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Smoothing Output Power Variations of Isolated Utility Connected Multiple PV Systems by Coordinated Control

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ABSTRACT

A Photovoltaic (PV) system's power output varies with the change of climate. Frequency deviations, tie line voltage swings are caused by the varying PV power when large PV power from several PV systems is fed in the utility. In this paper, to overcome these problems, a simple coordinated control method for smoothing the variations of combined PV power from multiple PV systems is proposed. Here, output power command is formed in two steps: central and local. Fuzzy control is used to produce the central smoothing output power command considering insolation, variance of insolation and absolute average of frequency deviation. In local step, a simple coordination is kept between the central power command and the local power commands by producing a common tuning factor. Power converters are used to achieve the same output power as local command power employing PI control law for each of the PV generation systems. The proposed method is compared with the method where conventional Maximum Power Point Tracking (MPPT) control is used for each of the PV systems. Simulation results show that the proposed method is effective for smoothing the output power variations and feasible to reduce the frequency deviations of the power utility.

Keywords: Multiple PV systems, Coordinated control, MPPT control, Output power variations, Smoothing

1. Introduction

Among various renewable energy systems, photovoltaic power generation systems (PV 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 varies depending on weather. In the future, when a significant number of PV systems will be connected to the grids of power utilities, combined power output variations may cause problems like voltage variation and large frequency deviation in electric power system operation[1]-[4]. Therefore, for penetrating multiple or clustered PV system's [5] output power in the utility without reduction of the reliability of utility power systems, suitable measures must be applied to the PV

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systems side.

On these issues, several studies have been carried out for reducing the output power variations of renewable power sources. Power characteristics of PV ensembles are presented in [6] where recorded data from 100 PV systems were used to study effects of combined power generation of these systems, compared to the characteristics of an individual system. It was claimed that a significant amount of power variations disappeared, however, large amount of short-term power variations were remained. In addition, when the numbers of PV power systems were decreased, the power variations increased. Smoothing of PV system output by tuning MPPT control is explained in [7]. In this method, when the insolation increases rapidly, the acting MPPT point changes to a new point where the maximum power is not produced with the current insolation. It was reported that this method could be applied to several PV power generation systems to achieve a combined output power variations smoothing. However, the condition of power utilities for example frequency deviation is not considered for tuning the MPPT and for limiting the new output voltage.

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 [8] to fully exploit the PV renewable energy. However, this coordination is not designed for multiple PV systems and it could not deal with the problems introduced in the power utility by output power variations of multiple PV power systems.

In this paper, a simple coordinated control method for smoothing the output power variations of multiple PV power generation systems considering instant insolations and frequency deviations from the power utility is proposed. In this control approach, the output power control is achieved by two levels: central and local. In the central control, insolations from all the PV systems are added together and an average insolation is formed. Based on this average insolation and power system's condition, the central output power command is derived. This method uses fuzzy control [9]-[11] to produce the central output power command and it has three inputs, which are absolute average of frequency deviation, average insolation, and variance of insolation. Here, the central output power command is decreased in time when large frequency deviation continuously occurs. Because the frequency deviation is introduced in the power utility by the load variation and it increases when a big amount of PV output power with variations because of rapid insolation change is given to the utility. On the other hand, central output power command increases when frequency deviation is small and this increase will not cross the maximum power available. If insolation changes rapidly in a short period, the PV system's output will be smaller than available maximum power when the new acting point of the PV array is not an optimal one. In local control, maximum power point tracking (MPPT) command is produced for each of the PV power generation systems by Perturb and Observe (P & O) method [12]. All maximum power commands are summed up together and by dividing the central power command by this sum, a common tuning factor is produced. This tuning factor is multiplied with each of the individual maximum power command and new local power commands are created for each of the PV power generation systems. Simple PI control law is employed to control the power converter associated with each PV power generation system for extracting output power equal to the local power command from the PV array. The proposed method is compared with the method where maximum power point tracking (MPPT) control is used for each of the PV system without any coordination and smoothing. Through simulation results, it is found that the proposed method is effective in achieving the following key features: smoothing of PV output power variations, decrease of frequency deviation to keep the reliability of power utility, and supplying the possible maximum amount of PV power to the utility without reducing the reliability of the utility.

An earlier version of this paper [13] had been published in ICPE'07, Korea. Current version of the paper is organized as follows: Section II provides the concept of a small power system, description of PV power generation system, control of power converter, a brief review of solar module characteristics and validation of solar cell model. Section III describes the coordinated output power command generation system. In Section IV, effectiveness of the proposed method is explained by simulation results. In Section V, feasibility of the proposed method and required communication hardware are described. Conclusions are drawn in Section VI.

