Multilevel Inverter for Grid-Connected Photovoltaic Systems with Active Filtering Function

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Abstract. This paper presents a single-phase inverter with multilevel topology adopted to interface photovoltaic systems with the electrical power grid, and at the same time, to eliminate harmonics currents and to compensate reactive power, operating as shunt active power filter. Multilevel inverters have been attracting increasing attention in the past few years as power converters of choice in high voltage and high power applications. Various topologies to implement these inverters have been introduced and studied recently. The theory of instantaneous reactive power applied to compensation of single-phase circuits is also presented in this paper. This theory is a particular case of the well-known p-q theory, which was originally developed for three-phase circuits. Simulation results demonstrate this control algorithm applied to multilevel single-phase topologies.

Keywords: Photovoltaic System, Active Power Filter, Multilevel Inverters, p-q Theory.

1 Introduction

There has been increasing interest in electrical power generation from renewable-energy sources, such as photovoltaic (PV). In the last decades, solar energy has been one of the most active research areas among renewable-energy sources. Photovoltaic modules can be used in stand-alone or grid-connected applications [1]. While photovoltaic systems connected to the electrical power grid are gaining more and more visibility, demand for energy is increasing worldwide.

To interface photovoltaic modules with the electrical power grid it is necessary to use a power electronics inverter, which has to perform two tasks: to inject a sinusoidal current into the grid and to ensure that the PV modules operate at the maximum power point (MPP).

Most of the topologies for PV systems are multi-stage, having a high frequency transformer or line-frequency transformer that adjusts the inverter DC voltage and isolates the PV modules from the grid. However, the conversion stages decrease the efficiency and make the system more complex [2].

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2 Contribution to Internet of Things

The use of multilevel inverters for photovoltaic applications is becoming popular in recent years. By using multiple levels on the DC bus, the stress on each switching device is reduced. Researches related to multilevel inverters have been reported in applications about FACTS (flexible AC transmission systems), active filters and grid interface for non-conventional energy sources.

By synthesizing the AC output terminal voltage from several levels of voltages, staircase waveforms can be produced, which approach the sinusoidal waveform with low harmonic distortion, thus reducing filter requirements.

The fact that multilevel converters need several DC sources in the DC side makes them attractive for photovoltaic applications.

In the last few decades, the proliferation of nonlinear loads, like switching power supplies, adjustable speed drives and commercial lighting, has resulted in serious degradation of power quality in the electrical grids, mainly because of harmonics problems. Reactive power consumption by the loads is another significant problem to the electrical power grids. Both harmonics and reactive power generate extra power losses in the distribution system transformers and cables, reducing the overall efficiency of the power system. Therefore, compensation of harmonics and reactive power is very important in order to reduce costs due to power losses and bad functioning of equipment in the consumers and in the electrical distribution system.

This paper presents an inverter with multilevel topology, which interfaces photovoltaic systems with the electrical power grid, and that at the same time compensates harmonics currents and reactive power. The presented solution can be an interesting option to the future Smart Grids, contributing to the Internet of Things.

3 p-q Theory

The p-q theory was first introduced by Akagi [3], and is also known as the instantaneous power theory. It is an interesting tool to apply to the control of active power filters (APF), or even to analyze three-phase power systems in order to detect problems related to harmonics, reactive power and unbalance.

The p-q theory applies a Clack transformation to the system voltages and currents, which is represented by the matrices in (1). This transformation converts the voltages and currents from the phases a-b-c to the α-β-0 coordinates. It has the advantage of allowing separating the zero sequence components of the voltage (v_0) and current(i_0).

With the voltage and currents determined in the α-β-0 coordinates, can be calculated the instantaneous real power (p), the instantaneous imaginary power (q), and the zero sequence power (p_0), according to (2).

The power components p and q depend only on the α and β coordinates of the voltages and currents, and the power component p_0 depends only on the 0 coordinate of the voltages and currents.

