigma} = \sum_{i=1}^Y \sum_{j=1}^N S_{i,j} \quad (1)$$

Where $S_{i,j}$ is the MVA-rating of the PV generating unit j being in the column i .

- The equivalent PV generating plant supplies the same amount of electric power to the grid:

$$P_{\Sigma,\Sigma} = \sum_{i=1}^Y \sum_{j=1}^N P_{i,j} \quad (2)$$

where $P_{i,j}$ is the electric power supplied by the PV generating unit j being in the column i and $P_{\Sigma,\Sigma}$ is the electric power supplied by the whole PV plant.

(1) and (2) imply that the equivalent PV plant can be defined by a simple addition of the MVA ratings and an addition of the electric power output of the individual generating units. Fig. 5 shows this one-PV generator equivalent. The incoming cloud shown in Fig. 4 is assumed to cover all the individual PV generating units in the equivalent plant at the same time.

Non-uniform Insolation Distribution

In this case the incoming cloud is such that:

- Its direction is as shown in Fig. 4.
- The cloud takes k seconds time to move from the first column to the second column of the PV generating units. In other words, the insolation is shifted by k seconds for each column of PV generating units.

Since the operating points of the PV units in each column are identical, the outputs of the PV units in each column are added and a multi-machine equivalent comprising of Y PV generating units is obtained. This multi-generators equivalent is shown in Fig. 6. The MVA ratings, $S_{\Sigma,\Sigma}$ the electric powers, $P_{\Sigma,\Sigma}$ of the equivalent PV plants are given by:

$$S_{\Sigma,\Sigma} = \sum_{i=1}^Y S_{i,\Sigma} \quad (3)$$

$$P_{\Sigma,\Sigma} = \sum_{i=1}^Y P_{i,\Sigma} \quad (4)$$

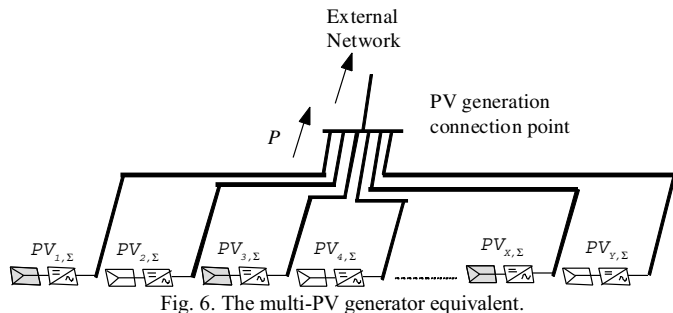


Fig. 6. The multi-PV generator equivalent.

B. Fuzzy based command power generation considering uniform insolation to all PV inverters

In order to control output power of all PV systems considering power system condition, output power command P_{inv}^* is decided by output power command system shown in Fig. 7. Output power command system consists mainly of two fuzzy control blocks and the rate of rated output power for PV system is decided by these fuzzy controls. Fuzzy reasoning is described by a set of “if-then” rules based on fuzzy rules. Fuzzy reasoning is effective when mathematical expressions are difficult by inherent complexity or nonlinearity.

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

$$\bar{S}_i = \frac{1}{T} \int_{t-T}^t S_i dt \quad (5)$$

where t is present time, T is integral interval, and S_i is instantaneous insolation. Fuzzy rules and membership functions of fuzzy control I are shown in TABLE II and Fig. 8, respectively. Fuzzy rules and membership functions that yield an output to reduce frequency deviations are defined by trial-and-error. The i th fuzzy rule is expressed as

$$\text{Rule } i: \text{if } \Delta f \text{ is } L_x \text{ and } \bar{S}_i \text{ is } M_y \text{ then } \gamma_l \text{ is } Z_l \quad (6)$$

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

where L_x, M_y denote the antecedents and Z_l are consequent part.

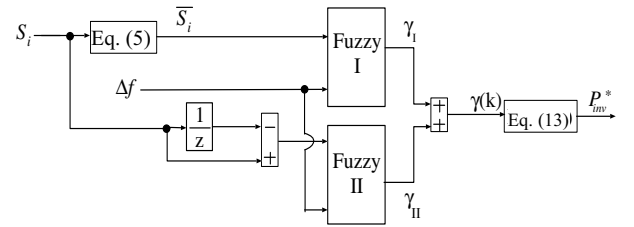


Fig. 7. Output power command generation system.

