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A New Islanding Detection Method using Phase-Locked Loop for Inverter-Interfaced Distributed Generators

Il-Yop Chung* and Seung-Il Moon†

Abstract – This paper proposes a new islanding detection method for inverter-interfaced distributed generators (DG). To detect islanding conditions, this paper calculates the phase angle variation of the system voltage by using the phase-locked loop (PLL) in the inverter controllers. Because almost all inverter systems are equipped with the PLL, the implementation of this method is fairly simple and economical for inverter-interfaced DGs. The detection time can also be shortened by reducing communication delay between the relays and the DGs. The proposed method is based on the fact that islanding conditions result in the frequency and voltage variation of the islanded area. The variation depends on the amount of power mismatch. To improve the accuracy of the detection algorithm, this paper injects small low-frequency reactive power mismatch to the output power of DG.

Keywords: Distributed Generator (DG), Interconnection Problem, Islanding Detection, Inverter Phase Locked Loop (PLL)

1. Introduction

Distributed generators (DG) have been considered as effective countermeasures against the limitation of the current power systems. For example, DGs can relieve the burden placed on the large-scale power system and enhance the reliability of power delivery. In addition, DGs can utilize renewable energy resources. However, the DG interconnection causes significant problems to the current power system, with islanding problems being the most representative of all [1].

Islanding occurs when a DG or group of DGs continue to energize a portion of the power system that has been disconnected from the main utility system. This disconnection could be due to a fault or operation of the upstream protective devices. In most cases, the islanding can lead to safety problems in the power systems. For example, during utility repair operations, the utility personnel may suffer a serious safety threat when they are exposed to the islanded circuit that otherwise would be de-energized. In addition, if the islanding is formed by trip of an automatic recloser, the reclosing operation of the recloser can cause out-of-phase damages to the power system [1]-[4].

Islanding detection techniques can be classified into three categories: the direct method, the passive method and the active method. The direct method is to monitor the states of all breakers in the power system. This method is the most efficient to detect islanding but hard to implement due to the involvement of comprehensive monitoring systems.

The passive method is based on the measurement of power system parameters such as frequency variation, phase displacement, and power variation. This idea relies on the fact that islanding conditions will result in the variations of power system parameters [5-7].

The active method is to breed small variations in the output of DGs. When the utility source remains connected with the DGs, these variations are relatively insufficient to trip protective relays. However, in the islanded networks, this designated deviation will enlarge to activate the relays [8-11]. The active method is generally considered more effective than passive methods because passive methods have a relatively large *Non-Detection Zone* (NDZ) [12, 13].

Due to the development of power-electronic devices, inverters can provide versatile controls to DGs [14, 15]. This paper focuses on the development of an islanding detection method that is befitting to the inverter-interfaced DG systems. The proposed method uses the internal signals of the *Phase Locked Loop* (PLL) circuits in order to detect the phase angle variation of the system voltage. This feature offers some advantages: 1) it improves the speed of detection and control of the islanding conditions because the detection method is integrated with the inverter controller and there is little communication delay; and 2) this method is economical because it shares the measurement equipment with the inverters whereas other protective relays have extra measurement equipment. In addition, to reduce

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the NDZ, this paper proposes to insert small reactive power disturbances to the DG output power. The performance of the proposed method is simulated and evaluated using PSCAD/EMTDC.

2. Basic Principle of Islanding Detection

Islanding conditions cause the change of the voltage and frequency of the islanded circuit. Let us consider a simple power system as shown in Fig. 1 [12, 13]. The load is assumed as constant impedance load (*R*, *L* and *C*).