In order to compensate reactive power, harmonics currents and current unbalance (eliminating the neutral wire current), it is necessary to compensate the power

components q and p_0, and the oscillating value of p ($\tilde{p}$). The compensation reference currents in the α-β-0 coordinates are obtained from (3) and (4), which come from the inverse of (2), and where $q_x = q$, and p_x is given by (6).

$$\begin{bmatrix} v_\alpha \\ v_\beta \\ v_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} . \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} . \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} p \\ q \\ p_0 \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta & 0 \\ -v_\beta & v_\alpha & 0 \\ 0 & 0 & v_0 \end{bmatrix} . \begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} \tag{2}$$

In order to compensate reactive power, harmonics currents and current unbalance (eliminating the neutral wire current), it is necessary to compensate the power components q and p_0, and the oscillating value of p ($\tilde{p}$). The compensation reference currents in the α-β-0 coordinates are obtained from (3) and (4), which come from the inverse of (2), and where $q_x = q$, and p_x is given by (6).

$$i_{c0}^* = \frac{p_0}{v_0} \tag{3}$$

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \cdot \begin{bmatrix} p_x \\ q_x \end{bmatrix} \tag{4}$$

An active power filter with a control system that presents a fast response, like the one based on the p-q theory, has basically two advantages [4]:

- It presents a good dynamic response, producing the correct values of compensating current in a short time after variations of the power system operating conditions;
- If the active filter has a fast control system, its energy storage element will suffer less to compensate the power system parameters variation.

The calculations of the p-q theory also allow a simple method to adjust and regulate the DC link voltage. For that it is necessary to calculate a regulation power (p_{reg}), which can be obtained through a proportional controller, K_p. Thus:

$$p_{reg} = K_p(v_{dc}^* - v_{dc}) \tag{5}$$

Where:

K_p – proportional controller;
v_{dc}^* – DC link reference voltage;
v_{dc} – DC link voltage.

The regulation power, besides regulating the DC link voltage, can be used to set the value of power to be injected in the electrical grid, produced by the solar photovoltaic system. The regulation power is included in the instantaneous real power value to be compensated, so that p_x is given by:

$$p_x = \tilde{p} - \bar{p}_0 + p_{reg} \tag{6}$$

The p-q theory is a theory for three-phase electrical systems. An easy way to apply this theory to single-phase systems consists in creating virtual voltages and currents for the two non-existing phases, delaying them by +120º and +240º in relation to the existing phase voltage and current.

In Fig. 1 is presented a block diagram of the proposed control system.

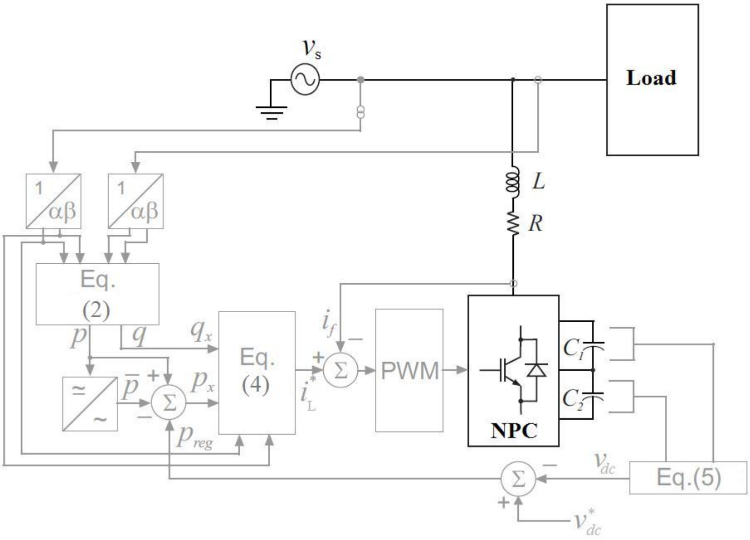


Fig. 1. Block diagram of the control system

4 Multilevel Inverters

The term multilevel was introduced by Nabae et al. [5], and their structures were developed from three-level inverters. These inverters have the ability to operate at high voltage levels using devices with low power voltages, producing low harmonic content at the output waveforms, when compared with the waveforms obtained with two-level inverters.

