Power Flow Control of a Single Distributed Generation Unit

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***Abstract*—This research addresses power flow control problem of a grid-connected inverter in distributed generation applications. A real and reactive power control solution is proposed on the basis of an existing voltage control strategy developed for island operations. The power control solution takes advantage of a newly designed system parameter identification method and a nonlinear feedforward algorithm, both of which are based on Newton–Raphson iteration method and implemented in real time. The proposed power control solution also performs grid-line current conditioning and yields harmonic free grid-line current. A phase locked loop based algorithm is developed as a part of the solution to handle possible harmonic distorted grid-line voltage and maintain harmonic free line current. The effectiveness of the proposed techniques is demonstrated by both simulation and experimental results.**

***Index Terms*—Distributed generation (DG), Newton–Raphson method, parameter estimation, power control, power conversion.**

I. Introduction

POWER control, including real power P and reactive power Q controls, of an inverter interfaced distributed generation (DG) unit in grid-connected mode with existence of local load is of great importance and interest. The challenges come from the fact that the system should also be able to supply quality power to the local load in island mode. Based on this fact, control solutions yielding stability, fast transient response, and less coupling between P and Q are desired.

Previous researches have been conducted to address this problem. As early as 1984, Key [1] pointed out that future grid-connected switched-mode inverters can provide compatible utility interfaces. Since then, Wall [2] has addressed a number of differences between an inverter interfaced DG unit and a synchronous generator in power system operation under normal, island, and fault conditions. Thomas *et al.* [3] have concluded that DG may have significant impact on power system stability if not properly compensated in reactive power, and Donnelly *et al.* [4] research has shown that DG could have significant impacts on transmission system stability at heavy penetration levels, where penetration is defined as the percentage of DG power in total load power of the system. A DG unit affects the system stability by generating or consuming active and reactive power. Therefore, the power control performance of a DG unit determines its impact on the utility grid it connects to. If the power control performs well, the DG unit can be used as means to enhance the system stability and improve power quality; otherwise it could undermine the system stability.

Line-interactive uninterruptible power supply (UPS) is able to pick up the load at power system failure and reverse power flow direction to battery charging when the power line is restored as addressed in the work of Chandorkar *et al.* [5]. However, the power flow control in line-interactive UPS does not match the requirement of DG systems by far.

Abdel-Rahim *et al.* [6] have developed a line-interactive inverter control technique which allows a certain output power factor setting. Similarly, Rajagopalan *et al.* [7] have presented an inverter control that allows some P and Q setting when it is connected to power system. However, neither of them has closed loop power control for arbitrary P and Q tracking. Teodorescu *et al.* [8] have proposed a three-phase ac–dc–ac power conversion system interfacing small wind turbines to utility grid. This system has been developed for both island and grid-connected operations. However, major endeavor has been used in island mode control. Although a current control approach under grid-connected mode has been presented, no power control behavior has been addressed and evaluated.

In 1987, Kalaitzakis *et al.* [9] first introduced the power control concept for synchronous generator paralleled with power system into the application of grid connected inverters, which states that active power P can be controlled by adjusting phase angle of output voltage and reactive power Q can be controlled by adjusting magnitude of output voltage. Since then, Chandorkar *et al.* [10] have developed an inverter control technique for line-interactive operation where P and Q can be separately controlled through closed-loop control, and Sedghisigarchi *et al.* [11] have performed a simulation research on P and Q dynamic control under reclosing operating condition although its control strategy is inadequately addressed and the transient response is slow.

Unified power flow controller (UPFC) is another application of grid-connected inverters where multiple topologies are available [12]. Yu *et al.* [13] have studied four different line current control techniques for three-phase line-interactive inverters with a series-parallel topology in a UPFC, in which a PI plus dq-axis decoupling method yields a good real and reactive power response. Experimental results on a 1 kW system have been presented to show the power flow control performance. However,

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due to the topology issue, this technique is difficult to be implanted into a typical DG unit where high performances in both island mode and grid-connected mode are required.

Liang *et al.* [14] have presented a power control method for a grid-connected voltage source inverter which achieves good P and Q decoupling and fast power response. However, this approach requires an interface inductor to be connected between the DG output terminal and power system, whose inductance value is assumed known. The existence of the interface inductor forces greater voltage magnitude and phase change at the DG terminal to perform certain regulations of the utility P and Q. Since knowledge of the value of power system equivalent impedance is not available in practical applications, if this inductor were removed, the approach would become invalid. Even though the possible error in the power factor angle of the impedance has been considered, it is the magnitude of the impedance that truly causes the sensitivity of P and Q responses, which is however not addressed. Therefore, the effectiveness of the control approach claimed in [14] is seriously undermined.

Illindala *et al.* [15] have presented a different power control strategy based on frequency and voltage droop characteristics of power transmission, which allows decoupling of P and Q at steady state. In this method, power regulation errors ΔP and ΔQ are used to generate output voltage phase angle and magnitude changes respectively, which decouples P and Q controls in steady state. Unfortunately, the presented simulation result does not show a satisfactory performance in response time which could be caused by low feedback gain and implies that higher gain may cause problems.

The same authors of this paper have published some preliminary research on power flow control in an inverter interfaced DG system [16], where an integral P and Q control based on a high performance inner voltage loop is proposed. However, the control technique does not take advantage of knowledge of the utility grid and therefore the performance is limited.

The above researches have shown that knowledge about the utility grid helps the control of DG unit in transients. There has not been any published work addressing the methodology of obtaining the knowledge of the grid and applying the knowledge in DG control in real time. In this paper, a power system parameter identification technique and a feedforward control technique applying the system identification results to real-time implementation will be proposed as an expansion of the technique developed in [16].

Newton–Raphson Method is an iterative root-finding algorithm that uses the first few terms of the Taylor series of a function $f(x)$ in the vicinity of a suspected root. Newton-Raphson Method is widely used in solving power flow problems due to its fast convergence property. In reported applications, Newton–Raphson Method is only used as an off-line solver for the specific mathematical problems. No on-line application of the method for real-time control purpose has been reported. In this paper, real-time implementation of Newton–Raphson Method in both system parameter estimation and feedforward control on a digital signal processor (DSP) will be presented.

If the local load of the DG unit is nonlinear, e.g., diode rectifier sort of load, it draws harmonic current from feeder. In island mode, the DG unit is the only feeder. However, in grid-connected mode, how the harmonic current is shared by the DG unit and grid becomes a concern. Harmonic free line current is always desired and how to let the DG unit take all the harmonic current is an important problem. In this paper, the power control technique proposed will address this problem.