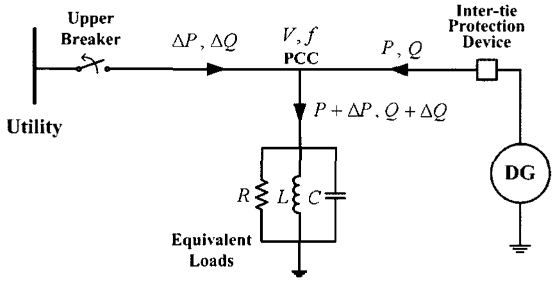


Fig. 1. Simplified circuit of power system for anti-islanding study

When the utility source is connected to the power system, the utility supplies active and reactive power as much as ΔP and ΔQ to the load. The DG supplies active power and reactive power as *P* and *Q* to the load. Then, the voltage magnitude and frequency (*V* and *f*) of the *Point of Common Coupling* (PCC) can be derived as (1).

$$\begin{aligned} P+\Delta P &= \frac{V^2}{R} \\ Q+\Delta Q &= \frac{V^2}{2\pi f L} \end{aligned} \tag{1}$$

Equation (1) can be rewritten as (2).

$$\begin{aligned} V &= \sqrt{R\,(P+\Delta P)} \\ f &= \frac{V^2}{2\pi L(Q+\Delta Q)} \end{aligned} \tag{2}$$

If the upper breaker opens, the rest of the circuit including the DG and the load becomes an island area. Because ΔP and ΔQ become zero, the new voltage and frequency (V' and f') can be obtained as (3).

$$\begin{aligned} V' &= \sqrt{R\,P} \\ f' &= \frac{V'^2}{2\pi L Q} = \frac{R\,P}{2\pi L Q} \end{aligned} \tag{3}$$

Then, the amount of the voltage and frequency variation is as (4) [12, 13].

$$\begin{aligned} \Delta V &= V'-V = \sqrt{R\cdot P} - \sqrt{R\cdot(P+\Delta P)} \\ \Delta f &= f'-f = \frac{V'^2}{L\cdot Q} - \frac{V^2}{L\cdot(Q+\Delta Q)} = \frac{R\cdot P}{L\cdot Q} - \frac{R\cdot(P+\Delta P)}{L\cdot(Q+\Delta Q)} \end{aligned} \tag{4}$$

Equation (4) suggests that the power mismatch (ΔP and ΔQ) causes voltage and frequency variation. Therefore, the islanding conditions can be detected by monitoring voltage and frequency changes. This is the basic motivation of the passive methods. However, if the power mismatch is small, the amount of voltage and frequency variation will be too small to distinguish islanding conditions. The range of the power mismatch where DGs cannot detect islanding conditions is referred to as the NDZ.

3. Reactive Power Disturbance Injection

As explained at the end of Chapter 2, small power mismatch makes it difficult for passive methods to detect islanding conditions. Therefore, to accurately detect islanding conditions, this paper adjusts small reactive power disturbance to the output of the inverter.

Fig. 2 shows the interconnection of the inverter-interfaced DG system and the concept of inverter operation when the DG operates in parallel with the utility system.

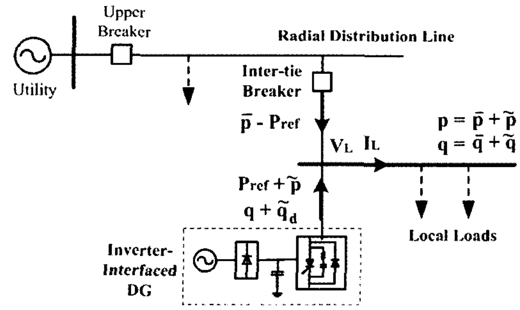


Fig. 2. DG Interconnection and instantaneous power relationship

The inverter control uses the instantaneous power theory [16]. The instantaneous power (*p*) and instantaneous imaginary power (*q*) can be defined as (5), where v_α, v_β and i_α, i_β mean the voltage and current of the load in the α-β coordinates, respectively. The relationship between the a-b-c coordinates and the α-β coordinates is as (6).

$$\begin{aligned} p &= v_\alpha \cdot i_\alpha + v_\beta \cdot i_\beta \\ q &= v_\alpha \cdot i_\beta - v_\beta \cdot i_\alpha \end{aligned} \tag{5}$$

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{6}$$

Equation (5) can be characterized as (7), where the bar (‒) indicates mean value and the tilde (~) means alternating components with zero mean value.

$$\begin{aligned} p &= \bar{p} + \tilde{p} \\ q &= \bar{q} + \tilde{q} \end{aligned} \tag{7}$$

In (7), $\bar{p}$ and $\bar{q}$ equals to the average 3-phase active and reactive power, respectively and $\tilde{p}$ and $\tilde{q}$ results from harmonic components.