In the Multilevel Inverters topologies, when the number of levels increases, the rate of total harmonic distortion (THD) of the output voltage decreases. However, the number of power devices also increases, increasing the complexity and cost of the inverter.

The main topologies of Multilevel Inverters are the Neutral Point Clamped (NPC) Inverter, the Flying Capacitor Inverter and the Cascaded H-Bridge Inverter.

Neutral Point Clamped Inverter

The output voltages of this topology have a lower harmonic content, enabling the use of semiconductor devices in half the threshold voltage of the devices used in the two-level topologies.

The three-phase three-level NPC inverter has a function of transferring energy from the source at the DC side to the AC side, or acting as a rectifier, transferring energy from the AC side to the DC side. This property of reversibility, usually present in other multilevel converters, requires two circuits connected to the inverter that are able to provide and/or receive this energy.

Flying Capacitor Inverter

Although the Flying Capacitor Inverter (FCI) topology is not as common as other structures, it has some distinct advantages over the diode-clamped topology, including the absence of clamping diodes and the ability to regulate the flying-capacitor voltages through redundant state selection, even if the number of voltage levels is greater than three.

Unlike the NPC inverter topology, the Flying Capacitor Inverter has redundant switching states for synthesizing the phase voltage, so that some phase voltage vectors can be synthesized by more than one switching state [6].

Cascaded H-Bridge Inverter

This topology consists of two or more single-phase full bridge converters with their outputs connected in series at the AC side. Thus, each converter creates three different levels of voltage. The major advantages of the Cascaded H-Bridge converters are scalable power rating, modularity, and cost effectiveness. The output voltage of the Cascaded H-Bridge converter is the summation of the output voltage of the individual H-bridges. By increasing the number of series H-bridge converters, the output voltage of the converter can be increased, while the switching frequency of the individual H-bridge converter can be decreased to achieve the same output waveform quality [7].

After studying the three basic topologies of the multilevel inverters (Neutral Point Clamped - NPC, Cascaded and Flying Capacitor), the NPC topology was chosen mainly due to its characteristics of easy control, especially when compared to the Flying Capacitor topology that has a difficult voltage control of the clamping capacitors [8][9]. The Cascaded H-Bridge inverter needs separate DC sources for real power conversions, and thus its applications are somewhat limited. The Flying Capacitor Inverter control would be very complicated, and the switching frequency and switching losses would be high for real power transmission [10].

5 Simulations Results

The proposed control system, with function of active power filter using the p–q theory, is applied to a single-phase NPC inverter connected to the electrical power grid. Simulations were performed in Matlab/Simulink for different loads: linear and non-linear. The linear load is composed by one inductance (1 mH) in series with one resistance (5 Ω). The non-linear load is composed by a single-phase rectifier with C = 640 μF in parallel with R = 5 Ω at the DC side.

The simulations conditions are the following: switching frequency T_s= 4 kHz, source voltage v_S= 230 V (RMS value), source frequency f_s= 50 Hz, source inductance L_S = 1mH, link DC voltage V_{dc} = 700V, and DC link capacitors $C_1 = C_2 = 4.7$ mF.

In order to compare the behavior of the output filter currents and the balance of the DC link voltages of the NPC inverter, simulations were performed with two different PWM techniques:

- In-Phase Disposition PWM (IPD PWM);
- Phase Opposition Disposition PWM (POD PWM).

Booth techniques require each of the 2 carrier waveforms for 3-level phase waveform. In the POD PWM the carrier waveforms are all in phase above and below the zero reference value, however, there is 180 degrees phase shift between the ones above and below zero respectively.

The IPD PWM technique, generally, is widely used in multilevel inverters. This technique is similar to the previously described one, except that all carriers are in phase. The zero reference is placed in the middle of the carrier set.