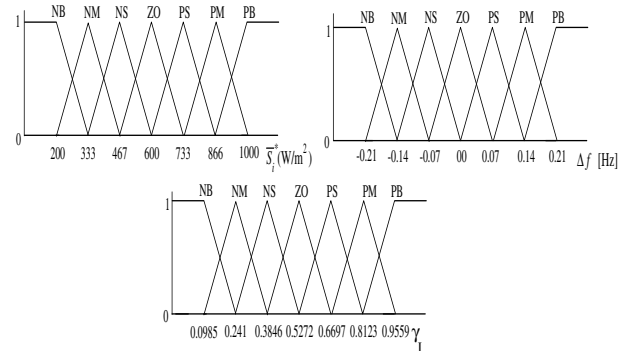


Fig. 8. Membership Functions of fuzzy control I.

TABLE II. FUZZY RULES OF FUZZY CONTROL I

		Δf							
		NB	NM	NS	ZO	PS	PM	PB	
$\bar{S}_i$	NB	NB	NB	NB	NB	NM	NS	ZO	
	NM	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

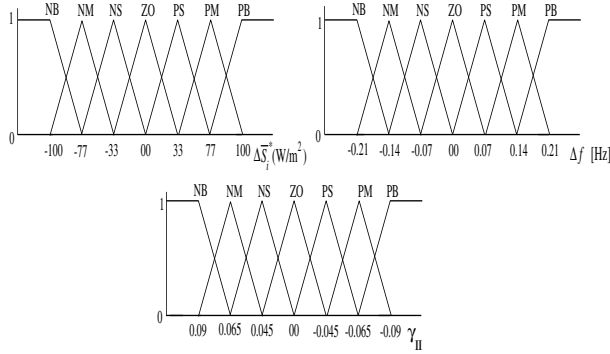


Fig. 9. Membership Functions of fuzzy control II.

TABLE III. FUZZY RULES OF FUZZY CONTROL II

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

Fuzzy reasoning output γ_I is calculated by

$$\gamma_I = \sum_{i=1}^{49} w_i Z_i / \sum_{i=1}^{49} w_i \quad (7)$$

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

$$w_i = w_{\Delta f} w_{\bar{S}_i} \quad (8)$$

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

Secondly, fuzzy control II is explained. Frequency deviation Δf and change of insolation ΔS_i are used as inputs of Fuzzy control II, where change of insolation ΔS_i is expressed as

$$\Delta S_i = S_i(t-1) - S_i(t) \quad (9)$$

Output power command that depends on power system condition rather than insolation condition is decided by using frequency deviation Δf as input for both fuzzy reasoning I and fuzzy reasoning II. Fuzzy rules and membership functions of fuzzy control II are shown in TABLE III and Fig. 9, respectively. Setup of fuzzy rules and parameters of membership functions are determined by prioritizing to prevent boosting of frequency deviation. The o th of fuzzy rules is expressed as

$$\text{Rule } o: \text{if } \Delta f \text{ is } H_c \text{ and } \Delta S_i \text{ is } I_z \text{ then } \gamma_{II} \text{ is } Q_h \quad (10)$$

$$c = 1, 2, \dots, 7, z = 1, 2, \dots, 7, h = 1, 2, \dots, 7$$

where H_c, I_z denote the antecedents and Q_h are consequent part. Fuzzy reasoning output γ_I is calculated by

$$\gamma_{II} = \sum_{i=1}^{49} w_o Q_h / \sum_{i=1}^{49} w_o \quad (11)$$

where w_o denotes the grade for the antecedent and is obtained by

$$w_o = w_{\Delta f o} w_{\Delta S_i o} \quad (12)$$

where $w_{\Delta f o}$ and $w_{\Delta S_i o}$ are the grade of antecedents for each rule.