As shown in Fig. 2, the object of the inverter control is to supply constant active power (P_{ref}) and improve power factor by providing the reactive power required by loads ($\bar{q}$). This DG system can also compensate harmonic components of the local loads by supplying $\tilde{p}$ and $\tilde{q}$. In addition, the reactive power disturbance $\tilde{q}_d$ for islanding detection is inserted. The pattern of the reactive power disturbance $\tilde{q}_d$ is illustrated in Fig. 3 where ΔQ_D is the amplitude of the triangular waveform and T_D is the period. In this paper, ΔQ_D is set as 2.5% of the output active power of the DG system according to [11].

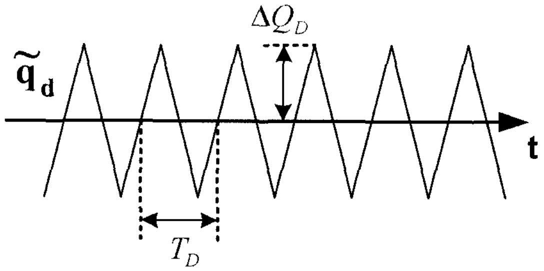


Fig. 3. Pattern of the reactive power disturbance for an active islanding detection method

Then, the reference current of the inverter can be obtained as (8).

$$\begin{bmatrix} i_{\alpha REF} \\ i_{\beta REF} \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix}^{-1} \cdot \begin{bmatrix} P_{ref} + \tilde{p} \\ q + \tilde{q}_d \end{bmatrix} \tag{8}$$

The implementation of detailed inverter control algorithms is explained in [14] and [15].

4. PLL Phase Angle Variation Detection

In this paper, a new islanding detection algorithm is proposed. The proposed method utilizes the internal signals of the PLL circuit of the inverter control system. Because all the inverters should have the PLLs for their own control, the proposed method is appropriate to the inverter-interfaced DG systems.

4.1 Phase Locked Loop System

PLLs detect the phase angle of the system voltage. The phase angle offers critical information to the inverters for synchronizing the turning on/off signals of power-electronic devices. Fig. 4 shows the control diagram of the PLL system used in this paper [17].

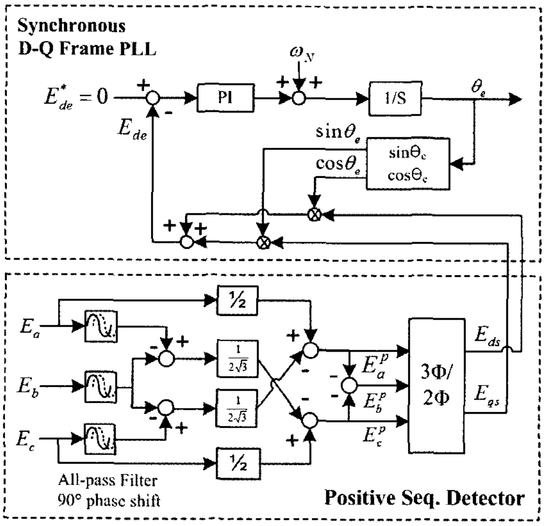


Fig. 4. Control diagram of the synchronous d-q frame PLL

The PLL illustrated in Fig. 4 consists of two parts: the synchronous d-q frame PLL part and the positive sequence detector part. The synchronous d-q frame PLL detects the phase angle in the d-q rotating reference frame, which is synchronized to the input voltage frequency [18]. The positive sequence detector eliminates the effects of the voltage unbalance and some low-order harmonics in the system voltage [17].