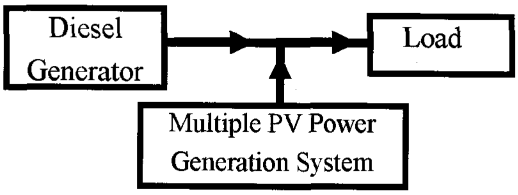


Fig. 1 Concept of small power utility with multiple PV systems

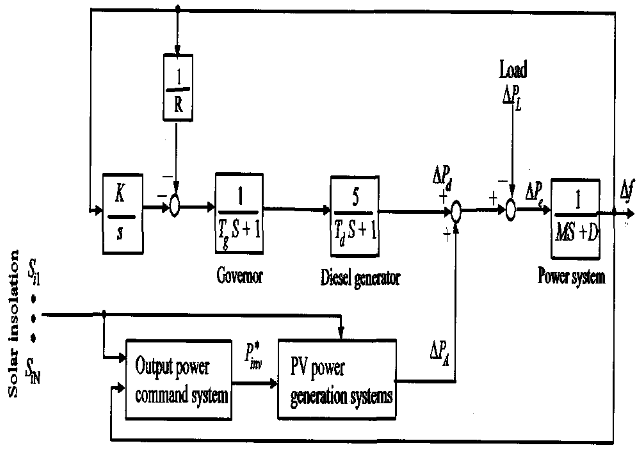


Fig. 2 Small power system model with multiple PV systems

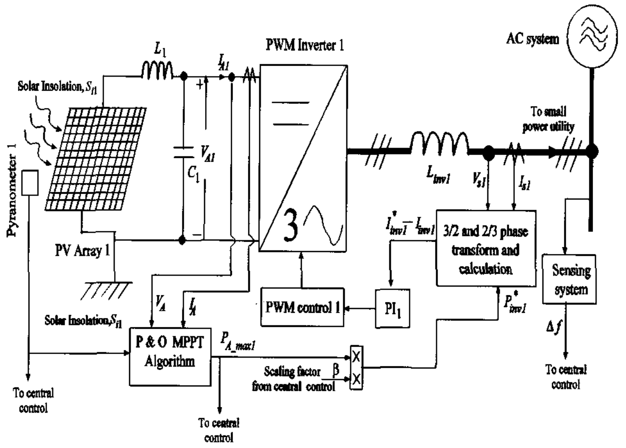


Fig. 3 Individual PV power generation system

2. Small Power System Model

The idea of multiple PV systems connected to small power utility is shown in Fig. 1. This is actually a PV–diesel hybrid power system consisting of diesel generator and multiple PV systems that generate power to supply the load demand. In addition, it is assumed that the isolated power utility is not connected to large power utility and is always operated independently as a stand-alone system.

The small power system model which consists of diesel generator, multiple PV power generation systems, and load is shown in Fig. 2 where, S_i is the insolation, N is the total number of PV power generation systems, P^*_{inv} is the central command power produced by fuzzy based central output power command generation system, ΔP_A is the combined power produced power by N PV power generation system, ΔP_d is produced 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, ΔP_L is the load, M is the inertia constant, D is the damping constant, and Δf is the frequency deviation of small power utility. The control of diesel generator described in [6] is also used in this paper to fully exploit the renewable energy.

In Fig. 3, PV power generation system including solar array, inverter and PI controller is shown where V_{A1} is the first solar array voltage, I_{A1} is the first solar array current, Δf is the frequency deviation, V_{s1} is the produced supply voltage by the inverter connected to first solar array, I_{s1} is the produced supply current by the inverter connected to first solar array, and $\left| I^*_{inv1} - I_{inv1} \right|$ is the error between command current and produced current. The control algorithm for the inverter [14] adopted here is simple. The inverter output voltages and currents are sensed and transformed from 3-phase to synchronously rotating 2-phase. The command currents are produced 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 produce the PWM pulses. For simple and less costly implementation, a Perturbed and Observed (P&O)[12]

algorithm was chosen in the present structure.

As the design of power converter [15] and the control system is significantly influenced by the solar module characteristics, these will briefly reviewed here. The solar module is a nonlinear device and can be represented as a current source model, as shown in Figure 4. The traditional $I - V$ characteristics of a solar module are given by the following equation [16]:

$$I_0 = N_p N_s I_g I_{sat}\left\{\exp\frac{qV_0}{AKT}\left(V_0+\frac{N_s R_s I_0}{N_p}\right)-1\right\}-I_{rsh} \qquad (1)$$

where I_0 and V_0 are the output current and output voltage of the solar module, respectively, I_g is the generated current under a given insolation, I_{sat} is the reverse saturation current, q is the charge of an electron, K is the Boltzmann constant, A is the ideality factor, T is the temperature (K), N_p is the number of cells in parallel, N_s is the number of cells in series, R_s is the internal series resistance, and I_{rsh} is the current due to intrinsic shunt resistance of the solar module.

The saturation current (I_{sat}) of the solar module varies with temperature according to the following equation [16]:

$$I_{sat} = I_{or}\left[\frac{T}{T_r}\right]^3 \exp\left[\frac{qE_g}{KT}\left(\frac{1}{T_r}-\frac{1}{T}\right)\right] \qquad (2)$$

$$I_g = I_{sc}\frac{S_i}{1000} + I_i(T - T_r) \qquad (3)$$

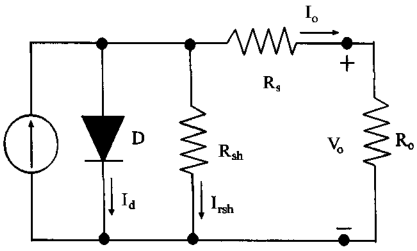
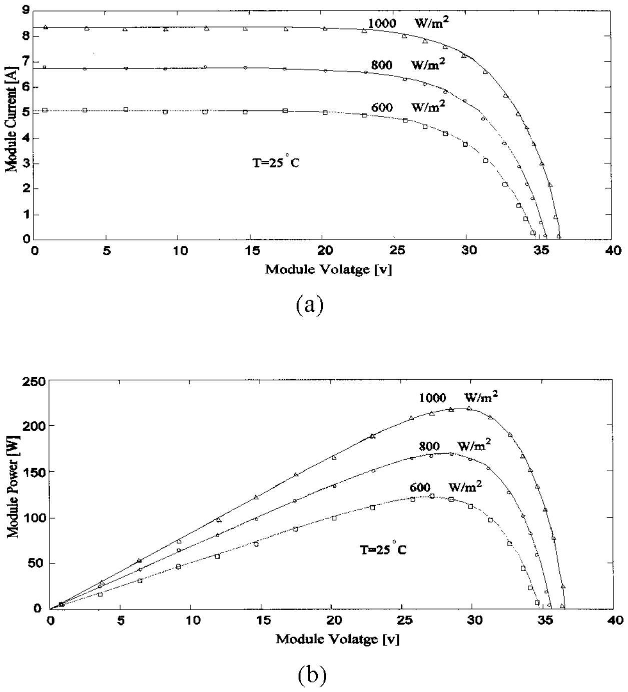


Fig. 4 Equivalent circuit of a solar module



(a)

(b)

Fig. 5 Solar module characteristic curves (a) Current–voltage curves (b) Power–voltage curves The discrete data points shown are taken from the manufacturer's curves [17], and show excellent correspondence with the model

where T_r is the reference temperature, I_{or} is the saturation current at temperature T_r, E_g is the band gap energy, I_t is the short circuit current temperature coefficient, I_{sc} is the short circuit current of solar module, and S_i is the insolation in W/m². The current due to shunt resistance is given by the following equation [16]:

$$I_{rsh} = \frac{V_0}{N_s R_{sh}} \qquad (4)$$

where R_{sh} is the internal shunt resistance of the solar module.