The sum of outputs of fuzzy control I, γ_I , and fuzzy control II, γ_{II} become output power command by using the following equation:

$$P_{inv}^* = P_{rated} \left\{ \gamma(k) + \frac{\gamma(k+1) - \gamma(k)}{T_s} f(t) \right\} \quad (13)$$

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

C. Fuzzy based coordinated command power generation considering different insulations todifferent PV inverters

In order to control the combined output power of multiple PV systems considering power utility and different 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 power systems by maintaining coordination between central and local levels to produce combined PV output power same as the central output power command. Central output power command P_{inv}^* is decided by the previously described fuzzy based central output power command generation system and shown in Fig. 10. This central output power command system consists of mainly two fuzzy controls. There are two inputs of fuzzy control I. One is frequency deviation Δf and the other is average insolation $\bar{S}_i^*$. Average insolation $\bar{S}_i^*$ is defined by

$$\bar{S}_i^* = \frac{1}{T} \int_{t-T}^t S_i^* dt \quad (14)$$

Frequency deviation Δf and change of insolation $\Delta \bar{S}_i^*$ are used as inputs of Fuzzy control II, where variance $\Delta \bar{S}_i^*$ is expressed as

The sum of outputs of Fuzzy control I, γ_I , and Fuzzy control II, γ_{II} become central output power command by using the following equation:

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

$$P_A = \sum_{N=1}^N P_{AN} \quad (17)$$

The diagram illustrates a multi-array solar power system. It consists of N solar arrays, each with its own Maximum Power Point Tracker (MPPT) and inverter. The solar insolation for each array is $S_1, S_2, \dots, S_N$. Each MPPT (MPPT 1 to MPPT N) tracks the maximum power point and outputs a reference power $P_{A_max\ 1}, P_{A_max\ 2}, \dots, P_{A_max\ N}$. These reference powers are compared with the actual power $P_{A_inv\ 1}, P_{A_inv\ 2}, \dots, P_{A_inv\ N}$ to generate an error signal β . The error signal β is used to adjust the inverter output. The inverters convert the DC power to AC power $P_{A1}, P_{A2}, \dots, P_{AN}$. The AC powers are then summed to produce the total output power P_A .

To generate coordination between central power command and individual local power command, a common tuning factor β is formulated. The tuning factor β can be expressed as

where P_{AmaxN} is maximum power point tracking (MPPT) command of each PV power generation system. The P& O algorithm is used to generate the MPPT output power command considering instant insolation, PV array voltage, and PV array current. The individual local output power command for each of the PV power generation systems can be obtained by the following equation

ESS power command P_{ESSi}^* for charging, discharging, and neutral modes can be expressed as follows

$$P_{ESSi}^* = 0 \text{ (Neutral mode, if } P_{\max i}^* = P_{\text{invi}}^* \text{)}$$

Numerical simulation results of control area 1, 2, and 3 are shown in Figs. 12, 13, and 14 respectively. Figs. 12(a), 13(a), and 14(a) show the insulations. Different insulations are used for each of the control areas. Figs. 12(b), 13(b), and 14(b) show the average insulations. Figs. 12(c), 13(c), and 14(c) show the change of insulations. Figs. 12(d), 13(d), and 14(d) show the load of each area.

Figs. 12(g), 13(g), and 14(g) show the PV powers with the conventional smoothing method. Figs. 12(h), 13(h), and 14(h) show the PV powers with the proposed method. From Figs. 12(g), 12(h), 13(g), 13(h), and 14(g), 14(h), it is seen that the PV powers with the proposed method are varying according to the load variation to provide frequency control. However, PV powers with the conventional method are smooth which means they cannot take part in frequency regulation and they are just trying to reduce the fluctuation of PV power by smoothing.