In the positive sequence detector, the positive sequence voltages (E_a^p, E_b^p and E_c^p) can be obtained by (9), where E_a, E_b and E_c are the system voltage.

$$\begin{bmatrix} E_a^p \\ E_b^p \\ E_c^p \end{bmatrix} = \frac{1}{3} \cdot \begin{bmatrix} 1 & a & a^2 \\ a^2 & 1 & a \\ a & a^2 & 1 \end{bmatrix} \cdot \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} \tag{9}$$

where, $a=-1/2+j\sqrt{3}/2$

The positive sequence voltages are transformed to the stationary reference frame voltages (E_{ds} and E_{qs}) as shown in (10). Then, the stationary reference frame voltages are transformed to the rotating reference frame voltages (E_{de} and E_{qe}) as (11), where θ_e is the phase angle of E_a^p.

$$\begin{bmatrix}E_{qs}\\E_{ds}\end{bmatrix}=\frac{2}{3}\begin{bmatrix}1 & -1/2 & -1/2\\0 & -\sqrt{3}/2 & \sqrt{3}/2\end{bmatrix}\cdot\begin{bmatrix}E_a^p\\E_b^p\\E_c^p\end{bmatrix} \tag{10}$$

$$\begin{bmatrix}E_{qe}\\E_{de}\end{bmatrix}=\begin{bmatrix}\cos\theta_e & -\sin\theta_e\\\sin\theta_e & \cos\theta_e\end{bmatrix}\cdot\begin{bmatrix}E_{qs}\\E_{ds}\end{bmatrix} \tag{11}$$

If θ_e is identical to the phase angle of E_a^p, E_{de} becomes zero. Therefore, the reference value of E_{de} is zero.

4.2 Proposed Islanding Detection Method

This paper proposes a new islanding detection method dubbed *the PLL phase angle variation method* based on the facts below:

- Islanding causes the system frequency change depending on the power mismatch.
- Islanding provokes the system impedance change that leads to the phase angle jump of the system voltage.
- The DG system used in this paper is controlled as a current-controlled inverter during the parallel operation with the utility systems. When the DG system is separated from the utility systems, the PCC suffers phase angle variation.

To summarize, detecting phase angle variation of the PLL circuit in the DG system provides a good solution for the islanding detection. The basic principle of the proposed method is as follows.

The positive sequence phase voltage can be written as (12) where E, θ and f are the magnitude, the phase angle, and frequency of the positive sequence system voltage, respectively.

$$\begin{bmatrix}E_a^p\\E_b^p\\E_c^p\end{bmatrix}=\begin{bmatrix}E\cdot\cos(\theta)\\E\cdot\cos(\theta-2\pi/3)\\E\cdot\cos(\theta-4\pi/3)\end{bmatrix} \tag{12}$$

where, $\theta=2\pi ft+\theta_0$

Then, the stationary reference frame voltages are obtained as (13) under the balanced condition ($E_a^p+E_b^p+E_c^p=0$).

$$\begin{bmatrix}E_{qs}\\E_{ds}\end{bmatrix}=\begin{bmatrix}E_a^p\\(E_c^p-E_b^p)/\sqrt{3}\end{bmatrix} \tag{13}$$

Applying (12) and (13) to (11), the rotating reference frame voltages can be obtained as (14) and (15) where, $\Delta\theta=\theta_e-\theta$.

$$\begin{aligned}E_{qe}&=\cos\theta_e\cdot E_a^p-\sin\theta_e\cdot(E_c^p-E_b^p)/\sqrt{3}\\&=E\cos\theta_e\cdot\cos\theta+E\sin\theta_e\cdot\sin\theta=E\cos(\Delta\theta)\end{aligned} \tag{14}$$

$$\begin{aligned}E_{de}&=\sin\theta_e\cdot E_a^p+\cos\theta_e\cdot(E_c^p-E_b^p)/\sqrt{3}\\&=E\sin\theta_e\cdot\cos\theta-E\cos\theta_e\cdot\sin\theta=E\sin(\Delta\theta)\end{aligned} \tag{15}$$

Equations (14) and (15) can be rewritten as (16).

$$\begin{bmatrix}E_{qe}\\E_{de}\end{bmatrix}=E\cdot\begin{bmatrix}\cos(\Delta\theta)\\\sin(\Delta\theta)\end{bmatrix} \tag{16}$$

If $\Delta\theta$ signifies the phase angle difference between the utility voltage angle and the PLL internal angle, and furthermore, it means phase angle variation of the system voltage. This paper proposes to observe the $\Delta\theta$ in order to detect islanding conditions. It is easy to calculate $\Delta\theta$ in the PLL system as (17).

$$\Delta\theta=\tan^{-1}\left(\frac{E_{de}}{E_{qe}}\right) \tag{17}$$

Normally, E_{de} and E_{qe} constantly equal zero and the value of system voltage magnitude, respectively. Therefore, $\Delta\theta$ is nearly zero under normal condition; however, during islanding condition, $\Delta\theta$ will change. Therefore, the DG system can detect islanding conditions by measuring $\Delta\theta$. Fig. 5 shows the flowchart of the proposed detection algorithm.

