Letters

A Nonlinear Adaptive Synchronization Technique for Grid-Connected Distributed Energy Sources

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***Abstract*—This letter introduces a new adaptive notch filtering (ANF) approach as a powerful tool for synchronization of converter-interfaced distributed generation systems that can potentially stimulate much interest in the field and provide improvement solutions for both grid-connected and stand-alone (islanding operation) modes of micro-grids. The proposed technique is simple and offers a high degree of immunity and insensitivity to power system disturbances, harmonics and other types of pollution that exist in the grid signal. A modified structure of the ANF-based synchronization technique is capable of decomposing three-phase quantities into symmetrical components, extracting harmonics, tracking the frequency variations, and providing means for voltage regulation and reactive power control. A prominent advantage of the proposed scheme is that it does not require a phase-locked loop for the synchronization. In addition, this very simple and very powerful power signal processor will simplify the control issues currently challenging the integration of distributed energy technologies onto the electricity grid. All converter-interfaced equipment, such as flexible ac transmission systems, custom power controllers, and active power filters, will benefit from this technique. Theoretical analysis is presented and the performance of the method is evaluated through simulation.**

***Index Terms*—Adaptive filters, distributed power generation, grid-connected converters, grid synchronization.**

I. Introduction

In all grid-connected converters such as the static VAR compensators, active power filters, and grid-connected distributed generation (DG) systems, a phase-detecting technique provides a reference phase signal synchronized with the grid voltage that is required to control and meet the power quality standards. This is particularly critical in converter-interfaced DG units where the synchronization scheme should provide a high degree of immunity and insensitivity to power system disturbances, harmonics, unbalances, voltage sags, and other types of pollution that exist in the grid signal [1]–[3]. An ideal synchronization scheme must 1) proficiently detect the phase angle of the utility signal, 2) smoothly track the phase and frequency variations, and 3) forcefully reject harmonics and disturbances. These factors, together with implementation simplicity and cost, are all important when examining the credibility of a synchronization scheme.

Various phase-angle detecting methods have already been developed and reported [1]–[13]. Among them, the voltage zero-crossing method has the simplest implementation; however, disturbances in the input signal, such as voltage sags and harmonics, influence the accuracy of the method. In addition, phase-tracking action is only possible at the zero-crossing points. The voltage zero-crossing technique has recently been improved to some extent by means of a number of digital techniques [4]. Filtering techniques including low-pass, space-vector, extended Kalman filters, and recursive weighted least-square estimation have also been employed for grid synchronization [1]–[3], [5], [6]. When compared to the zero-crossing methods, these techniques offer improved performance. However, unexpected variations in grid voltage due to faults and disturbances can potentially decimate the phase-angle detecting process [1]–[3]. Nowadays, the phase-locked loop (PLL) is the state-of-the-art technique in detecting the phase angle of the grid voltages [1], [6]–[8]. This technique can successfully reject harmonics, voltage sags, notches and other kind of disturbances; however, traditional PLL-based algorithms fail to handle the unbalanced situation [9]–[13]. Notch filters [12], and the decoupled double synchronous reference frame-PLL [13] have been introduced to handle the unbalanced phenomenon. These techniques, however, require some improvement, especially when the input signal is distorted by harmonics. In fact, three-phase PLL schemes output an average phase angle that does not accurately present the individual phase angles [10].

An advanced phase-detecting scheme is a powerful approach that might be employed to detect current harmonics and extract the reactive current component for power quality purposes. Current approaches for power quality control exist in both frequency and time domains. Frequency-domain approaches are the fast Fourier transform and discrete Fourier transform techniques. Important time-domain schemes are the instantaneous p–q, the synchronous d–q, notch filters, approximated bandpass resonant filters, and stationary frame filters [14]–[22].