In practice, the voltage of utility grid is often somewhat harmonic distorted. If not properly handled, the distortion may cause undesired interaction between the DG units and the grid as shown by Enslin *et al.* [17]. Whether the DG unit can identify the harmonic components in the grid voltage and compensate for them to maintain clean sinusoidal line current becomes a challenge. In this paper, a mechanism coping with this situation will be proposed.

In this paper, Section II will introduce the system topology and review the existing voltage and current control technique on top of which the new power control technique is developed. Section III will address the nature of the power control problem and review the conventional integral control technique developed in [16], including the proof of its stability. In Section IV, a Newton–Raphson Method based on-line power system parameter identification technique will be proposed to obtain the Thevenin parameters of the utility grid in real-time. Moreover, a Newton–Raphson Method based feedforward controller will be proposed on top of a conventional integral power controller to achieve better power control performance in transients. Section V will present a phase-locked loop based harmonic identifying algorithm to handle the harmonic corrupted grid voltages and maintain harmonic free line currents. Both simulation and experimental results will be presented in Sections VI and VII, respectively.

II. System Topology and Island Mode Control

The proposed control solution is developed for a grid-connected DG unit shown in Fig. 1. The DG unit consists of a dc bus powered by any dc source or ac source with a rectifier, a voltage source inverter, an L–C filter stage, a Δ/Yg type isolation transformer with secondary side filtering. The DG unit has a local load, linear or nonlinear, and is connected to the utility grid through a three-phase static switch. The utility grid is modeled by Thevenin's Theorem as an equivalent three-phase ac source with equivalent internal impedance Z.

In island mode, the inverter conducts voltage control, where the load voltage $V_{\mathrm{out}ABC}$ should track the given reference. The voltage control goal is to provide strong voltage regulation, low steady state error in rms, fast transient response, and low total harmonic distortion (THD). If the voltage of the utility main E_{ABC} is measured and used as the reference, $V_{\mathrm{out}ABC}$ will be controlled to match E_{ABC} in magnitude and synchronized in phase angle.

In grid-connected mode, the DG unit conducts power control, where the output active power P and reactive power Q from the DG unit to the utility grid should be regulated to desired values P_{ref} and Q_{ref}. Both P_{ref} and Q_{ref} can be positive or negative, which provides possibility for the DG unit to help with the energy production and stability enhancement of the power system or sustain power supply to local load when it exceeds the capacity of the DG. The control goals of power regulation are stability, low steady state error, and fast response with low coupling between P and Q.

The power flow control technique developed in this research is based on the voltage and current control technique proposed

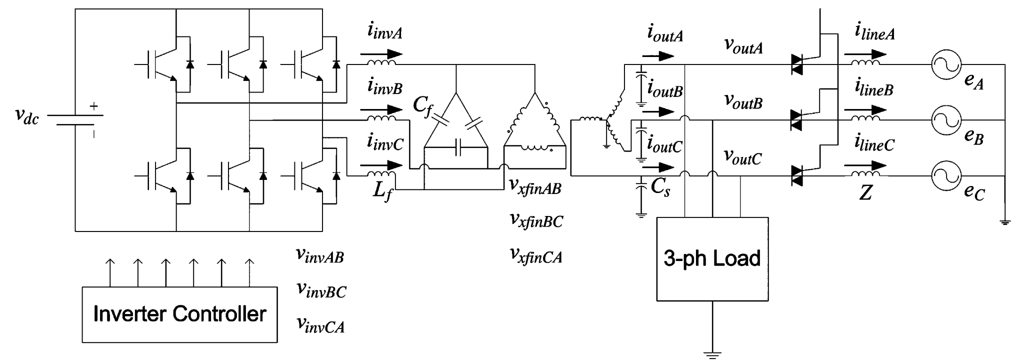

Fig. 1. Grid-connected DG unit with local load.

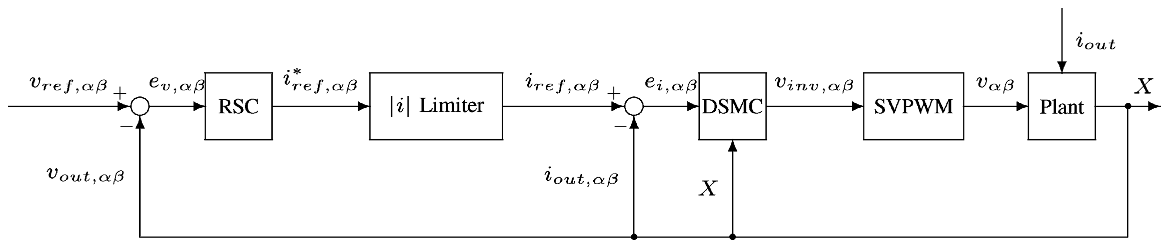

Fig. 2. Control structure for island mode.

in [18] for island mode control. For completeness, the main attributes of the voltage and current controls are reviewed below.

For high quality of $V_{\mathrm{out}ABC}$ with strong regulation, low THD, and overload protection, a dual-loop voltage and current control structure is used as shown in Fig. 2, where the inner loop is for current control and outer loop is for voltage control. A robust servomechanism controller (RSC) is used for voltage control and a discrete-time sliding mode controller (DSMC) is used for current control. The three-phase quantities are transformed from ABC reference frame into a stationary $\alpha\beta$ reference frame since there is no 0-axis current involved in control.

The DSMC is used in the current loop to limit the inverter current under overload condition because of the fast and overshoot-free response it provides. The RSC is adopted for voltage control due to its capability to perform zero steady state tracking error under unknown load and eliminate harmonics of any specified frequencies with guaranteed system stability. The theory behind the RSC is based on the solution of robust servomechanism problem (RSP) [19] where the internal model principle [20] and the optimal control theory for linear systems are combined. The internal model principle is applied in the DG voltage control by including the fundamental frequency mode and the frequency modes of the harmonics to be eliminated into the controller. The linear quadratic LQ optimal control theory of linear systems is combined in the RSC in order to guarantee the stability of the closed-loop system and provide arbitrary good transient response based on desired control priorities.