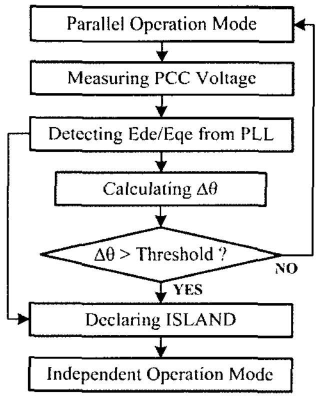


Fig. 5. Flowchart of the PLL phase angle variation detection method

5. Case Studies

Fig. 6 provides the simulation models of the distribution system and the inverter-interfaced DG system using PSCAD/EMTDC. The DG system comprises a synchronous generator, transformer, an ac-dc rectifier, a dc-link capacitor, a PWM (*Pulse Width Modulation*) inverter, and a harmonic filter. The DG power generated by the synchronous generator is converted to dc power and stored in the dc-link capacitor. The inverter supplies appropriate ac power to the power system by controlling the dc power. The inverter has two operation modes such as parallel operation mode and independent operation mode. In the parallel operation mode, it controls the output currents by utilizing the CRPWM (*Current-Regulated PWM*). In the independent operation mode, it controls output voltage by using the sine PWM. The DG system is interconnected with the power system through the inter-tie breaker. This paper assumes that the DG system can supply electric power to the upstream of the inter-tie breaker as well as the local load. Detailed control algorithms and operating strategies of the DG system are explained in [14] and [15]. Table 1 lists the parameter values of the DG system and the test power system.

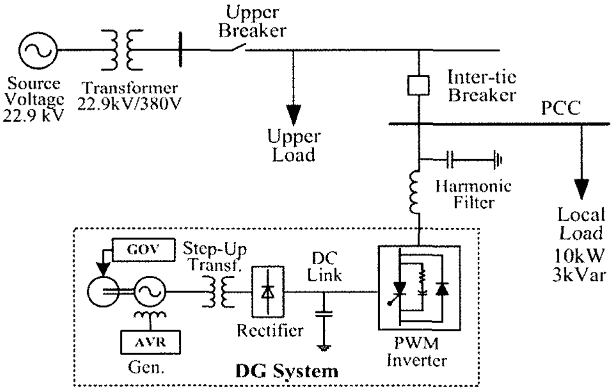
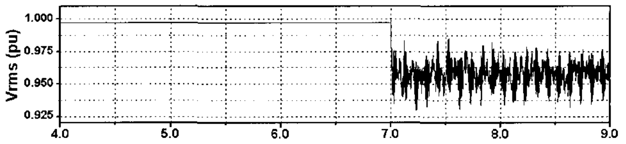


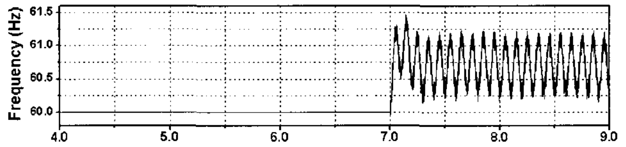
Fig. 6. Single-line diagram of the inverter-interfaced DG system and the test power system

Table 1. Parameters of the model system

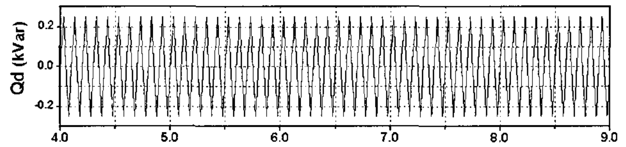
Component	Value
Source Voltage	22.9kV
Transformer	1MVA, 22.9kV/380V, %Z=5%
Local Load	10kW, 3kVar
Upper Load	10kW, 0.03kVar
Synchronous Generator	30kVA, 380V rated
Step-Up Transformer	100kVA, 380V/450V, %Z=5%
Rectifier	3-phase diode rectifier
DC-Link	700V rated, C=3300uF
PWM Inverter	20kW, 380V rated
Harmonic Filter	L=1.5mH, C=20uF