For the solar module, Equations (1)-(4) are used in the development of MATLAB/SIMULINK based computer simulations. Figures 5(a) and (b) shows the simulated ampere-volt and power-volt curves of the solar module for different insolation at constant temperature. Here, the discrete data points shown are taken from the manufacturer's data sheet [17] for validating the model. From these curves, it is observed that the output characteristics of the solar module are nonlinear and vitally affected by the variation of insolation.

3. Coordinated Output Power Command Generation

To control the combined output power of PV systems considering power utility and insolation conditions, output power command is produced in two levels: central and local. Individual local output power commands are given to each of the PV power systems by keeping coordination between central and local levels to produce combined PV output power same as central output power command. The coordination is simple. However, it is effective for smoothing and smoothing the combined output power variations. Central output power command P_{inv}^* is decided by the fuzzy based central output power command generation system shown in Fig. 6. This central output power command system consists of mainly two fuzzy controls. These fuzzy controls are described by a set of "if-then" based fuzzy rules. Fuzzy control is effective when mathematical expressions are difficult by inherent complexity or nonlinearity. Therefore, no deterministic model is needed.

First, Fuzzy control I is explained. There are two inputs of fuzzy control I. One is absolute average of frequency deviation Δf_s and the other is average insolation $\bar{S}_i^*$. The former, which is an index to estimate power system condition, is expressed by

$$\Delta f_s = \frac{1}{T}\int_{t-T}^{t} |\Delta f|\,dt \tag{5}$$

where t is present time and T is integral interval. Since absolute value of frequency deviation Δf is used, absolute average of frequency deviation Δf_s increases or decreases with increase or decrease in frequency deviation Δf of the power system. Therefore, (5) shows frequency deviation quantitatively at any given time. Average insolation $\bar{S}_i^*$ is defined by

$$\bar{S}_i^* = \frac{1}{T}\int_{t-T}^{t} S_i^*\,dt \tag{6}$$

where $S_i^* = \frac{1}{N}\sum_{N=1}^{N} S_{iN}$.

where N is the total number of PV power generation systems, S_{iN} is instantaneous insolation of each PV power generation system, $\bar{S}_i^*$ is summation of insolation of each PV power generation system divided by N. Fuzzy rules and membership functions of Fuzzy control I are shown in Table 1 and Fig. 7, respectively. Here, central output power control of PV systems according to power system condition is succeeded by using absolute average of frequency deviation Δf_s as input of fuzzy control.

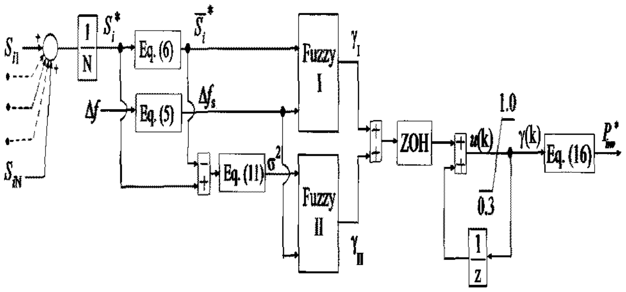


Fig. 6 Fuzzy based central output power command generation system

Table 1 Fuzzy rules of fuzzy reasoning I

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

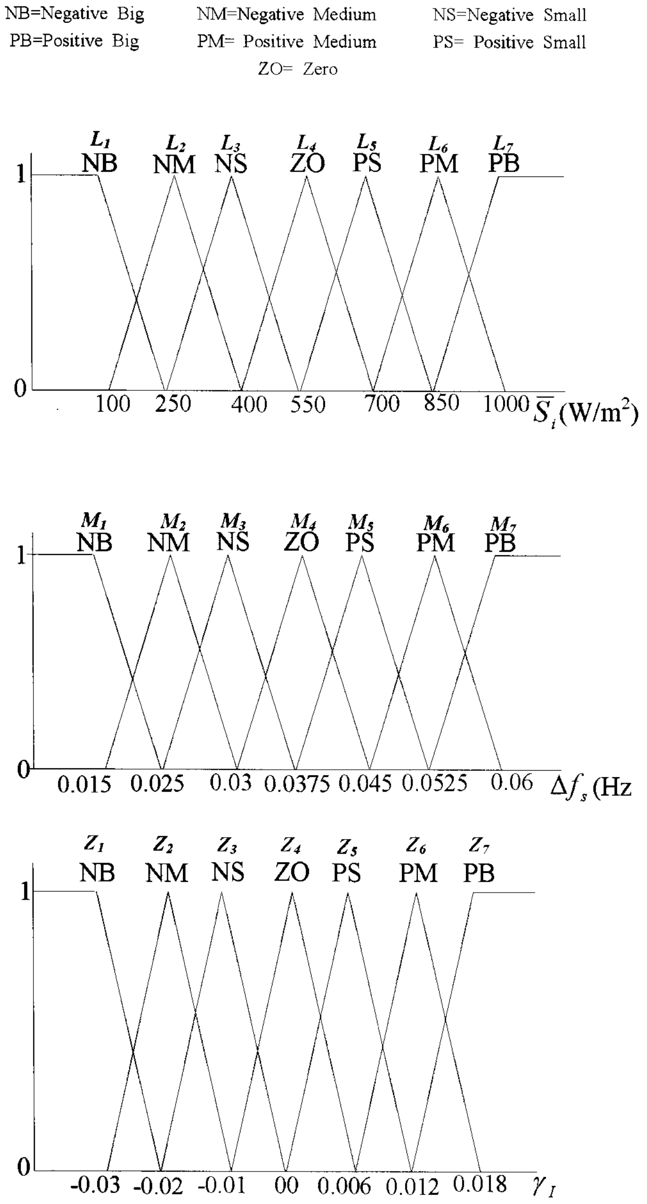


Fig. 7 Membership functions of fuzzy reasoning I

It is undesirable to increase central output power command for PV systems considerably by insolation condition because chance of insolation decrease at short times is high. The important considered in this paper is preventing large frequency deviations. The frequency deviation Δf of magnitude more than ± 0.2Hz is prevented rather than increase of produced power of PV systems. Thus, membership functions are determined so decreasing tendency is strong compared with increasing tendency of central output power command of PV systems. When frequency deviation Δf is more than ± 0.2Hz in certain times, fuzzy rules and membership functions that yield an output to decrease the output power command are defined by trial-and-error. The ith fuzzy rule is expressed as