The Flying Capacitor inverter presents difficulties in controlling the balancing of the voltage of the clamped capacitors and of the flying capacitor, too, for booth PWM techniques. One problem is that an excessive number of storage capacitors are

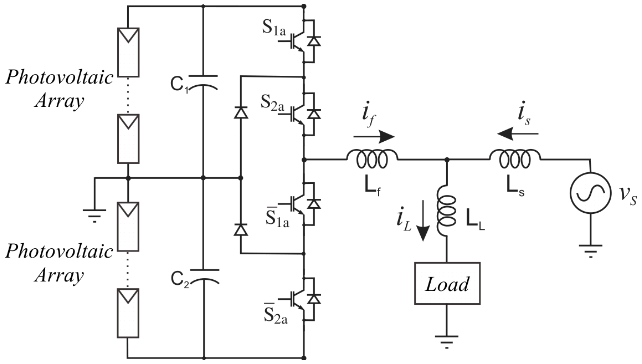


Fig. 2. Single-phase NPC inverter connecting the PV system to the electrical power grid

required when the number of converter levels is high. The Cascaded H-Bridge inverter and the NPC inverter present good results in balancing the DC link voltage. But the Cascaded inverter needs separate DC sources for real power conversions, and thus its applications are somewhat limited. Reactive power flow can be controlled more easily in the NPC inverter.

The NPC inverter presents the best behavior among the multilevel inverters. Using the IPD PWM, the NPC inverter has a lower THD grid current. Therefore, the NPC inverter with the IPD PWM was chosen to be simulated with the two loads.

In order to validate the control system for the NPC topology, the single-phase NPC leg connected to the grid was tested as an inverter. In fact, a three-phase NPC topology can be obtained using three independent single-phase inverters, like the one shown in Fig. 2, connected through the common neutral.

The grid voltage and current, the reference current, the filter current and the load current are shown in the Fig. 3 and Fig. 4, respectively for a linear and non-linear load. For booth loads the NPC inverter presents the best current control among the studied multilevel topologies. The control of the DC link presents good results for the NPC and the Cascaded inverters.

6 Experimental Results

In order to obtain results for the single-phase NPC inverter topology with active power filter function, it was developed an experimental laboratory prototype. The complete system control was executed in discrete time using the TMS320F2812 DSP from *Texas Instruments*, working with sampling and switching frequencies of 10 kHz. The conditions of the experimental results are the same of the simulation results, except that the adopted experimental grid voltage was 115 V. The two loads conditions are the same, too.