In a DG unit shown in Fig. 1, most of the voltage harmonics, like the triplets (third, ninth, 15th, ...) and even harmonics, are either non-existing or uncontrollable, or negligible in values. Therefore, only the fundamental and the fifth and seventh harmonics are left for the control to handle. Since the overload protection is a strongly desired feature for inverter systems, a DSMC is included in the inner loop to limit the current under overload conditions. With the existence of the DSMC in the inner loop, the RSC in the outer loop is designed taking the dynamics of the DSMC into account, so that the stability and robustness of the overall control system is guaranteed. More analysis on the system dynamics and robustness with respect to parameter uncertainties has been presented by the same authors in [21].

III. Real and Reactive Power Control Issues and the Integral Approach

As addressed in [16], the nature of the power flow control of an inverter interfaced DG system with a high performance voltage control can be described below.

A. The Power Control Problem

Since the DG unit uses a voltage source inverter with a strong voltage control, its output active and reactive power are determined by the unit's output voltage, including magnitude and phase angle, as stated in

$$P = \frac{V_{\mathrm{out}}E}{X}\sin\delta \tag{1}$$

$$Q = \frac{V_{\mathrm{out}}^2 - V_{\mathrm{out}}E\cos\delta}{X} \tag{2}$$

where E is the equivalent main voltage, X is the equivalent line reactance where the resistance is ignored, and δ is the power angle. Since the DG unit output voltage control already exists, the task of the power controller is to generate voltage command for the voltage controller based on the desired power values P_{ref} and Q_{ref} and actual values P and Q as illustrated in Fig. 3.

It is apparent that the desired DG output voltage V and the power angle δ can be calculated from (1) and (2) given desired P and Q values and system parameter X. If this is true, the power control problem is solved. However, in practical systems, the

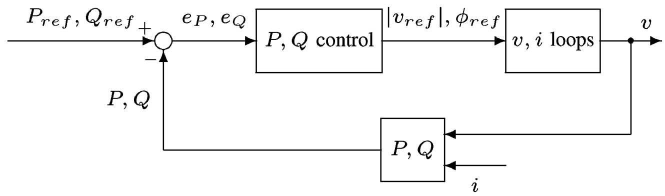

Fig. 3. Control structure for grid-connected mode.

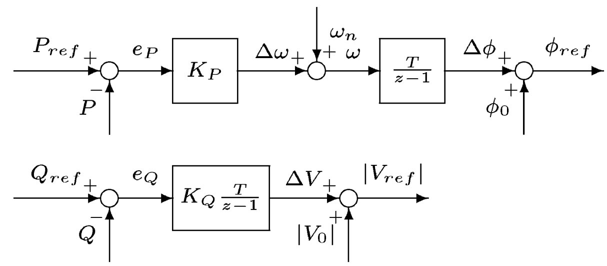

Fig. 4. Power regulator for P and Q.

above approach is not feasible based on the existing techniques due to the following three reasons.

- Equations (1) and (2) show that the power system parameters X and E need to be known to solve the equations, which is difficult based on the existing approaches. Practically, the value of X may change due to the operation of the power system.
- Both P and Q are sensitive to variation of X since it appears in the denominators and especially when X is small. The more the difference between the power system capacity and the DG's power rating, the less the value of X could be.
- Both the equations are nonlinear which are difficult to solve in real time which prevents the idea being implemented in practice.

Therefore, power control solutions requiring knowledge of X have not been practically used and people tend to search for other solutions, e.g., the integral control.

B. Integral Control

It can be observed from (1) and (2) that both P and Q will be affected by only adjusting one of V and δ, which is so called coupling between P and Q. However, variations of V and δ have different levels of impact on P and Q as described in the following partial derivatives:

$$\frac{\partial P}{\partial \delta} = \frac{V_{\text{out}} E}{X} \cos\delta \tag{3}$$

$$\frac{\partial P}{\partial V_{\text{out}}} = \frac{E}{X} \sin\delta \tag{4}$$

$$\frac{\partial Q}{\partial \delta} = \frac{V_{\text{out}} E}{X} \sin\delta \tag{5}$$

$$\frac{\partial Q}{\partial V_{\text{out}}} = \frac{2V_{\text{out}} - E\cos\delta}{X}. \tag{6}$$

With normalized V, E, and X, it can be observed from (3)–(6) that, when $|\delta|$ is small and V is close to 1 which is true for large capacity power systems, $\partial P/\partial\delta$ is close to 1 and $\partial P/\partial V_{\text{out}}$ is close to 0 and conversely, $\partial Q/\partial\delta$ is close to 0 and $\partial Q/\partial V_{\text{out}}$ is close to 1. This fact indicates that P is more sensitive to δ and Q is more sensitive to V_{out} especially when the DG unit is connected to a large capacity system where the power angle δ is usually small. The different levels of sensitivity of P and Q to δ and V_{out} provide a chance to control P and Q relatively independently, not completely independently though.

Based on the above analysis, an integral approach to conduct the power flow control can be developed to control P by adjusting δ and control Q by adjusting V_{out}. If the phase angle associated with the system voltage E is assumed to be 0, $\delta = \phi$ holds, where ϕ is the phase angle associated with V_{out}. The voltage and phase angle references can be generated as

$$\phi_{\text{ref}} = \int [K_P(P_{\text{ref}} - P) + \omega_n]\, dt + \phi_0 \tag{7}$$

$$V_{\text{ref}} = \int K_Q(Q_{\text{ref}} - Q) dt + V_0 \tag{8}$$

where $\omega_n = 2\pi{\cdot}60$ rad/s is the system nominal angular frequency, ϕ_0 and V_0 are the initial voltage and phase angle at the moment that the DG unit is connected to the grid from island mode. The integral power controller is illustrated in Fig. 4 where the integration is implemented in discrete-time.

C. The Stability Issue

In the integral control, P and Q controls are decoupled under steady state due to the integration of the errors. However, in the transient, the P Q coupling cannot be eliminated. Moreover, both P and Q are nonlinear functions of V_{out} and ϕ, which increases the complexity to analyze the system behavior. Due to the coupling issue and the nonlinearity, the stability of the power control must be investigated.