$$\text{Rule } i: \text{if } \Delta f_s \text{ is } L_x \text{ and } \bar{S}_i \text{ is } M_y \text{ then } \gamma_l \text{ is } Z_l \qquad (8)$$

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

where L_x , M_y show the antecedents and Z_l are consequent part. Fuzzy reasoning output γ_l is calculated by

$$\gamma_l = \sum_{i=1}^{49} w_i Z_l \Big/ \sum_{i=1}^{49} w_i \qquad (9)$$

where w_i shows the grade for the antecedent and is calculated by

$$w_i = w_{\Delta f_s i} w_{\bar{S}_i i} \qquad (10)$$

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

Second, Fuzzy control II is explained. Absolute average of frequency deviation Δf_s and variance σ^2 of average insolation S_i^* are used as inputs of Fuzzy control II, where variance σ^2 is expressed as

$$\sigma^2 = \frac{1}{T}\int_{t-T}^{t}\left(S_i^* - \bar{S}_i^*\right)^2 dt \qquad (11)$$

Output power command that depends on power system condition rather than insolation condition is decided by using absolute average of frequency deviation Δf_s as input for both fuzzy control I and fuzzy control II. In addition, when insolation variations are large, the variance of average insolation σ^2 is used as one of the inputs since the objective is to keep decreasing tendency. Fuzzy rules and membership functions of Fuzzy control II are shown in

Table 2 and Fig. 8, respectively. Setup of fuzzy rules and parameters of membership functions are determined to prevent boosting frequency deviation.

Table 2 Fuzzy rules of fuzzy reasoning II

		Δf_s						
		NB	NM	NS	ZO	PS	PM	PB
σ^2	NB	PB	PB	PB	PB	PM	PS	ZO
	NM	PB	PB	PB	PM	PS	ZO	NS
	NS	PB	PB	PM	PS	ZO	NS	NM
	ZO	PB	PM	PS	ZO	NS	NM	NB
	PS	PM	PS	ZO	NS	NM	NB	NB
	PM	PS	ZO	NS	NM	NB	NB	NB
	PB	ZO	NS	NM	NB	NB	NB	NB

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

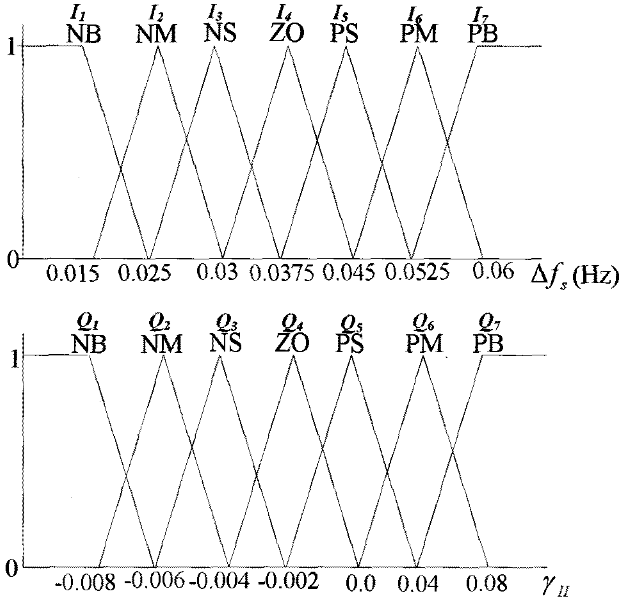


Fig. 8 Membership functions of fuzzy reasoning II

The *o*th of fuzzy rules is expressed as

$$\text{Rule } o: \text{if } \Delta f_s \text{ is } H_c \text{ and } \sigma^2 \text{ is } I_z \text{ then } \gamma_{II} \text{ is } Q_h \qquad (12)$$

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

where H_c , I_z denote the antecedents and Q_h are consequent part. Fuzzy reasoning output γ_{II} is calculated by

$$\gamma_{II} = \sum_{i=1}^{49} w_o Q_h \Bigg/ \sum_{i=1}^{49} w_o \qquad (13)$$

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

$$w_o = w_{\Delta f_s o} w_{\sigma^2 o} \qquad (14)$$

where $w_{\Delta f_s o}$ and $w_{\sigma^2 o}$ are the grade of antecedents for each rule.

The fuzzy rules and membership functions presented in Fuzzy reasoning 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 leveling and maximum acquisition of available PV power. Various methods have been proposed recently for tuning the fuzzy controller such as the 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 performance indexes, Taguchi tuning method [19], and tuning the membership functions [20], [21]. Most of these methods need a performance index. Two performance indexes can be made based on frequency deviation (tends to zero) and maximum PV power (tends to maximum). It will be easy to define performance indexes if one hour ahead insolation and temperature prediction are possible. However, in the present literature, selection of scaling factors is still based on a trail-and-error method.