This letter presents a new synchronization method that demonstrates not only an advanced synchronization performance in a corrupted grid environment but also effectively handles the unbalanced situations. The proposed synchronization device does not require a synchronizing tool such as PLL, and its main building block is a modified adaptive notch filter (ANF) system of nonlinear dynamical equations. The prime

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application of the proposed synchronization method is found in distributed generation systems, e.g., micro-grid systems, where grid synchronization is of concern in both grid-connected and islanding operation modes. The proposed approach is adapted to meet special interests including the real-time extraction and measurement of harmonics and reactive components of a power signal of a time-varying characteristic. The adaptive nature of the proposed technique allows perfect tracking of frequency and amplitude variations. The structural simplicity of the algorithm makes it desirable from the standpoint of digital implementation in both software, e.g., a digital signal processor (DSP), and hardware environments, e.g., a field programmable gate array (FPGA) or application-specific integrated circuit (ASIC) environments. A theoretical analysis is presented, and simulation results confirm the validity of the analytical work.

II. ANF-Based Synchronization Technique

A. Problem Definition

Very often, when a signal exhibits some periodicity, it is modeled by a single or a sum of sinusoids given by

$$u(t) = \sum_{i=1}^{n} A_i \sin\phi_i, \quad \text{where } \phi_i = \omega_i t + \varphi_i. \tag{1}$$

Nonzero amplitudes, $A_i, i = 1, 2, \ldots, n$, the nonzero frequencies, $\omega_i, i = 1, 2, \ldots, n$, and the phases $\varphi_i, i = 1, 2, \ldots, n$, are typically unknown parameters. Estimating unknown parameters, especially unknown frequencies, is a required task in many applications and is a fundamental issue in systems theory and signal processing.

B. ANF Dynamic and Structure

A modified lattice-based discrete-time ANF [23]–[25] is employed in this letter. The dynamic behavior of this ANF is characterized by the following set of differential equations:

$$\begin{aligned} \ddot{x} + \theta^2 x &= 2\zeta\theta e(t) \\ \dot{\theta} &= -\gamma x \theta e(t) \\ e(t) &= u(t) - \dot{x} \end{aligned} \tag{2}$$

where θ is the estimated frequency and ζ and γ are adjustable real positive parameters that determine the estimation accuracy and the convergence speed of the ANF. For a single sinusoid input signal $(n = 1), u(t) = A_1 \sin(\omega_1 t + \varphi_1)$, this ANF has a unique periodic orbit located at

$$o = \begin{pmatrix} \bar{x} \\ \dot{\bar{x}} \\ \bar{\theta} \end{pmatrix} = \begin{pmatrix} -\frac{A_1}{\omega_1}\cos(\omega_1 t + \varphi_1) \\ A_1 \sin(\omega_1 t + \varphi_1) \\ \omega_1 \end{pmatrix}. \tag{3}$$

The third entry of O is the estimated frequency, which is identical to its correct value, ω_1.

C. Stability Analysis

Dynamic equations in (2) are stable, which means that the proposed ANF is stable. This was mathematically proved in [23]–[25]. However, we proceed with a brief discussion on the stability of the proposed ANF. Using the first equation of (2), the right-hand side term of the θ update law can be rewritten as

$$\dot{\theta} = -\frac{\gamma}{2\zeta} x(\ddot{x} + \theta^2 x). \tag{4}$$

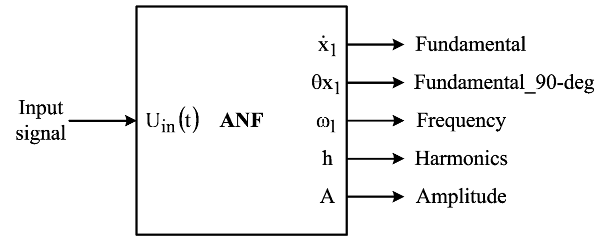

Fig. 1. Proposed signal-processing unit.

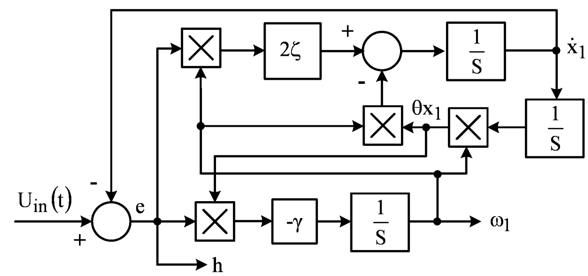

Fig. 2. Detailed implementation of the proposed structure.