Due to the strong regulation of the DG output voltage V_{out} and its phase angle ϕ, the dynamics of the voltage control loop can be simplified into a first-order system with a transfer function representation

$$\phi(s) = \frac{a_\phi}{s + a_\phi} \phi_{\text{ref}}(s) \tag{9}$$

$$V_{\text{out}}(s) = \frac{a_V}{s + a_V} V_{\text{ref}}(s) \tag{10}$$

where a_ϕ and a_V are the inverses of the time constants of ϕ and V_{out} dynamics. Since the scope of this discussion is about power control stability of a DG unit connected to a large power system, whose time constant is in a range of seconds and much greater than that of the voltage tracking response measured in a range of 0.01 s or less, the DG power response has the room to be much slower than the voltage tracking and still fast compared to the power system. Therefore, it is reasonable to ignore the dynamics of the voltage tracking when power control is concerned, i.e. $a_\phi \to \infty$, $a_V \to \infty$, and $\phi \to \phi_{\text{ref}}$, $V_{\text{out}} \to V_{\text{ref}}$.

At the moment that the DG is switched from island mode to grid-connected mode, V_0 and ϕ_0 should match E and ϕ_E, where

ϕ_E denotes the phase angle associated to E. Therefore, (7) and (8) can be rewritten into

$$\delta = \int [K_P(P_{\text{ref}} - P) + \omega_n]\, dt \tag{11}$$

$$\Delta V = \int K_Q(Q_{\text{ref}} - Q) dt \tag{12}$$

where $\delta = \phi_{\text{ref}} - \phi_E$ and $\Delta V = V_{\text{ref}} - E$. Assuming large capacity power system with small power angle δ, it is reasonable to have $\sin\delta \approx \delta$ and $\cos\delta \approx 1$. Equations (11) and (12) can be rewritten in differential format

$$\dot{\delta} = K_P\left(P_{\text{ref}} - \frac{EV_{\text{out}}}{X}\delta\right) \tag{13}$$

$$\Delta\dot{V} = K_Q\left(Q_{\text{ref}} - \frac{V_{\text{out}}}{X}\Delta V\right). \tag{14}$$

Since the dynamics of DG voltage tracking is ignored, the stability of the power loop can be evaluated using Lyapunov's direct method where there is no external excitation, i.e., $P_{\text{ref}} = 0$ and $Q_{\text{ref}} = 0$

A Lyapunov function can be defined as

$$\xi(\Delta V, \delta) = \frac{1}{2}\Delta V^2 + \frac{1}{2}\delta^2 \tag{15}$$

where $\xi > 0$ holds unless $\Delta V = 0$ and $\delta = 0$. The derivative of the above function is

$$\begin{aligned}\dot{\xi}(\Delta V, \delta) &= \Delta V \cdot \Delta\dot{V} + \delta \cdot \dot{\delta} \\ &= -K_Q\frac{V_{\text{out}}}{X}\Delta V^2 - K_P\frac{EV_{\text{out}}}{X}\delta^2.\end{aligned} \tag{16}$$

From (16), it can be observed that $\dot{\xi}(\Delta V, \delta) < 0$ holds when $\Delta V \neq 0$ or $\delta \neq 0$, given positive values of K_P, K_Q, E, V_{out}, and X. Therefore, the proposed power control loop is asymptotically stable within a large range around the equilibrium point $\Delta V = 0$ and $\delta = 0$.

IV. Newton-Raphson Parameter Estimation and Feedforward Control

A. Newton–Raphson Parameter Identification

The power flow control plant is governed by the two nonlinear equations given in (1) and (2). Recall the initial idea mentioned in Section III that a direct solution of V_{ref} and δ_{ref} is desired assuming that the other parameters are known. This thought has not become practical only because it lacks means of implementation although the idea itself is very reasonable and instructive. In these two equations, under conventional integral control, V, δ, P, and Q are all known. If the nonlinear equations can be solved for E and X, the Thevenin equivalent circuit parameters are obtained and can be used to improve the power flow control performance. Direct analytical solution of the equations is difficult due to the nonlinearity. In this research, a real time achievable numerical solution based on Newton–Raphson Method has been developed. The algorithm is presented as follows.

To avoid cumbersome mathematical derivations, it is reasonable to replace the equations from the reactance based model to a susceptance based model, i.e., use a system susceptance B to take the place of $1/X$. This change does not affect achieving the goal of identifying the system parameters and meantime simplifies the problem and leads to a Newton–Raphson parameter estimator as depicted in Fig. 5.

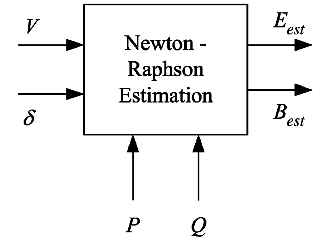

Fig. 5. Newton–Raphson method based nonlinear parameter estimator.

Rewrite (1) and (2) into the form of

$$\begin{cases} f(E,B) = BVE\sin\delta - P = 0 \\ g(E,B) = BV^2 - BVE\cos\delta - Q = 0. \end{cases} \tag{17}$$

The Jacobian is then obtained as

$$J_{est} = \begin{bmatrix} \frac{\partial f}{\partial E} & \frac{\partial f}{\partial B} \\ \frac{\partial g}{\partial E} & \frac{\partial g}{\partial B} \end{bmatrix} \tag{18}$$

where

$$\begin{aligned} \frac{\partial f}{\partial E} &= BV\sin\delta \\ \frac{\partial f}{\partial B} &= VE\sin\delta, \\ \frac{\partial g}{\partial E} &= -BV\cos\delta \end{aligned}$$

and

$$\frac{\partial g}{\partial B} = V^2 - VE\cos\delta.$$

Given initial values E_0 and B_0, the iterations can be conducted. Solve the linearized equation

$$J_{est}\begin{bmatrix}\Delta E_k \\ \Delta B_k\end{bmatrix} = \begin{bmatrix} f(E_k, B_k) \\ g(E_k, B_k)\end{bmatrix} \tag{19}$$

for ΔE_k and ΔB_k, and

$$E_{k+1} = E_k - \Delta E_k \tag{20}$$

$$B_{k+1} = B_k - \Delta B_k. \tag{21}$$

Newton–Raphson is known for fast convergence. However, if the nonlinear equations have saddles or multiple roots, the algorithm may not converge to the desired roots. Therefore, the convergence condition needs to be checked before this approach can be implemented.

It can be observed from (18) that all four Jacobian elements hold monotonicity with given parameters. Therefore, no saddles or multiple roots exist and the iteration converges to the right solution.