As can be seen from Fig. 6, the discrete value $u(k+1)$is got by the sum of outputs of Fuzzy control I, γ_I , and Fuzzy control II, γ_{II} , through zero-order-hold, and the rate of current rated output power of PV arrays. Then, new rate of central rated output power for PV arrays $\gamma(k+1)$ becomes central output power command by the following equation:

$$\gamma(k+1) = \gamma(k) + u(k+1) \qquad (15)$$

Since, the rate got by (15) changes step, it is necessary to convert it into a smooth output power command. Linear output power command is produced in each sampling time by using the following equation:

$$P_{inv}^{*} = NP_{rated}\left\{\gamma(k) + \frac{\gamma(k+1)-\gamma(k)}{T_s} f(t)\right\} \tag{16}$$

Finally, (16) becomes central output power command P_{inv}^{*} to the PV power generation systems, 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 $f(t) = t(0 < t < T_s)$. After producing central output power command, local output power command for each of the PV power generation systems is produced by a simple coordinated control. The N PV power generation systems with coordinated control are shown in Fig. 9. Here the combined PV output power ΔP_A is expressed as

$$\Delta P_A = \sum_{N=1}^{N} P_{AN} \tag{17}$$

where P_{AN} is the output power of each PV power generation system. To achieve combined output power ΔP_A equal to the central output power command P_{inv}^{*} coordinated control method for each of the PV power generation systems is needed. To produce coordination between central power command and individual local power command, a common tuning factor β is developed. The tuning factor β can be expressed as

$$\beta = \frac{P_{inv}^{*}}{\sum_{N=1}^{N} P_{A\max N}} \tag{18}$$

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

$$P_{invN}^{*} = P_{A\max N} \times \beta \tag{19}$$

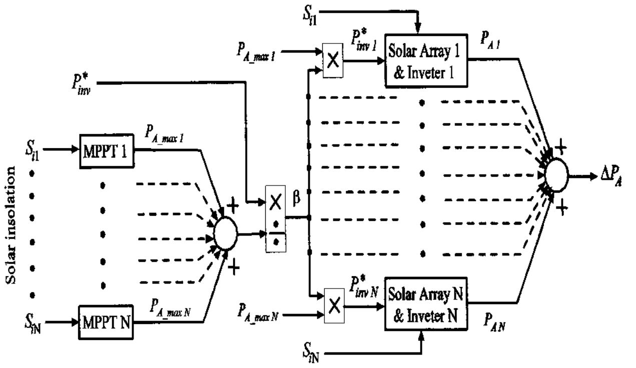


Fig. 9 Coordinated local output power command generation system

4. Simulation Results

In this paper, the effectiveness of output power variations smoothing of PV power generation systems and frequency deviation decrease of power utility using the proposed coordinated method is examined by simulation with system model and parameters as mentioned in [22]-[24].

Table 3 Simulation Parameters

Parameters of PV module	
Cell	Poly-crystaline silicon
Rated output power	216 W (+10%/-5%)
Open circuit voltage, V_{oc}	36.50 V
Short circuit current, I_{sc}	8.10 a
Shunt resistance, R_{sh}	50 Ω
Series resistance, R_s	5 Ω
Ideality factor, A	1.450
Inverse Saturation Current, I_{or}	3.047e-07 A
S.C. current temperature constant, I	1.73e-03 A/^{0}K
Reference temperature, T_{ref}	25 ^{0}C
Boltzman's constant, K	1.38e-23
Charge of an electron, q	1.602e-19 C
Bandgap voltage, E_g	1.11 eV
Number of cells in series, N_s	60
Standard insolation, S_i	1000 W/m^2
Dimension	0.75 m^3

Parameters of PV array	
Rated output power	225 kW
Open circuit voltage	584 V
Short circuit current	526.50 A
Number of modules in series	16
Number of modules in parallel	65
Total number of cells	62,400

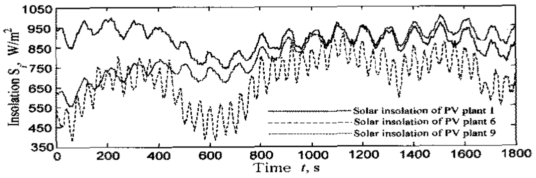
Parameters of Power converter	
Inverter power rating	225 kW
Nominal ac output voltage	480 V (3-φ)
Nominal ac output frequency	50 Hz
Maximum ac line current	271 rms
Maximum dc input voltage	600 V
Maximum dc input current	781 A
Efficiency	94.5%

Parameters of small power system	
Inertia constant, M	0.150 puMW.sec/Hz
Damping constant, D	0.008 puMW/Hz
Governor time constant, T_g	0.10 sec
Time constant, T_t	0.25 sec
Time constant, T_r	8.0 sec
Speed regulation, R	2.5 Hz/puMW

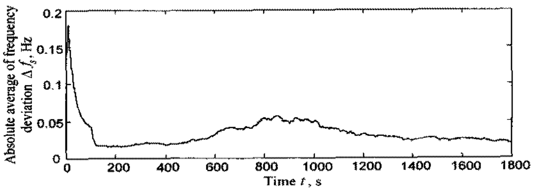
Parameters of PI controller	
Proportional constant, K_P	0.1
Integral constant, K_I	10

To use parameters of real systems in [23], [24], the rated output power of each PV array is 225 kW. The total number of PV power generation system used in this paper is 10 and the combined rated output power of ten PV power generation system is 2.25 MW. Simulation parameters for power system, PV array, power converter and PI controller are shown in Table 3. Integral time T is 100s, sampling time T_s to get discrete value of output power command is 10s, and sampling time of PI controller is 1ms. Simulation time is 30 minutes.

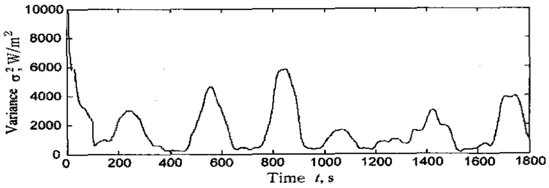
Different isolations are used for PV power generation systems. Insolations for PV plants 1, 6, and 9 are shown in Fig. 10(a). Absolute average of frequency deviations, variance of insolations and load are shown in Figs. 8 (b), (c), and (d) respectively. The comparative simulation results using MPPT control and proposed coordinated method are shown in Fig. 11. Figs. 11(a), (b), (c) show output power produced by coordinated method and available maximum power for PV plants 1, 6, and 9 respectively.