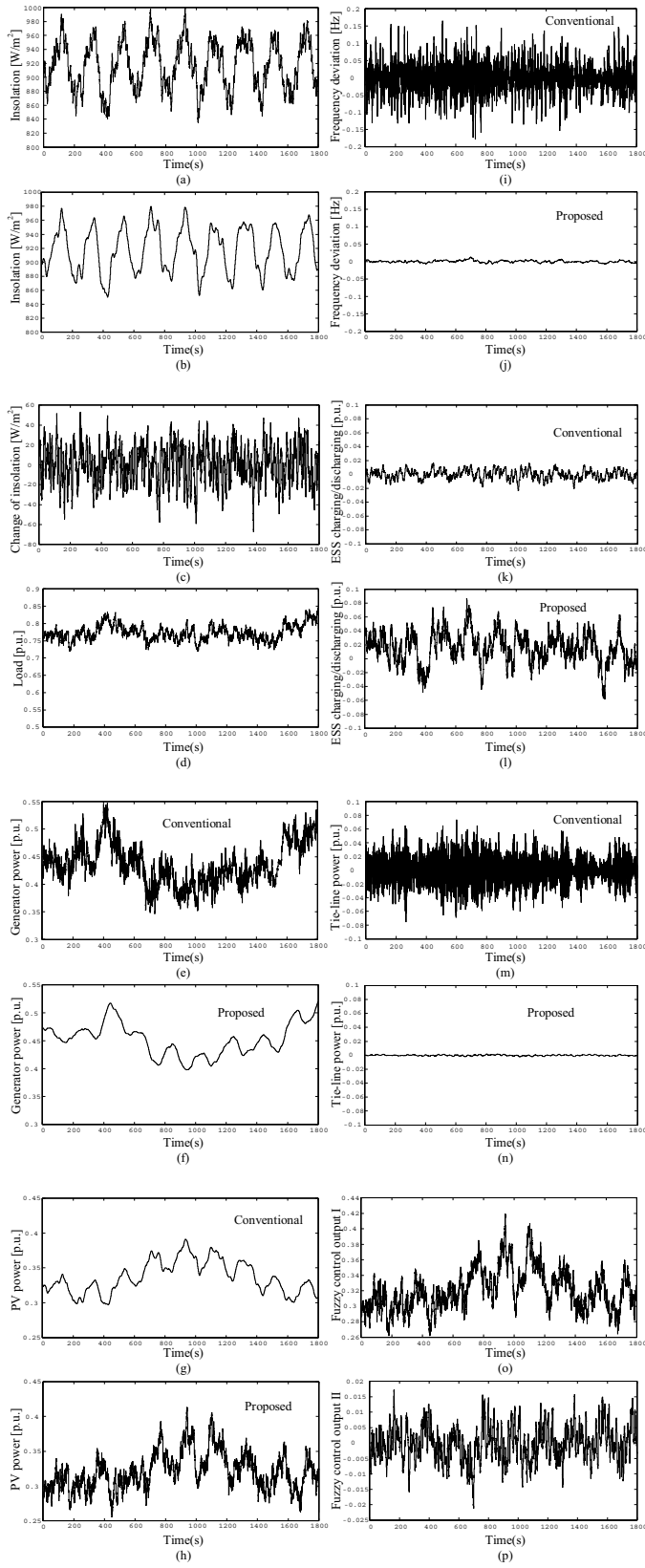


Fig. 12. Comparative simulation results of the proposed methods and the conventional smoothing based method [1] for control area 1.