Due to the fast convergence, three to five iterations can yield solutions close enough to the true ones. Each control period can run one or multiple iterations depending on the load of control

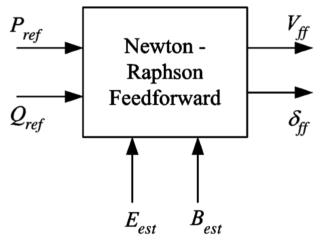

Fig. 6. Newton-Raphson method based nonlinear feedforward controller.

tasks. Moreover, no derivatives need to be computed in generating the Jacobian and the linear equation solution can be obtained using precalculated formula to save time. Thus, the proposed parameter estimation technique can be implemented on microprocessors in real time.

B. Newton-Raphson Feedforward Control

Given the real-time implementation of Newton-Raphson parameter estimation, the Thevenin equivalent circuit parameters of the power system can be approximately obtained. The acquired information can be used to perform P and Q feedforward control using the similar technique—with knowledge of the parameters E and B, from estimation, plus P_{ref} and Q_{ref}, from desired power flow requirement, the voltage command can be solved also using Newton-Raphson Method. This technique makes the idea of direct solution of V_{ref} and δ_{ref} implementable in real time and results in a P and Q feedforward controller as depicted in Fig. 6. The algorithm can be derived as follows.

Rewrite (1) and (2) into the form of

$$\begin{cases} f(V_{\mathrm{ref}}, \delta_{\mathrm{ref}}) = BV_{\mathrm{ref}}E\sin\delta_{\mathrm{ref}} - P_{\mathrm{ref}} = 0 \\ g(V_{\mathrm{ref}}, \delta_{\mathrm{ref}}) = BV_{\mathrm{ref}}^2 - BV_{\mathrm{ref}}E\cos\delta_{\mathrm{ref}} - Q_{\mathrm{ref}} = 0. \end{cases} \tag{22}$$

The Jacobian is then obtained as

$$J_{ff} = \begin{bmatrix} \frac{\partial f}{\partial V_{\mathrm{ref}}} & \frac{\partial f}{\partial \delta_{\mathrm{ref}}} \\ \frac{\partial g}{\partial V_{\mathrm{ref}}} & \frac{\partial g}{\partial \delta_{\mathrm{ref}}} \end{bmatrix} \tag{23}$$

where

$$\begin{aligned} \frac{\partial f}{\partial V_{\mathrm{ref}}} &= BE\sin\delta_{\mathrm{ref}} \\ \frac{\partial f}{\partial \delta_{\mathrm{ref}}} &= BV_{\mathrm{ref}}E\cos\delta_{\mathrm{ref}} \\ \frac{\partial g}{\partial V_{\mathrm{ref}}} &= 2BV_{\mathrm{ref}} - BE\cos\delta_{\mathrm{ref}} \end{aligned}$$

and

$$\frac{\partial g}{\partial \delta_{\mathrm{ref}}} = BV_{\mathrm{ref}}E\sin\delta_{\mathrm{ref}}.$$

Given initial values $V_{\mathrm{ref,0}}$ and $\delta_{\mathrm{ref,0}}$, the iterations can be conducted. Solve the linearized equation

$$J_{ff}\begin{bmatrix} \Delta V_{\mathrm{ref,k}} \\ \Delta\delta_{\mathrm{ref,k}} \end{bmatrix} = \begin{bmatrix} f(V_{\mathrm{ref,k}}, \delta_{\mathrm{ref,k}}) \\ g(V_{\mathrm{ref,k}}, \delta_{\mathrm{ref,k}}) \end{bmatrix} \tag{24}$$

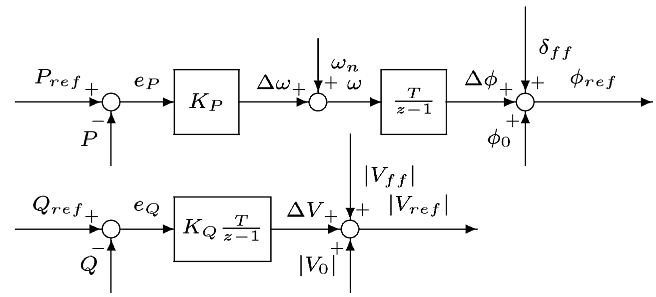

Fig. 7. Power regulator combining integral control and feedforward.

for $\Delta V_{\mathrm{ref,k}}$ and $\Delta\delta_{\mathrm{ref,k}}$, and

$$V_{\mathrm{ref,k+1}} = V_{\mathrm{ref,k}} - \Delta V_{\mathrm{ref,k}} \tag{25}$$

$$\delta_{\mathrm{ref,k+1}} = \delta_{\mathrm{ref,k}} - \Delta\delta_{\mathrm{ref,k}}. \tag{26}$$

Similarly, the convergence condition needs to be checked before this approach can be practiced. It can be observed from (23) that all four Jacobian elements hold monotonicity with given parameters. Therefore, no saddles or multiple roots exist and the iteration converges to the right solution.

Also similar to the parameter estimator proposed above, due to the fast convergence of Newton-Raphson Method, three to five iterations can yield solutions close enough to the true ones.

Combining the proposed Newton-Raphson based feedforward controller with the conventional integral control, it can be stated that even though small convergence errors still exist after a small number of iterations, the resulting V_{ref} and δ_{ref} are close to the steady state values and stability of the integral control can be maintained due to the global stability of the technique proved in Section III-C. The overall power regulator is shown in Fig. 7.

V. Harmonic Power Control

A harmonic power controller has been proposed to be applied together with the proposed fundamental power flow control technique to handle harmonic distorted grid line voltage and prevent harmonic power from flowing between the DG unit and the utility grid. The block diagram of the ith harmonic power controller is shown in Fig. 8.

The harmonic controller has the same algorithm as the conventional integral power control of the fundamental power. Specially, $P_{\mathrm{ref,i}}$ and $Q_{\mathrm{ref,i}}$ are both zero to achieve zero P_i and Q_i. The nominal frequency and phase angle of the i-th harmonic, $\omega_{0,i}$ and $\phi_{0,i}$, are obtained from a standard phase-locked loop (PLL). The nominal voltage of the harmonic $|V_{0,i}|$ is calculated using the frequency and phase angle information provided by the PLL.

VI. Simulation Results

Simulations have been conducted on a 5 kVA DG unit with a topology shown in Fig. 1 connected to a 120 V line-to-neutral power system with an equivalent reactance 0.1 Ω under a number of different scenarios as shown below.