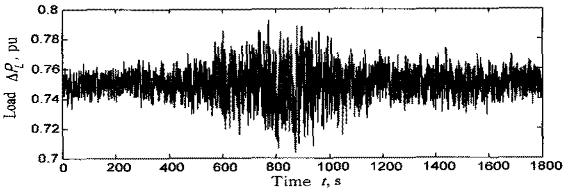
(a) Insolations of PV plant one, six, and nine



(b) Absolute average of frequency deviations



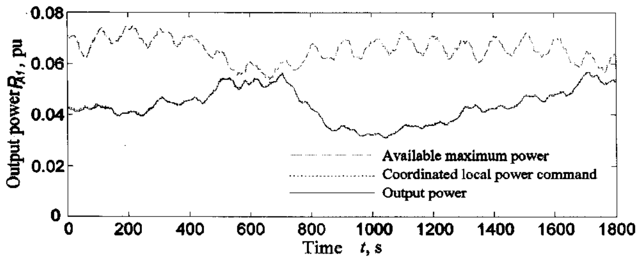
(c) Variance of insolations



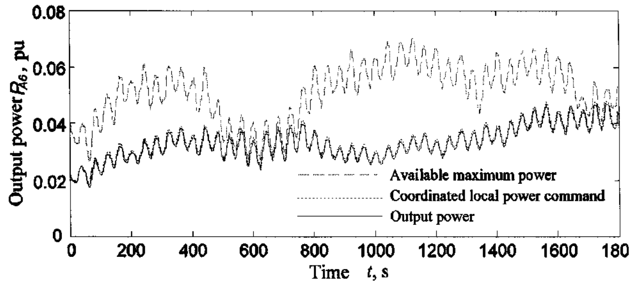
(d) Electrical load

Fig. 10 Insolations, absolute average of frequency deviations, variance of insolations, and load

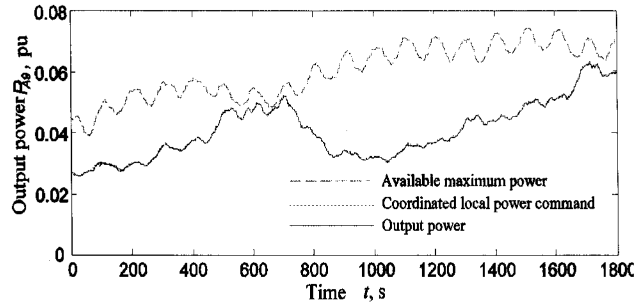
From these figures, it is seen that individual smoothing of output power variations is not achieved. Here, the individual output power of each PV plant is varying. However, from Fig. 11(d), it can be seen that when these varying powers are added together, the combined output power of ten PV plants are significantly smoothed and leveled.



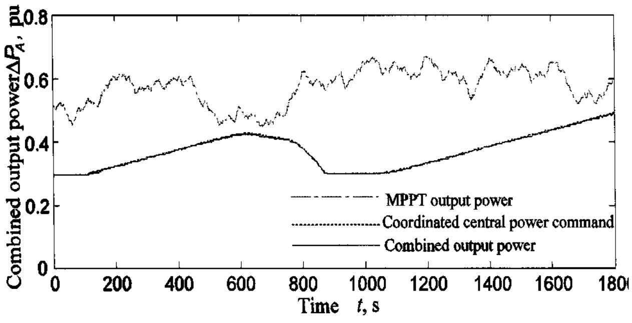
(a) Output power of PV system 1



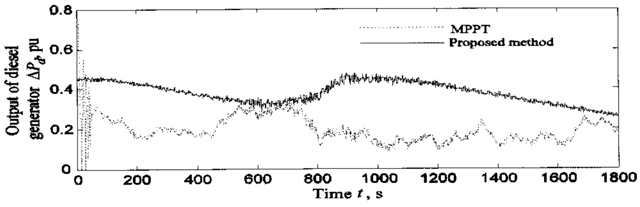
(b) Output power of PV system 6



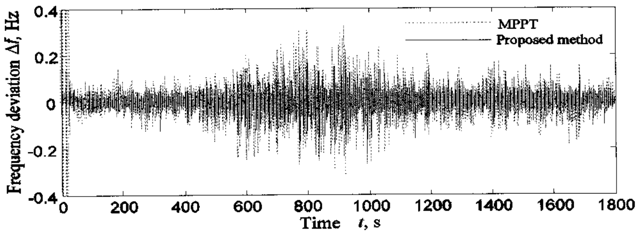
(c) Output power of PV system 9



(d) Comparison of combined output power from 10 PV systems



(e) Comparison of output power from diesel generator



(f) Comparison of frequency deviation

Fig. 11 Comparative simulation results of MPPT control and proposed method

Therefore, coordinated control works successfully to achieve smoothed and leveled output power from varying output power of individual PV plants. Another advantage of this coordinated method is that if a PV plant's output decreases with insolation decrease, to compensate the shortage of power, other PV plants can produce maximum power.

Output power of diesel generator ΔP_d, are shown in Fig. 11(e). From Fig. 11(e), it is seen that the diesel generator output power produced with MPPT control varies to cancel variation of output power, ΔP_A and load, ΔP_L. On the other hand, diesel generator power produced with proposed method varies less. This is because the combined PV output power is controlled considering frequency deviation of the power utility and it is smoothed by the proposed method.

Fig. 11(f) shows frequency deviation Δf. From Fig 11(f), it is seen that frequency deviation produced with MPPT control deviates more than ± 0.2Hz often. This is a severe problem for keeping power system reliability. Therefore, combined output power of ten PV plant produced by MPPT control has harmful effects on power system. However, frequency deviation produced with proposed method does not deviate by more than ± 0.2Hz often. Therefore, the proposed method is effective in keeping power system reliability.

From t=0s to t=50s, the frequency deviation is high, and the combined output power remains steady to reduce the frequency deviation. From t=50s to t=600s, the frequency deviation is low, and the combined output power increases to supply possible maximum power. However, from t = 600 s to t =1050 s, the frequency deviation is high, therefore, the combined output power first decreases, then remains steady to reduce frequency deviation. From t=1050s to t=1800s, the frequency deviation decreases, and the combined output power increases to supply possible maximum power. Therefore, it can be said that penetration of combined output power in the power utility with smoothing effect is controlled by the proposed method.