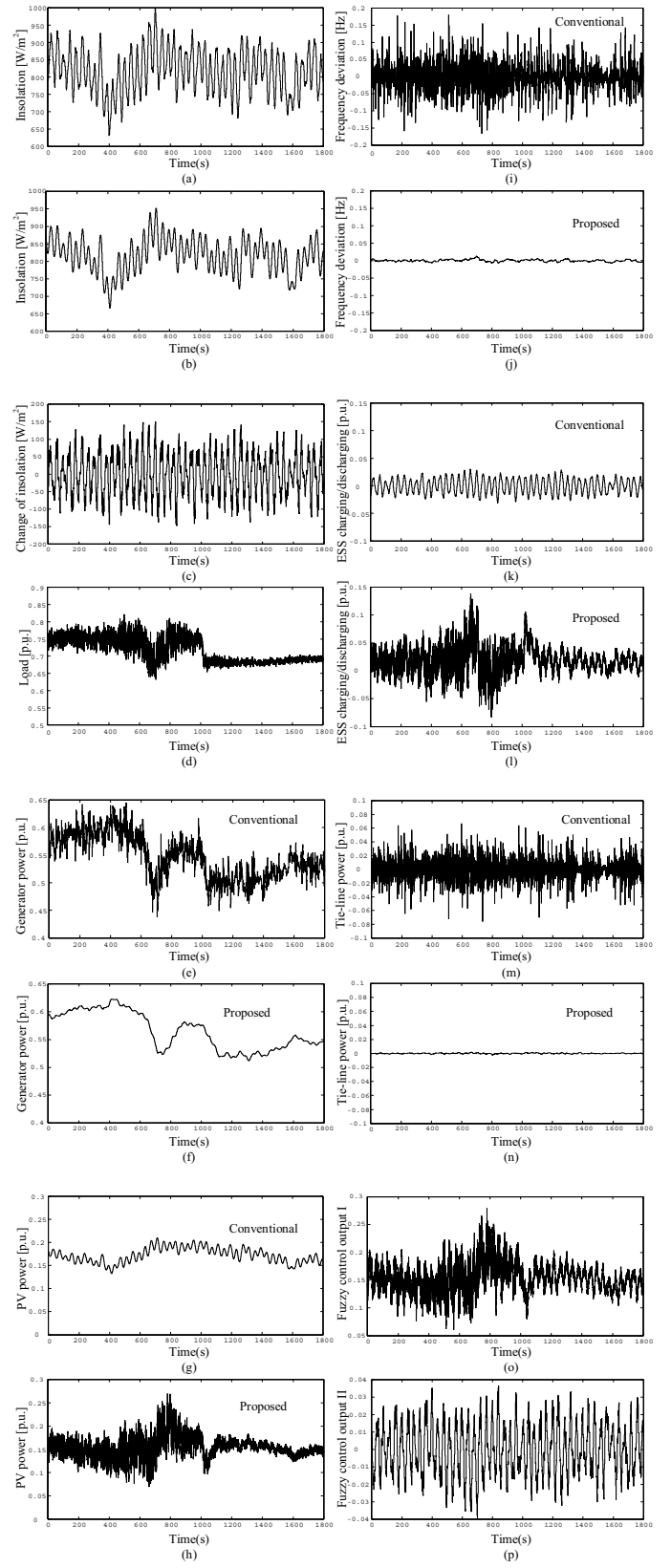


Fig. 13. Comparative simulation results of the proposed methods and the conventional smoothing based method [1] for control area 2.