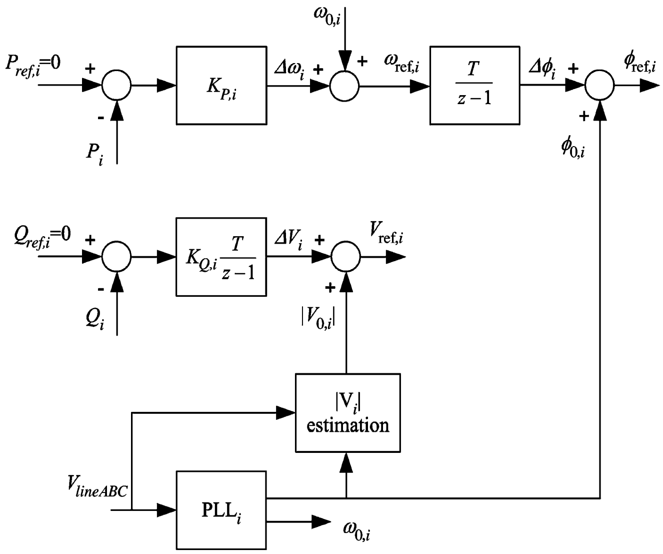

Fig. 8. Control block diagram of harmonic compensation under harmonic distorted grid voltage.

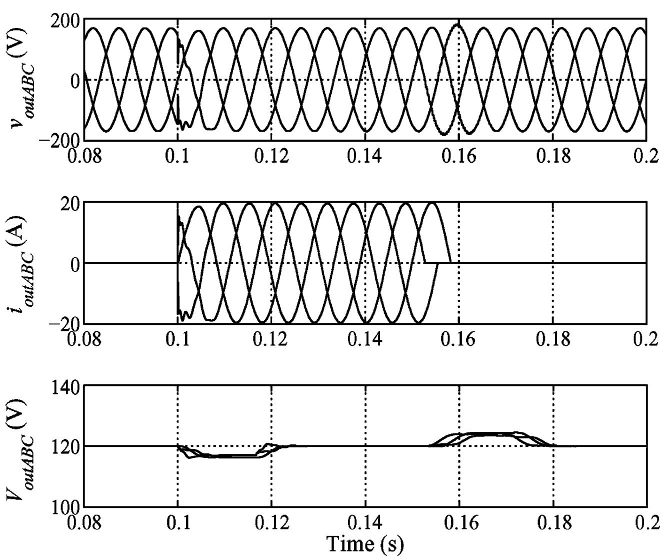

Fig. 9. Transient response of V_{out} in instantaneous and rms at step load increase from 0% to 100% and decrease from 100% to 0%.

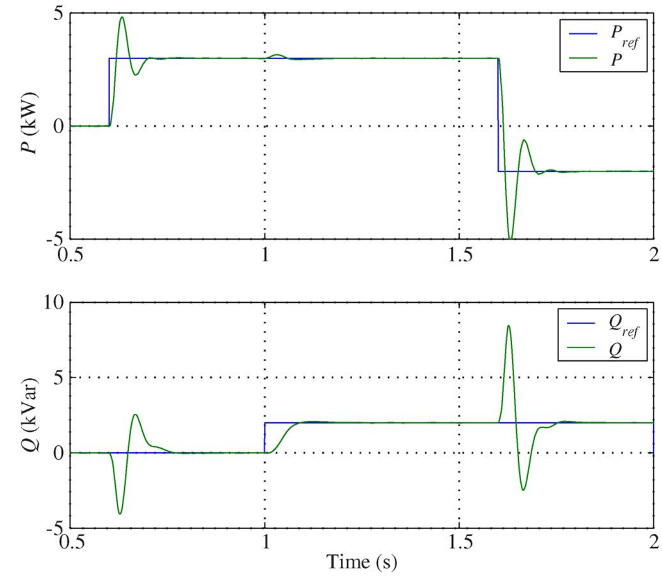

Fig. 10. P, Q regulation under nonlinear local load without feedforward.

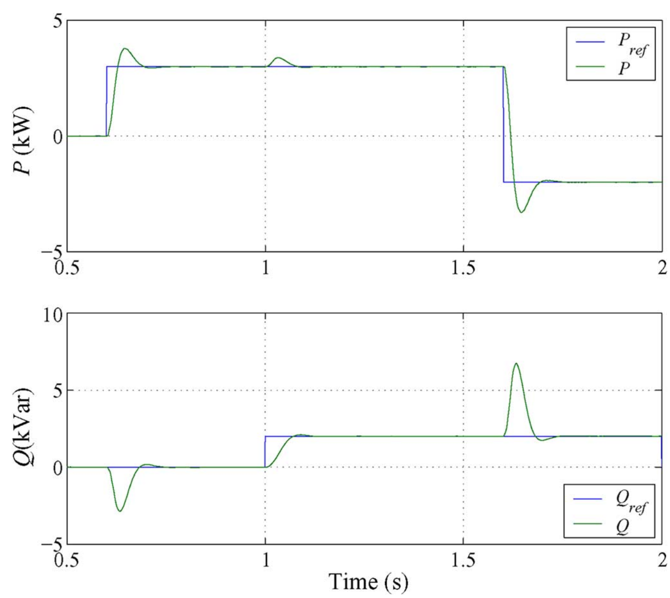

Fig. 11. P, Q regulation under nonlinear local load with feedforward.

A. Island Mode

Under island mode, a 100% step load increase is applied to the DG output terminal. After steady state is reached, the load steps back down to zero. The voltage response under these transients is shown in Fig. 9 [16].

Simulation data shows that the voltage tracking error under steady state is nearly zero and the THD is 0.4%. It can be observed from Fig. 9 that the load disturbance has little impact on V_{out} waveform and the rms transients last for only 0.02 s with 3% or so peak variations.

B. In Grid-Connected Mode

In grid-connected mode, P and Q outputs to the utility grid need to be controlled for system stabilization, compensation, or handling of local load disturbances. Fig. 10 illustrates the P and Q regulation under various step references under nonlinear local load without the Newton–Raphson parameter estimation and feedforward. Fig. 11 illustrates that with the Newton–Raphson parameter estimation and feedforward. It can be observed from these figures that under the power command step changes, transient coupling between P and Q cannot be removed while the steady state decoupling can be achieved. By comparing these two figures, it is obvious that the one with the Newton-Raphson parameter estimation and feedforward yields significantly less transient coupling and overshoot, and is therefore more effective.