5. Feasibility Analysis

In the present, the proposed method will increase system cost, as the combined PV output is less than of the combined PV output of MPPT control. However, the power loss presented by the proposed method can be avoided by using small-capacity energy storage (like lead acid battery) with each of the PV systems. The battery will be charged by the power difference between local maximum PV power and local command PV power at the daytime. In this way, every battery of individual PV system will be charged and their stored energy can be supplied to the load at night. Therefore, all the available maximum power of individual PV system can be used to supply the load. However, this addition of small batteries will increase the system cost, specifically, it will increase installation cost of the system. On the other hand, this addition will offer some technical, economical, and environmental benefits in the long run.

Usually, PV power plant has long lifetime like 10 or 15 years. Therefore, if power loss of one day is considered, the combined power loss of 10 or 15 years will be big. However, using a small battery with the proposed method, all the available maximum power will be supplied to the system. The cost of battery system is small compared with the cost of PV power generation system. Therefore, in the long run, the proposed method with battery will be cost-effective considering the fact that it is supplying all the available maximum PV power. In recent times, most of the hybrid systems are equipped with batteries where renewable sources are expected to supply greater part of load demand. This offers some technical benefit as well.

Considering the situation when insolation will decrease suddenly or no insolation will be present (some hours in a day and in all-night), battery power can be used for load leveling, frequency regulation, etc. Therefore, the proposed method can be a good tradeoff between supplying available maximum power and keeping power quality. Besides, as the proposed coordinated method will collectively control PV systems based on the data such as the amount of power generated by the PV systems, the amount of battery charge/discharge, and the amount of power consumed, it is expected that such centralized control will improve the overall efficiency of the area where PV systems are clustered and will enhance the performance significantly. Furthermore, the collected data will also be used for diagnosing battery life and facilitating early detection of system malfunction. The practical development of the proposed coordinated control system described in Section III is difficult, as it will need a high-speed communication network or regional Internet protocol network with a central control server and a data collection server. Each of the PV systems needs to be equipped with measurement unit, data unit, battery system, MPPT tracker, inverter, and pyranometer. Each of the measurement units and control units of individual PV systems will be connected with data collection server and central control server through the high-speed communication network. A simple layout of the needed communication system for the proposed method is shown in Fig. 12. The diesel generator and utility are not shown in Fig. 12. However, both of them will also be connected with the communication network for collecting data of diesel power and frequency deviations. After collecting all the needed data, central and local command will be decided. The MPPT tracker connected with individual PV system will supply available PV maximum power. To produce PV power same as local command PV power, the battery will be charged by the power difference between

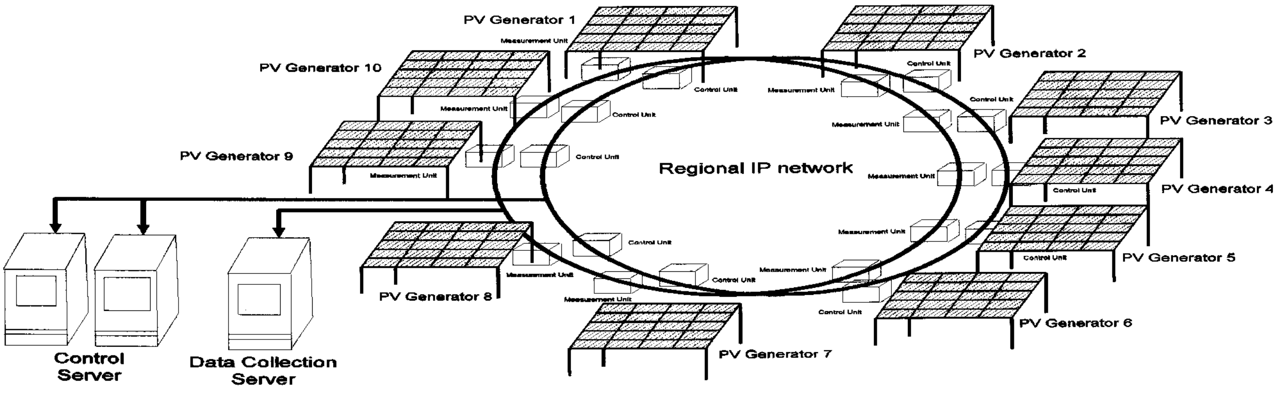


Fig. 12 Simple communication system layout for the proposed method

individual maximum PV power and local command PV power at daytime. At night, this stored battery energy will be supplied to the utility. However, all these actions depend on exact data collection and speed of the communication network and they should be performed at the same instant. The regional IP network should have optical fiber connection for high-speed communication.

6. Conclusions

This paper presents a coordinated control method for output power variations smoothing of PV plants considering power system condition and insolation condition. Central output power command is defined by fuzzy control, which has three inputs for absolute average of frequency deviation, average insolation, and variance of insolation. Setup of fuzzy rules and parameters of membership functions are determined by to prevent increase of frequency deviation. Local output power command for each of the plants is produced by coordination between central power command and maximum power tracking command. The PV plants are controlled with the help of PI controllers and power converters to level the output power so as not to influence the power system at times with large frequency deviation. On the other hand, at times with small frequency deviation, the proposed system can manage to increase produced power near available maximum power. From the simulation results, it can be said that the PV power generation systems with the proposed coordinated method achieve flexible output power control without introducing any harmful effects to power system, and the effectiveness of the proposed method for smoothing output power variations and for keeping power system reliability is confirmed.

References

[1] S. Yanagawa, T. Kato, K. Wu, A. Tabata, and Y. Suzuoki, "Evaluation of LFC capacity for output fluctuation of photovoltaic generation systems based on multi-point observation of insolation", in Proc. IEEE Power Engineering Society Summer Meeting, pp. 1652-1657, 2001.

[2] A. Woyte, V.V. Thong, R. Belmans, and J. Nijs, "Voltage fluctuations on distribution level introduced by photovoltaic systems", *IEEE Trans. Energy Convers.*, Vol. 21, No. 1, pp. 202-209, March 2006.