Close to the periodic orbit O, where $\bar{\theta} = \omega_1$ and $\ddot{\bar{x}} = -\omega_1^2 \bar{x}$, we have

$$\dot{\theta} \approx -\frac{\gamma}{2\zeta} x^2 \left(\theta^2 - \omega_1^2\right). \tag{5}$$

The above derivation shows that close to the desired orbit the adaptation process is slow and the search in parameter space of θ will go in the correct direction (i.e., $\{\theta > \omega_1 \Rightarrow \dot{\theta} < 0\}$, and vice versa).

D. ANF as the Building Block of a Grid-Synchronization Unit

Fig. 1 shows the schematic structure of the proposed grid-synchronization unit, where the ANF in Section II-B is functioning as the main cell. The input is a distorted sinusoidal signal or, in general, a periodic signal. The power of the proposed synchronization structure is that it outputs useful signal information such as the fundamental component, its 90° phase-shift, its amplitude, its frequency, $\sin / \cos$ functions of its phase angle, and harmonics. The state-of-the art technology in grid-connected converters is the use of a PLL device to find the phase angle of the grid voltage. We will show that in the proposed approach there is no need for a synchronizing tool such as PLL. In addition, having access to additional signal information enables the user to synchronize the on/off times of the switching devices, calculate active/reactive power, and transform the feedback variables to a frame suitable for control purposes.

A close observation, at (2) and (3), reveals that the fundamental component and its 90° phase shift are essentially $\dot{\bar{x}}$ and $\bar{\theta}\bar{x}$, respectively. Therefore, the amplitude of the fundamental component is easily determined from $A_1 = (\bar{\theta}^2 \bar{x}_1^2 + \dot{\bar{x}}_1^2)^{1/2}$. A detailed implementation of the proposed structure is shown in Fig. 2. Output θ provides the fundamental frequency of the input signal, ω_1, and the ANF is composed of simple adders, multipliers, and integrators. Two additional multipliers, a summer, and a square root function determine the amplitude of the fundamental component. The $\sin / \cos$ functions of the phase angle are simply obtained by dividing the fundamental component and its 90° phase shift by the amplitude of the fundamental component.

E. Filter Parameters and Initial Conditions

The basic structure of Fig. 2 has two independent design parameters, γ and ζ. Parameter γ determines the adaptation speed, hence, the capability of the proposed algorithm in tracking the signal characteristics variations. Particularly, the convergence rate of the estimated frequency is proportional to γ. Parameter ζ determines the depth of the notch and, hence, the noise sensitivity of the filter. A tradeoff between the (steady-state) accuracy and (transient) convergence speed can be carried out by adjusting design parameters ζ and γ. By increasing γ, one can achieve a faster convergence speed; however, at the same time, ζ should be increased to avoid oscillatory behaviors. It can be proved that for micro-grid and distributed energy applications a wide range of parameters values, ζ and γ, is acceptable, i.e., the structure is robust with respect to variations in the internal parameters. The proposed ANF structure has three integrators. The initial condition for the integrator that outputs the frequency, ω, is set to the nominal power system frequency. In other words, the initial condition for this integrator is set to $2\,\pi$ 50 or $2\,\pi$ 60 rad/s (similar to the center frequency of the voltage-controlled oscillator in PLL schemes). The initial conditions for all other integrators are set to zero.