(a) System Voltage

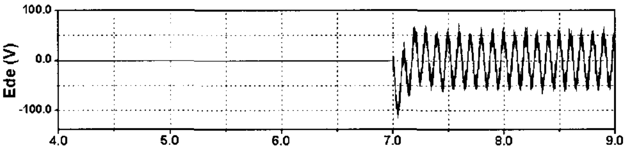


(b) System Frequency

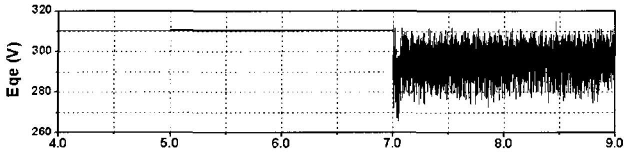


(c) Injected Reactive Power Disturbance

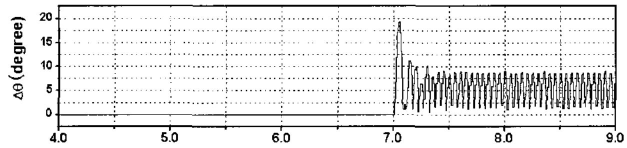
Fig. 7. Simulation results - system voltages, system frequency and injected reactive power disturbance



(a) d-axis voltage of the rotating reference frame



(b) q-axis voltage of the rotating reference frame



(c) Islanding detection index: Δθ

Fig. 8. Simulation results

The simulation scenario is as follows. From 0 sec to 5.0 sec, the synchronous generator starts and charges the dc-link. From 5.0 sec to 7.0 sec, the DG system starts to supply 20kW and 3kVar and reaches the steady state condition. Then, at 7.0 sec, the upper breaker opens and the islanding condition occurs.

In the test system, the power mismatch is so small that it causes only a little voltage and frequency variation. The upper load is set to 10kW and 0.03kVar. Therefore, the power mismatch becomes about 1% only in reactive power mismatch.

Fig. 7 shows the RMS voltage and frequency of the system voltage and the injected reactive power disturbance. The normal window protection relays are set to 0.8 ~ 1.15 p.u as voltage limitation and 58.5 ~ 61.5 Hz as frequency limitation. Because the results of Fig. 7 do not exceed those limitations, the window protection relays cannot detect this islanding case. This means this case is in the NDZ of the window protection relays.

Fig. 8 presents the d-q axis voltage of the rotating reference frame and the proposed islanding detection index (Δθ). In Fig. 8, the phase angle variation was sampled at every half cycle. The phase angle variation suddenly changes after the islanding occurs. Therefore, by calculating Δθ, the DG can detect islanding cases.

Fig. 9 indicates the effect of reactive power disturbance injection. Since the reactive power disturbances increase the phase angle variation, the accuracy of the proposed method can be improved.

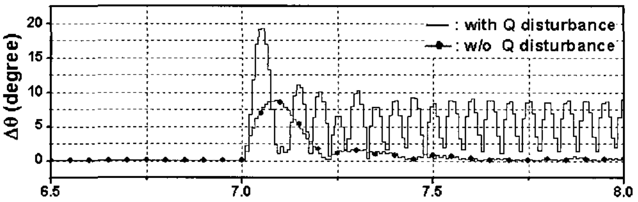


Fig. 9. Effect of reactive power disturbance injection

6. Conclusion

This paper proposed a new active method to detect islanding condition. The DG system detects islanding condition by the PLL phase angle variation detection method. To reduce the NDZ of the islanding detection, the DG system breeds a small disturbance in the reactive power output. The proposed method is easily implemented in the inverter-interfaced DG systems. This feature gives them important advantages such as relieving communication burden, reducing implementation cost, and improving power system safety. The simulation result shows that the proposed method is effective even in a small power mismatch case.

Acknowledgments

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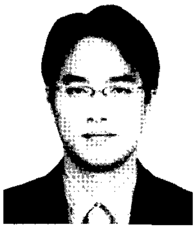

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