When nonlinear local load exists, the line current i_{line} is not supposed to be affected with the proposed control. Fig. 12 [16] exhibits the current waveforms at three different locations of the system including the line current i_{line}, the unit output current i_{out}, and the inverter current i_{inv}. The waveforms show that all current harmonics are taken by the DG unit and the system line

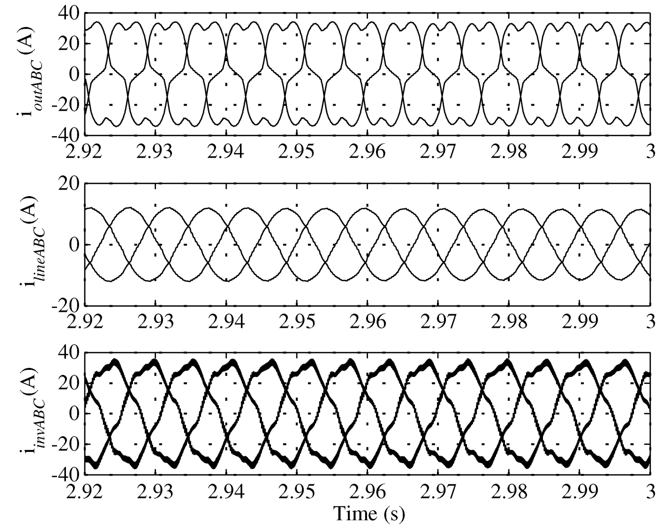

Fig. 12. Current waveforms of DG unit output current $i_{\rm out}$, system line current $i_{\rm line}$, and inverter current $i_{\rm inv}$ under nonlinear local load.

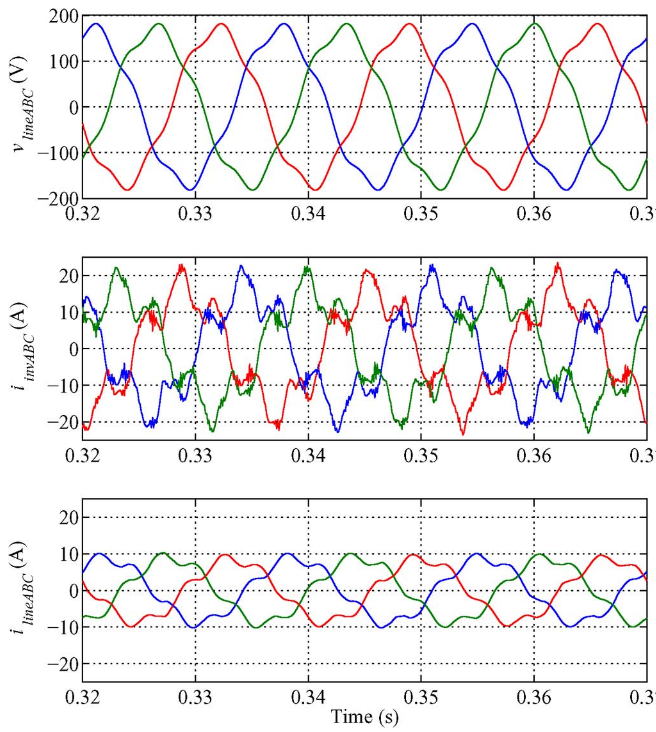

Fig. 13. $v_{\rm lineABC}$, $i_{\rm invABC}$, and $i_{\rm lineABC}$ under the fifth harmonic distorted grid voltage without the fifth harmonic power control.

current is clean. This is because the voltage control loop eliminates the voltage harmonics at the DG output and avoids harmonic current flowing to or from the utility grid.

C. Line Current Conditioning Under Harmonic Distorted Grid Voltage

The effectiveness of the harmonic power controller has been demonstrated by comparing two simulation scenarios where one incorporates the harmonic power controller under a fifth harmonic distorted utility grid voltage while the other does not. The waveforms under the scenario where there is no harmonic power

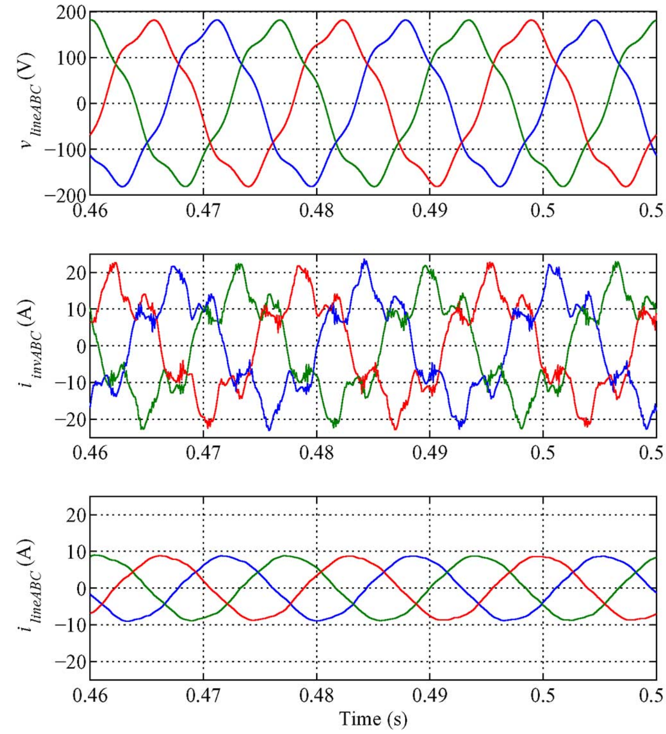

Fig. 14. $v_{\rm lineABC}$, $i_{\rm invABC}$, and $i_{\rm lineABC}$ under the fifth harmonic distorted grid voltage with the fifth harmonic power control.

control is shown in Fig. 13 while the other one, where there is the harmonic power controller, is shown in Fig. 14.

It is clearly seen from Trace 3 of the two figures that the result with the harmonic power control yields much less line current harmonics, which verifies the importance of this technique under harmonic corrupted utility grid voltage.

VII. Experimental Results

Power flow control experiments have been conducted on a 5 kVA grid-connectable inverter unit, where the main parameters are: dc bus voltage 540 V, output filter inductance 1.8 mH, filter capacitance 55 μF, Δ/Y isolation transformer equivalent leakage reactance 5%, transformer secondary filter capacitor 5 μF. SEMIKRON IGBT modules SKM 50 GB 123D are used in the inverter. A Texas Instruments TMS320LF2407A digital signal processor (DSP) with a Spectrum Digital evaluation module (EVM) is used as the digital controller. An Omron relay controlled contactor is used to operate the grid connection.