III. Potential Applications of the Proposed Technique

A. Applications in Three-Phase Systems

In the abc frame, synchronization can be implemented by means of the three aforementioned single-phase ANF systems introduced in the previous section. Grid information required for grid synchronization is extracted by the three ANFs in a very simple and straightforward manner with no need for a PLL system. One advantage of this implementation is that it provides distinctive information about the amplitude, frequency and phase angle of each phase voltage. This distinguishing feature, as it provides additional information, is very beneficial for grid monitoring and island detection. In addition, the new synchronization technique employs mathematical tools that streamline the control formulation and thus the system implementation. In fact, in all control functions that employ the synchronization scheme in this letter, the use of a PLL system and $dq \rightarrow abc$ transformation module are unnecessary. Furthermore, as discussed later in this letter, the availability of the fundamental component of the grid voltages or currents, and its 90° phase shift is ideal for sequencing component decomposition under unbalanced system operations. This aspect is very beneficial in three-phase distributed power generation systems, where the ride-through capability of the synchronization tool under the unbalanced system situation and its capability for disturbance rejection are of great importance. The concept of symmetrical components that was originally defined for phasors can be extended to the signals as functions of time by replacing the complex phasor $\alpha = e^{j120^o}$ with a 120° phase-shift operator in the time domain [3], [26], [27]

A three-phase signal, $v(t)$, can be decomposed to $v(t) = v^+(t) + v^-(t) + v^0(t)$, where, $v^+(t), v^-(t)$, and $v^0(t)$ are positive-, negative-, and zero-sequence components, respectively. Sequence components are determined from

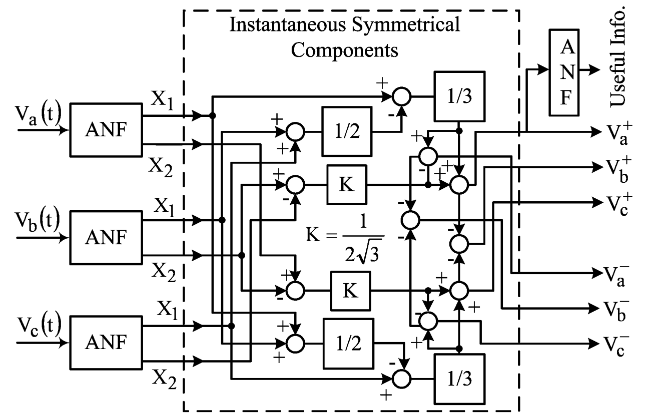

Fig. 3. Proposed structure for three-phase systems.

$$
\begin{aligned}
v^+(t) &= T_2 X_1(t) + T_1 X_2(t)\\
v^-(t) &= T_2 X_1(t) - T_1 X_2(t)\\
v^0(t) &= (I - 2T_2) X_1(t)
\end{aligned} \tag{6}
$$

where $X_1(t)$ and $X_2(t)$ stand for the fundamental component of the input signal and its 90° phase shift, receptively. T_1 and T_2 are 3×3 matrices given by

$$T_1 = \frac{1}{2\sqrt{3}} \begin{pmatrix} 0 & 1 & -1 \\ -1 & 0 & 1 \\ 1 & -1 & 0 \end{pmatrix} \tag{7}$$

$$T_2 = \frac{1}{3} \begin{pmatrix} 1 & -0.5 & -0.5 \\ -0.5 & 1 & -0.5 \\ -0.5 & -0.5 & 1 \end{pmatrix} \tag{8}$$

and I is a 3×3 identity matrix.

The positive- and negative sequence extractor unit, shown in Fig. 3, is comprised of three ANFs and simple arithmetic operators. ANFs adaptively extract the fundamental voltages and their 90° phase-shift. The reminder system receives these components and calculates the positive- and negative-sequence voltages based on (6)–(8). The extracted positive sequence component is then passed to another ANF that outputs useful information for grid synchronization or other control purposes.

B. Harmonic/Reactive-Current Extraction

In this section, the power signal processor in Fig. 2 is used to develop a novel and simple mechanism for extracting the harmonic and reactive current components of a signal. The approach, although intended to extract harmonic and reactive current components, also outputs useful information such as amplitude, $\sin$ and $\cos$ of the phase angle and frequency of the fundamental component, and, with more modifications, outputs the total harmonic distortion, and power factor.