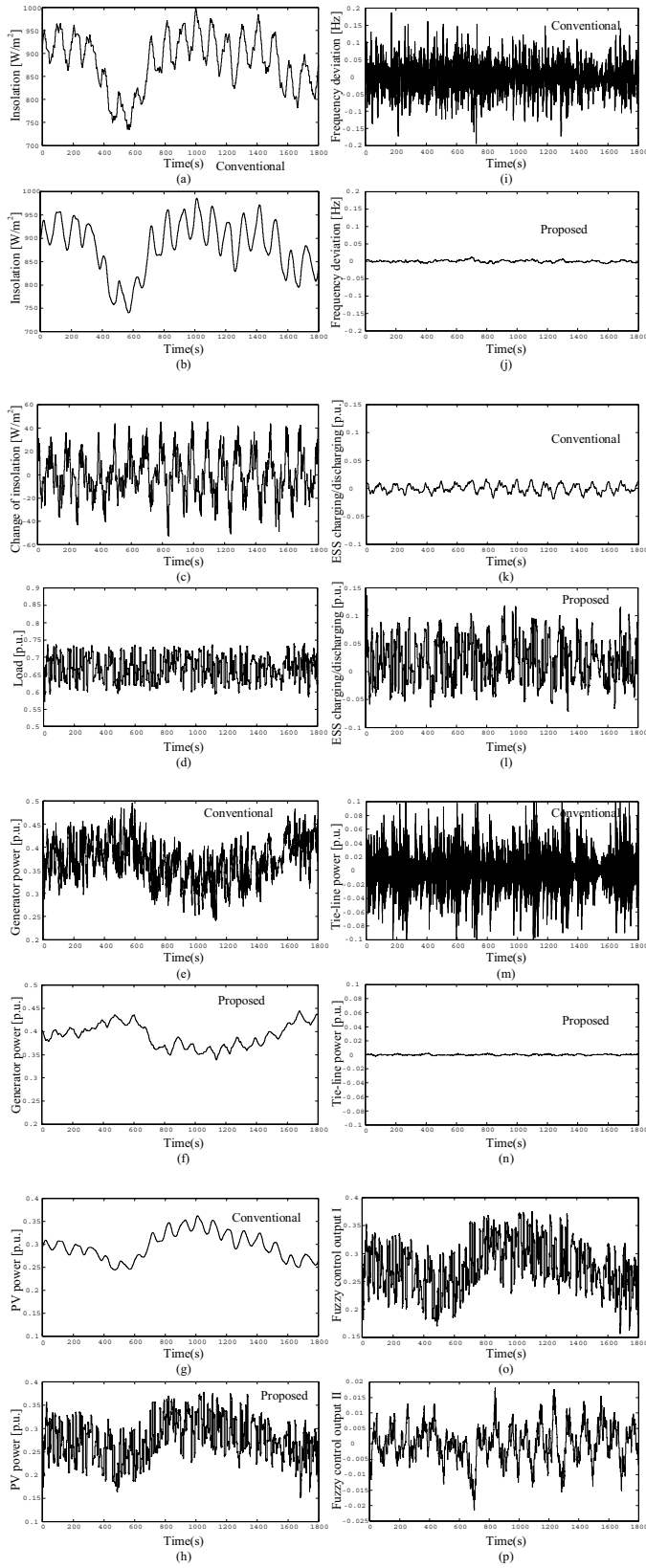


Fig. 14. Comparative simulation results of the proposed methods and the conventional smoothing based method [1] for control area 3.

Figs. 12(i), 13(i), and 14(i) show the frequency deviations with the conventional smoothing method. Figs. 12(j), 13(j), and 14(j) show the frequency deviation with the proposed method. From Figs. 12(i), 12(j), 13(i), 13(j), and 14(i), 14(j), it can be said the frequency control performances are better achieved by the proposed method as the frequency deviations with the proposed method are almost zero. This happens as the PV inverters acted like virtual generators by responding to a low frequency with the increase in their active power output and to a high frequency with the decrease in their active power output.

Figs. 12(k), 13(k), and 14(k) show the ESS charging/discharging powers with the conventional smoothing method. Figs. 12(l), 13(l), and 14(l) show the ESS charging/discharging powers with the proposed method. From Figs. 12(k), 12(l), 13(k), 13(l), and 14(k), 14(l), it can be said that the ESS powers required for the proposed method are higher than those of the conventional method. Considering the plug-in-electric vehicles and other energy storage systems, these can easily be maintained in the future smart power systems.

Figs. 12(m), 13(m), and 14(m) show the tie-line power fluctuations with the conventional smoothing method. Figs. 12(n), 13(n), and 14(n) show tie-line power fluctuations with the proposed method. From Figs. 12(m), 12(n), 13(m), 13(n), and 14(m), 14(n), it can be said that tie-line power fluctuations reduction are better achieved by the proposed method as the tie-line power fluctuations with the proposed method are almost zero. This happens as the PV inverters acted like virtual generators and try to address the issue of tie-line power fluctuations.

Figs. 12(o), 13(o), and 14(o) show the outputs of the fuzzy control I. Figs. 12(p), 13(p), and 14(p) show the outputs of the fuzzy control II. It can be observed that the outputs are changed in accordance to their inputs.

IV. CONCLUSIONS

This paper presents a fuzzy based frequency control approach by the grid-connected MW class PV generators. From the simulation results, it is seen that the proposed method works efficiently in the case of insolation and load variations.

In the proposed method, fuzzy controls are used as fuzzy controls are effective when mathematical expressions are difficult by inherent complexity or nonlinearity or uncertainty. Load and insolation variations are typical problems to be solved for large penetration of PV power in the utility. So, fuzzy control of PV inverters can be an intelligent solution towards the smart grid.

The current practice of smoothing PV power with the help of batteries cannot provide frequency control or ramp control according to the frequency deviations. Therefore by using the proposed method power consumers can play a vital role in the control of power system and can also reduce the burden on conventional generators far away.

In the proposed method, only active power controls of OV inverters for the purpose of frequency control are shown. In the future research, voltage control will also be included with the proposed frequency control and the response of the proposed frequency and voltage controller in the case of power system fault will be presented.

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