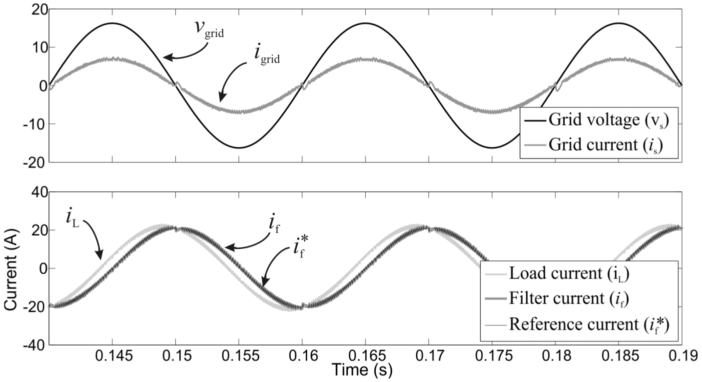


Fig. 3. NPC inverter with linear load using a PWM technique IPD

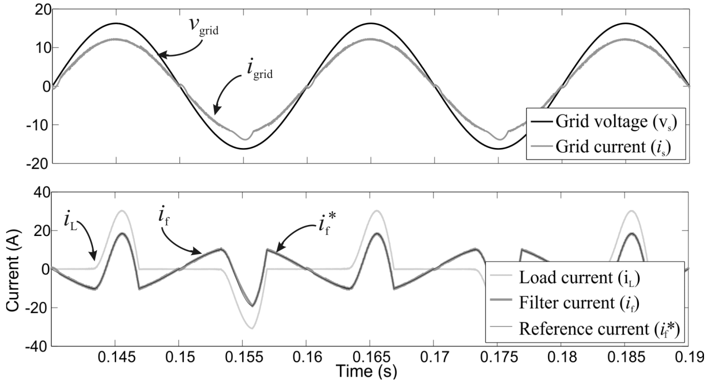
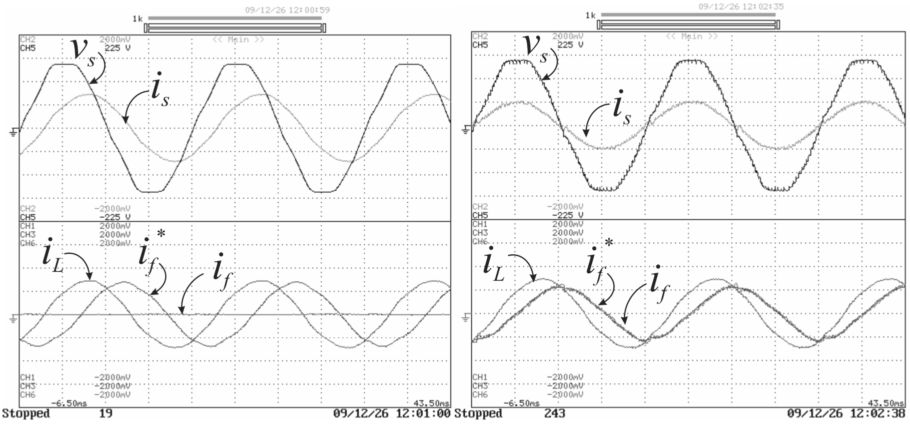


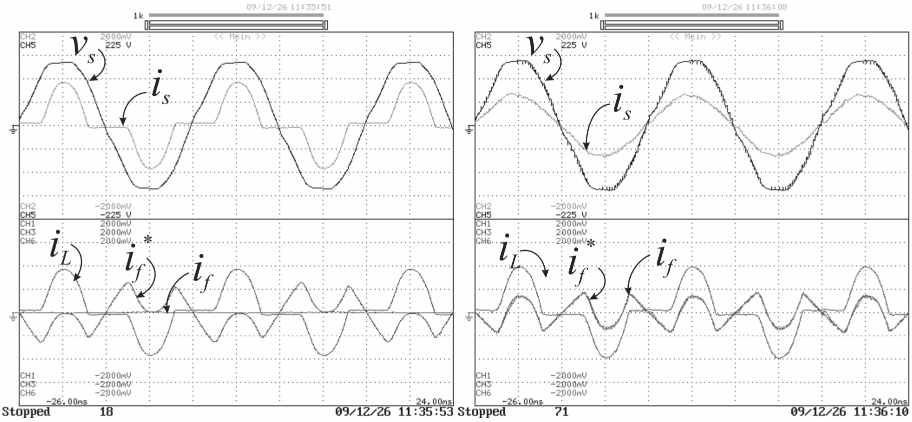
Fig. 4. NPC inverter with non-linear load using a PWM technique IPD

Fig. 5 shows the results for operation with the linear load, without and with active power filter function, in which, for this case, the inverter compensates reactive power. In Fig. 5(a) the active filter function is off, and the grid current (i_s) is delayed almost 90^o in relation to the grid voltage (v_s). The amplitude of the reference current (i^*_f) is close to the amplitude of the load current (i_c), since the load current should be almost completely compensated. However, the filtering current is zero, because the active filter function is off. In Fig. 5(b) the active filter function is on, and the filtering current (i_f) follows its reference current. As result, the grid current (i_s) has its amplitude reduced, and it becomes in phase with the grid voltage.



(a) (b)

Fig. 5. Experimental results of the single-phase NPC inverter with linear load: (a)Without active filtering; (b)With active filtering



(a) (b)

Fig. 6. Experimental results of the single-phase NPC inverter with non-linear load: (a)Without active filtering; (b)With active filtering

Fig. 6 shows the experimental results for operation with the non-linear load (single-phase rectifier with RC parallel load), without and with active power filter function, in which, for this case, the inverter compensates mainly harmonics currents. Fig. 6(a) shows the waveforms when the active filter function off. The grid current (i_s) is distorted but almost in phase with the grid voltage (v_s). In Fig. 6(b) the active filter function is on, the filtering current (i_f) follows the reference current (i^*_f), compensating the harmonics currents, and the grid current becomes sinusoidal.