Let $i(t) = i^f(t) + i^h(t)$ be a distorted load current and $i^f(t) = I_1 \sin(\phi_i)$ represent its fundamental component, which is extracted by an ANF unit. At the output of the ANF, the following are available: 1) information about the amplitude, phase angle and the frequency of the fundamental component, and 2) the harmonic content of the input signal. The fundamental

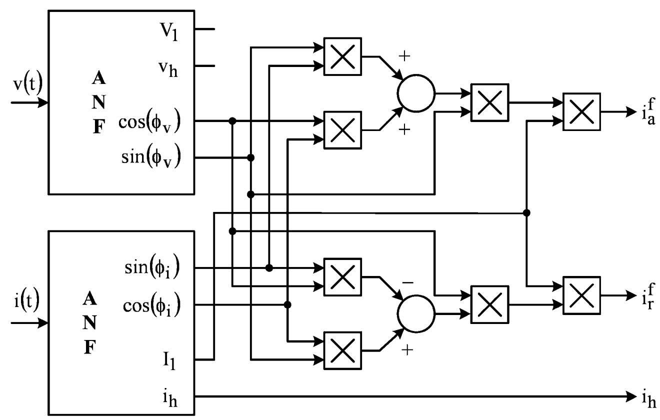

Fig. 4. Proposed structure for harmonic/reactive-current extraction.

component, $i^f(t)$, of a current signal, $i(t)$, can be written as $i^f(t) = I_1 \sin(\phi_i) = i_a^f(t) + i_r^f(t)$, where $i_a^f(t)$ and $i_r^f(t)$ represent active and reactive components of $i^f(t)$, respectively, as expressed by [21], [22]

$$i_a^f(t) = I_1 \cos(\phi_i - \phi_v) \sin(\phi_v) \quad (9)$$
$$i_r^f(t) = I_1 \sin(\phi_i - \phi_v) \cos(\phi_v). \quad (10)$$

It is noteworthy that $I_1, \cos\phi_i, \sin\phi_i, \cos\phi_v$, and $\sin\phi_v$ are all available at the output of the two ANFs. The remaining step is the calculation of the $\sin$ and $\cos$ functions of the phase-angle difference between the voltage and current. This task can be performed by very simple calculations, as

$$\cos(\phi_i - \phi_v) = \cos(\phi_i)\cos(\phi_v) + \sin(\phi_i)\sin(\phi_v) \quad (11)$$
$$\sin(\phi_i - \phi_v) = \sin(\phi_i)\cos(\phi_v) - \cos(\phi_i)\sin(\phi_v). \quad (12)$$

Fig. 4 shows the single-phase diagram of the harmonic/reactive-current component extractor introduced in this section. The two identical ANF units are to extract voltage and current information. This structure also provides harmonic content of the voltage, peak fundamental components, $\sin$ and $\cos$ functions of phase angles of the voltage and current, and the phase angle difference between the phase voltage and phase current. A close observation reveals that the proposed structure, when compared to its counterparts, has the following advantages: 1) an adaptive structure that can track signal variations, 2) simplicity that results in a simple implementation, 3) the lack of a need for a synchronizing tool like a PLL, 4) simultaneous extraction of harmonics and all useful information, such as frequency, amplitude, and phase angle, embedded in a signal, and 5) adjustable accuracy and speed of response.

IV. Performance Evaluation

Performance of the ANF-based synchronization method is evaluated by means of a number of simulations. The proposed ANF-based systems are simulated using Matlab/Simulink. The parameters of the ANF are set to $\gamma = 800$ and $\zeta = 0.6$. The initial condition for the integrator that outputs the frequency, ω, is set to 2 π 60 rad/s (the nominal power system frequency). The initial conditions for all other integrators are set to zero.