The Newton-Raphson parameter estimation and feedforward control have been developed and included in the power control code on the DSP, where the estimated parameters are used in the feedforward path. A control sampling period of 185 μs has been applied in the tests and the DSP takes 40% of a sample time, i.e., around 74 μs, to execute the required control code in each sampling period, including three iterations in both the estimation and feedforward algorithms. The power control performance of the real-time implementation of the technique has been demonstrated by comparing Fig. 15, where the technique is not used, to Fig. 16, where the technique is adopted. It can be observed that the latter is significantly faster with comparable amount of transient coupling between P and Q.

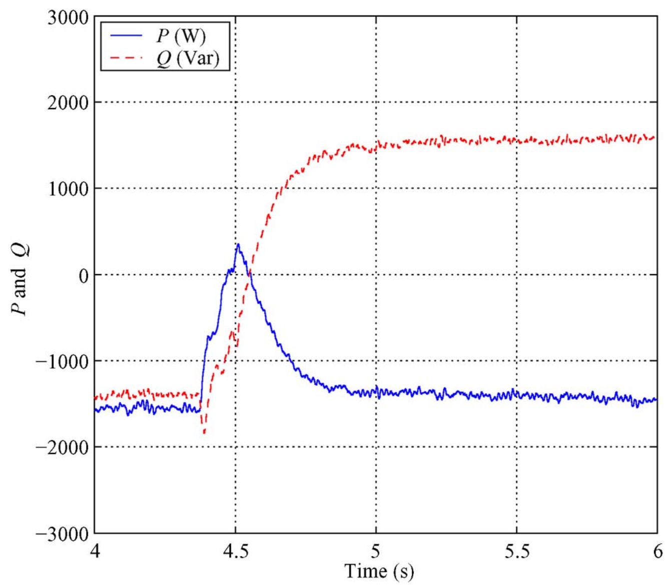

Fig. 15. Experimental P, Q regulation transients without feedforward.

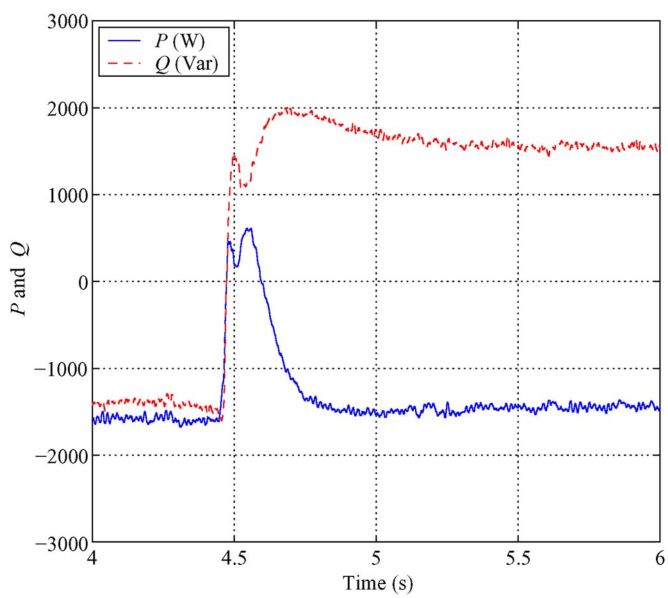

Fig. 16. Experimental P, Q regulation transients with feedforward.

The single-phase current transients under the above two scenarios have been presented and compared in Fig. 17, where the envelopes of the two current waveforms can be clearly seen and the bottom trace which includes the feedforward yields better performance.

VIII. Conclusion

This paper has presented a power flow control approach for a single distributed generation unit connected to the utility grid with a local load. The proposed control technique is based on a robust servomechanism voltage controller and a discrete-time sliding mode current controller designed for a three-phase three-wire inverter topology with an isolation transformer. In order to obtain the parameters of the utility grid and use the information to generate feedforward control of power flow, a parameter estimation technique and a feedforward power flow control technique, both based on Newton-Raphson Method, have been developed and implemented in real-time on a DSP together with the traditional integral power control. The stability of the power control loop has been proved using Lyapunov direct method. A harmonic power control technique based on PLL has been proposed to handle harmonic distorted utility grid voltage and generate harmonic free line current. Both simulation and experimental results under various scenarios have demonstrated the effectiveness of the proposed solution in power regulation and line current conditioning.

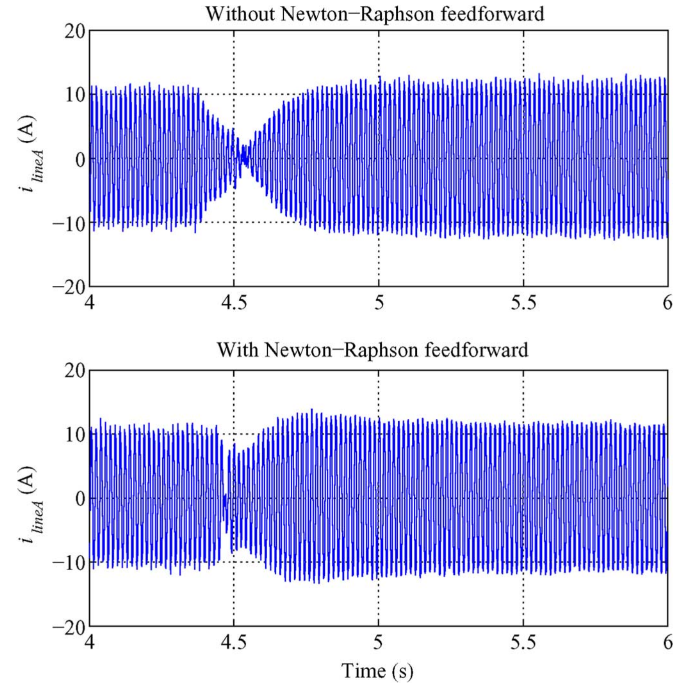

Fig. 17. Experimental i_a transients without feedforward (the top trace) and with feedforward (the bottom trace).

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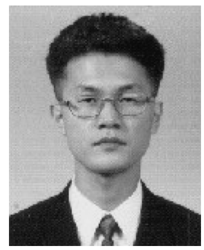

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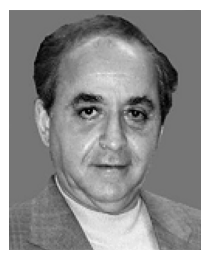

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