7 Conclusions

This paper presents a single-phase multilevel NPC (Neutral Point Clamped) inverter with active filtering function, to be used to interface photovoltaic systems with the electrical power grid, and at the same time, to eliminate harmonics currents and to compensate reactive power, operating as shunt active power filter.

The control system is based on the p-q theory, proposed by Akagi, adapted to work in single-phase electrical systems. This control theory permits the compensation of harmonics currents and reactive power, and the setting of the power produced by the photovoltaic system, to be injected by the inverter in the electrical power grid.

Three multilevel inverters topologies are presented, and the choice of the NPC topology is explained.

The single-phase multilevel NPC inverter with active filtering function is tested, and are presented both simulation and experimental results, obtained with a laboratory prototype. Simulations and experiments were performed with two types of load, corresponding to different active filtering conditions: linear load, with reactive power compensation; non-linear load, with harmonics currents compensation.

The studied multilevel inverter presented satisfactory performance for the cases here evaluated, showing that the combined operation of active filtering and interfacing of a photovoltaic system with the electrical power grid can be an interesting possibility.

References

1. Oliveira, K.C.: Avaliação da Conversão da Energia Fotovoltaica em Sistemas Isolados. Master Thesis, UFPE (March 2007)
2. Gubía, E., Sanchis, P., Ursúa, A., López, J., Marroyo, L.: Ground currents in single-phase transformerless photovoltaic systems. Progress in Photovoltaics: Research and Applications 15(7), 629–650 (2007)
3. Akagi, H., Kanazawa, Y., Nabae, A.: Instantaneous Reactive Power Compensators Comprising Switching Devices without Energy Storage Components. IEEE Transactions on Industry Applications (3), 625–630 (1984)
4. Afonso, J.L., Freitas, M.J.S., Martins, J.S.: p-q Theory power components calculations. In: ISIE 2003 - IEEE Int. Symposium Ind. Electronics, Rio de Janeiro, Brazil, June 9-11 (2003)
5. Nabae, A., Takahashi, I., Akagi, H.: A new neutral-point-clamped PWM inverter. IEEE Transactions on Industry Applications (5), 518–523 (1981)
6. Rech, C., Gründling, H.A., Hey, H.L., Pinheiro, H., Pinheiro, J.R.: Uma metologia de projeto generalizada para inversores multiníveis híbridos. Revista Controle & Automação 15(2), 190–201 (2004)
7. Anuradha, K., Muni, B.P., Kumar, A.D.R.: Cascaded Multilevel Converter based DSTATCOM using p-q theory with DC link voltage balancing. In: International Conference on Power and Energy Systems, ICPS, December 22-24, pp. 1–6 (2011)
8. Oliveira, K.C., Cavalcanti, M.C., Afonso, J.L., Farias, A.M., Neves, F.A.S.: Transformerless photovoltaic systems using neutral point clamped multilevel inverters. In: IEEE Int. Symposium on Industrial Electronics (ISIE), July 4-7, pp. 1131–1136 (2010)
9. Cavalcanti, M.C., Farias, A.M., Oliveira, K.C., Neves, F.A.S., Afonso, J.L.: Eliminating Leakage Currents in Neutral Point Clamped Inverters for Photovoltaic Systems. IEEE Trans. Industrial Electronics 59(1), 435–443 (2012), doi:10.1109/TIE.2011.2138671, ISSN: 0278-0046
10. Lai, J.-S., Peng, F.Z.: Multilevel converters-a new breed of power converters. In: Thirtieth IAS Annual Meeting Industry Applications Conference (IAS), Conference Record of the 1995 IEEE, October 8-12, vol. 3, pp. 2348–2356 (1995)