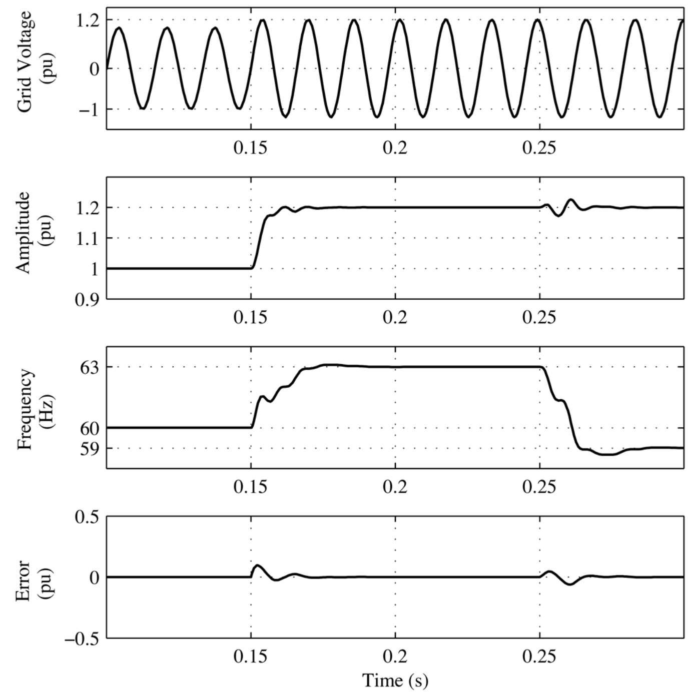

Fig. 5. Response of the ANF-based method to both frequency and amplitude step changes.

A. ANF Performance Evaluation

Fig. 5 demonstrates the adaptability of the proposed method with respect to amplitude and frequency variations. The input signal frequency jumps from 60 to 63 Hz and the amplitude jumps from 1 to 1.2 pu at $t = 0.15$ s. At $t = 0.25$ s, the input signal frequency jumps from 63 Hz to 59 Hz. Fig. 5 shows the extracted amplitude, frequency, and the error between the actual and the extracted input signal. The fast response and accurate performance of the proposed method are revealed even under simultaneous variations in both amplitude and frequency.

B. Three-Phase Systems

The performance of the proposed three-phase structure is evaluated in Fig. 6. A three-phase programmable voltage source is used to produce step variations in the positive-, negative-, and zero-sequence voltages. Under normal conditions, the input to the system is a set of balanced three-phase sinusoidal voltages of 1.0 pu amplitude. Since the system is balanced, no negative- or zero-sequence components exist. At $t = 0.15$ s, a step change ($-$ 0.2 pu) in the amplitudes of all three-phase voltages is applied. Simultaneously, 0.1 pu negative-sequence, 0.06 pu fifth and 0.05 pu seventh harmonics are added to the input signal, as shown in Fig. 6. Fig. 6 shows that the proposed structure tracks all these variations and successfully extracts positive-, negative- and zero-sequence (not shown here) components. In addition, the extracted phase angle of the positive-sequence component, shown in Fig. 6, can be used for synchronization. Results show that the proposed system needs one cycle to detect the fault, track the new phase angle of the grid voltage, and decompose symmetrical components. The accuracy of the results and the speed convergence is adjusted through the filter parameters ζ and γ. A tradeoff must be performed to find appropriate ζ and γ such that the resultant system response meets the standard demands in the field of grid-connected DG systems.

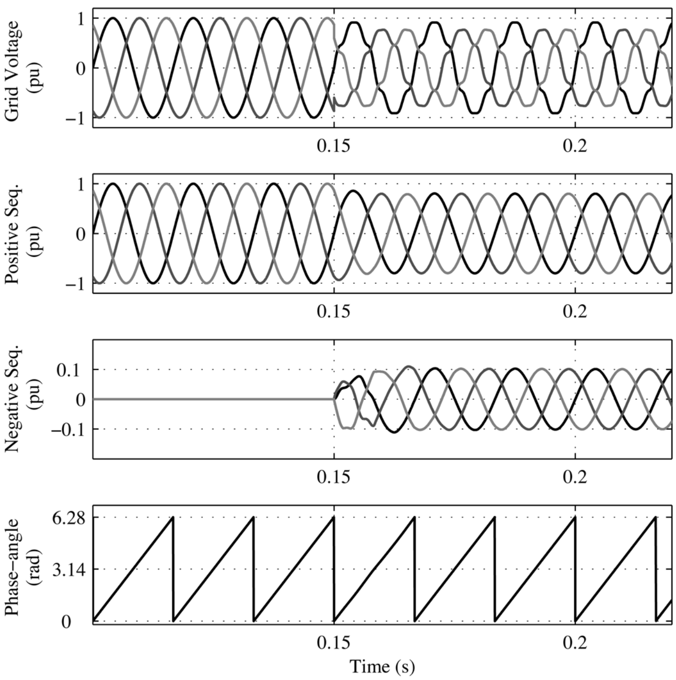

Fig. 6. Response of the proposed three-phase system to a distorted signal.