[3] H. Asano, K. Yajima and Y. Kaya, "Influence of photovoltaic power generation of required capacity for load frequency control," *IEEE Trans. Energy Convers.*, Vol. 11, No. 1, pp. 188-193, March 1996.

[4] J-Y Lim, B-B Kang, and I-S Cha, "Study on Characteristics of the Combined Generation System by Solar and Wind Energy with Power Storage Apparatus for the Geographical Features", *Journal of Power Electronics*, Vol. 2, No. 1, pp.11-18, 2002.

[5] K-S Lee, K. Yamaguchi, and K. Kurokawa, "Proposed

Distribution Voltage Control Method for Connected Cluster PV Systems", *Journal of Power Electronics*, vol. 7, no. 4, pp.286-293, 2007.

[6] E. Wiemken, H.G. Beyer, W. Heydenreich, and K. Kiefer, "Power characteristics of PV ensembles: experiences from the combined power production of 100 grid connected PV systems distributed over the area of Germany", *Solar Energy,* Vol. 70, No. 6, pp. 513-518, 2001.

[7] N. Ina, S. yanagawa, T. Kato, and Y. Suzuoki, "Smoothing of PV system output by tuning MPPT control", Electrical Engineering in Japan, Vol. 152, No. 2, pp. 10-17, 2005.

[8] D. Canever, G.J.W. Dudgeon, S. Massucco, J.R. McDonald, and F. Silvestro, "Model validation and coordinated operation of a photovoltaic array and a diesel power plant for distributed generation", in Proc. IEEE Power Engineering Society Summer Meeting, Vol.1, pp. 626-631, 2001.

[9] L. H. Tsoukalas and R. E. Uhrig, Fuzzy and Neural Approaches in Engineering, NewYork, USA: Jhon Wiley & Sins. Inc., 1997.

[10] C.C. Lee, "Fuzzy logic in control systems: fuzzy logic controller-part I and part II", IEEE Trans. Syst., Man, Cybern., Vol. 20, No. 2, pp. 404-435, Mar./April 1990.

[11] AG. Abo-Khalil, D-C Lee, J-W Choi, and H-G Kim, "Maximum Power Point Tracking Controller Connecting PV System to Grid", *Journal of Power Electronics,* Vol. 6, No. 3, pp.226-234, 2006.

[12] N. Femia, G. Petrone, G. Sp, "Optimization of perturb and observe maximum power point tracking method", *IEEE Trans. Power Electron.*, Vol. 20, No. 4, pp. 963-973, July 2006.

[13] Tomonobu Senjyu, Manoj Datta, Atsushi Yona, Hideomi Sekine, and Toshihisa Funabashi, "A Coordinated Control Method for Leveling Output Power Fluctuations of Multiple PV Systems", in Proceeding of the 7th International Conference on Power Electronics, 2007 (ICPE'07), EXCO, Daegu, Korea, pp. 445-450, October 22-26, 2007.

[14] K. Kobayashi, I. Tanako, and Y. Sawada, "A study of a two stage maximum power point tracking control of a photovoltaic system under partially shaded insolation conditions", *Solar Energy Materials & Solar Cells,* Vol. 90, pp. 2975-2988, 2006.

[15] B-D Min, J-P Lee, J-H Kim, T-J Kim, D-W Yoo, K-R Ryu, J-J Kim, and E-H Song, "A Novel Grid-Connected PV PCS with New High Efficiency Converter", *Journal of Power Electronics*, Vol. 8, No. 4, pp.309-316, 2008.

[16] C. Hua, J. Lin, and C. Shen, "Implementation of a DSP controlled photovoltaic system with peak power tracking", *IEEE Trans. Ind. Electron.*, Vol. 45, No. 1, pp. 99-107, Feb. 1998.

[17] [Online] Available: http://solar.sharpusa.com/files/sol_dow_ND216U1ss.pdf.

[18] T. F. Wu, C. H. Yang, Y. K. Chen, and Z. R. Liu, "Photovoltaic inverter systems with self-tuning fuzzy control based on an experimental planning method", in Proc. 34th Ind. Appl. Soc. Annu. Meet., Vol. 3, pp. 1887–1894, 2001.

[19] Y. K. Chen, C. H. Yang, and Y. C.Wu, "Robust fuzzy control photovoltaic inverter with Taguchi method", *IEEE Trans. Aerosp. Electron. Syst.,* Vol. 38, pp. 940–954, Jul. 2002.

[20] D. Burkhardt and P. Bonissone, "Automated fuzzy knowledge base generation and tuning", in Proc. FUZZ IEEE, San Diego, CA, pp. 179–188, Mar. 1992.

[21] G. Bartolini et al., "Development of performance adaptive fuzzy controllers with application to continuous casting plants", in Proc. Cybern. Syst. Res. Amsterdam, TheNetherlands:North Holland, pp. 721- 728, 1982.

[22] T. Senjyu, T. Kaneko, A. Yona, N. Urasaki, T. Funabashi, F. Yamada, and S. Sugimoto, "Output power control for large wind power penetration in small power system", in Proc. IEEE PES Gen. Meeting, pp. 1–7, 2007.

[23] [Online] Available: http://www.sunpowercorp.com/For-Businesses/Case-Studies/~/media/Downloads/for_business_SPWRLVVWD_CS.ashx.

[24] [Online] Available: http://www.xantrex.com/web/id/214/p/1840/pt/23/product.asp.

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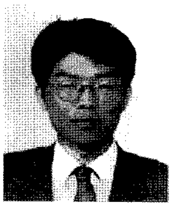

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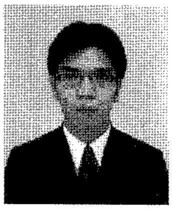

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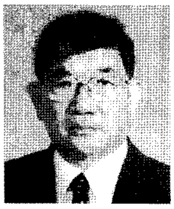

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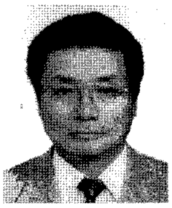

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