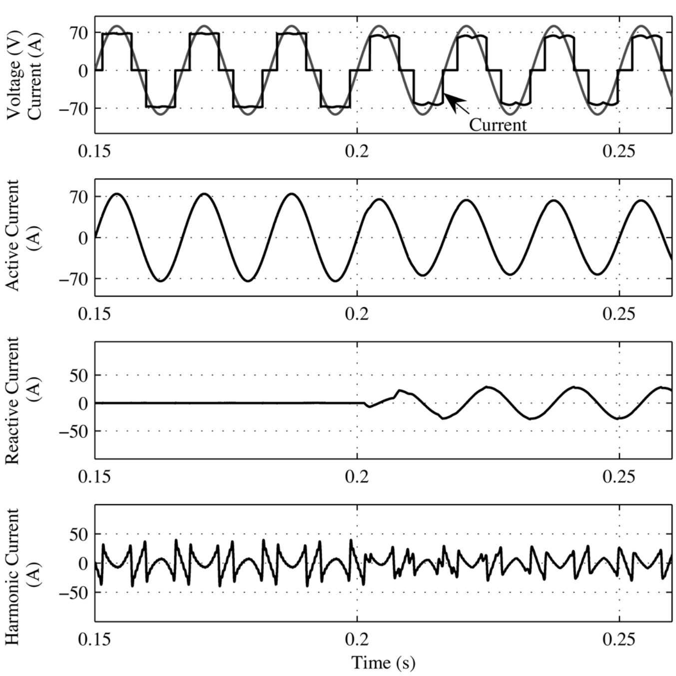

Fig. 7. Response of the proposed technique to 45° phase shift in the nonlinear load current.

C. Harmonic and Reactive Current Components

The capability of the synchronization method in extracting the harmonic and reactive current components is evaluated on a typical nonlinear load. A typical nonlinear load (a three-phase thyristor rectifier) is selected for this set of evaluations. Such a phase-controlled rectifier is a well-known load and its power factor drops dramatically with the delay angle (firing angle) of the thyristors. Initially, the firing angle was zero, and the fundamental current is in phase with the voltage, as expected. A 45° step change in the firing angle occurred at $t = 0.2$ s. Fig. 7 shows that the current and the voltage are in phase (no reactive current component) before $t = 0.2$ s. At $t = 0.2$ s, the load current is phase-shifted because of the firing angle of the three-phase thyristor rectifier. Fig. 7 shows that the proposed scheme was effective in extracting the active and reactive components of the load current and the load harmonic current within one cycle of the system voltage. These extracted components are normally used to generate reference currents for the control system in various applications.

V. Conclusion

This letter presents a new synchronization algorithm based on the concept of ANF for grid-connected converters. It provides frequency adaptivity and tolerance to unbalanced system conditions. Further advantages are that the method is extendable to meet special interests including real-time extraction and measurement of harmonics and reactive components of a power signal of a time-varying characteristic. The prominent features of the proposed technique are: 1) its simplicity—a major advantage for implementation within embedded controllers, 2) the lack of a need for a synchronizing tool like a PLL, 3) its capability for measuring positive and negative sequences in unbalanced three-phase systems, 4) simultaneous extraction of harmonics and all useful information embedded in a signal, such as frequency, amplitude, and phase angle, and 5) adjustable accuracy and speed of response. The structural simplicity of the algorithm makes it desirable from the standpoint of digital implementation in both software, e.g., a DSP, and hardware, e.g., FPGA or ASIC environments. Theoretical analysis is presented, and the simulation results confirm the validity of the analytical work.

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