APPLICATION OF DISTRIBUTED GENERATION SOURCES FOR MICRO-GRID POWER QUALITY ENHANCEMENT

by

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ABSTRACT

In conventional power generation systems, large centralized plants operating on fossil fuel mainly generate the electric power. The generated electricity has to travel through the long transmission and distribution lines to be delivered to the end users. In addition to being costly, this structure yields poor reliability and low efficiency. On the other hand, serious concerns have been raised about the shortage of fossil fuels, global warming, and energy security. As a result, the power systems are moving toward more distributed structures based on renewable energy resources.

During the last decade, the concept of small-scale energy resources distributed over the grid has gained a considerable interest. This concept is often called distributed generation (DG). DG systems are mainly using renewable energy sources as their prime movers. Renewable energy sources (including biomass, wind, solar, hydropower, and geothermal) can provide clean, efficient, reliable and adequate energy supply while making modern energy services accessible and affordable.

However, despite the substantial benefits of distributed generation, the application of an individual DG system can cause as many problems as it may solve. To avoid such problems and to realize the emerging potential of distributed generation, a system approach has been taken, in which generation and loads are considered as a subsystem called “micro-grid”.

One important issue in the existing power network is the capability of renewable energy sources to increase the power quality of the micro-grid. One aspect of this feature is harmonic compensation using distributed resources.

In this thesis an adoptive notch filter (ANF) is employed in the control system of a distributed generation (DG) system for harmonic compensation. It is shown that the performance of the system is highly improved using the adoptive notch filter.

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Chapter 1

Introduction

1.1 Renewable Energy Systems

During the past centuries, energy has been available from conventional fossil fuels (e.g. coal, oil and natural gas). Fossil fuels are relatively easy to generate energy since they only require a simple direct combustion. However, due to increasing concerns about the price of fossil fuels and their environmental side effects (e.g. greenhouse gas emissions, air pollution, global warming concerns and climate change), the interest in renewable energy resources has been raised as they can play an important role in producing clean, local, and inexhaustible energy to supply growing demand for electricity. Renewable energy resources including wind, solar, and hydro are seen as a reliable alternative to the traditional energy resources such as oil, natural gas, or coal [3]. Figure 1.1 shows installed capacity at the end of 2005 of PV power systems, reporting in the IEA-PVPS 2006.

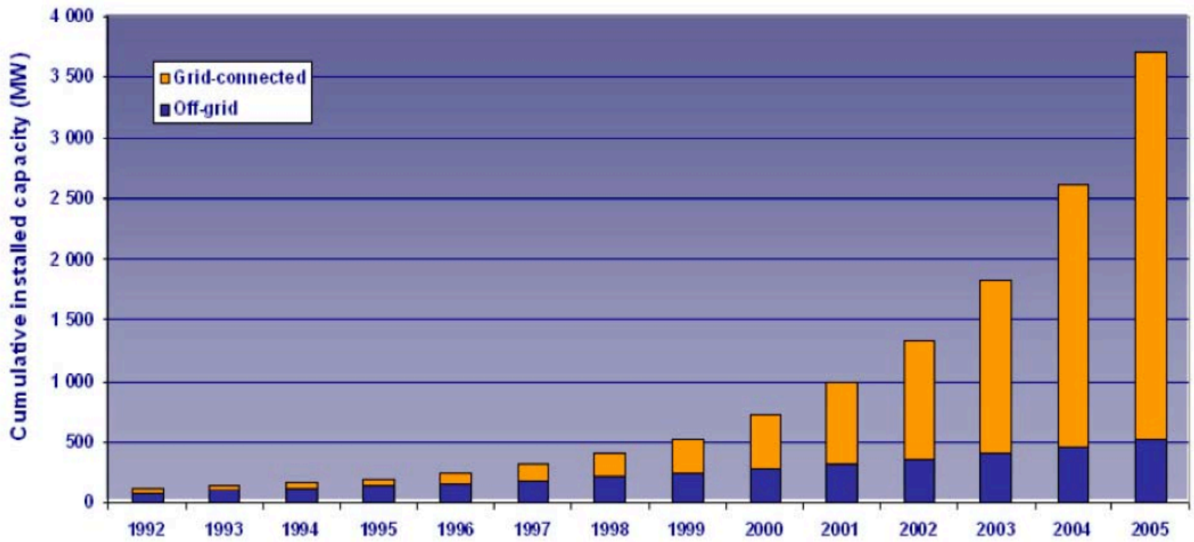

Figure 1.1 Installed PV power in the world at the end of 2005 [1]

Also, Figure 1.2 illustrates the development of the wind turbine technology during the last 25 years.

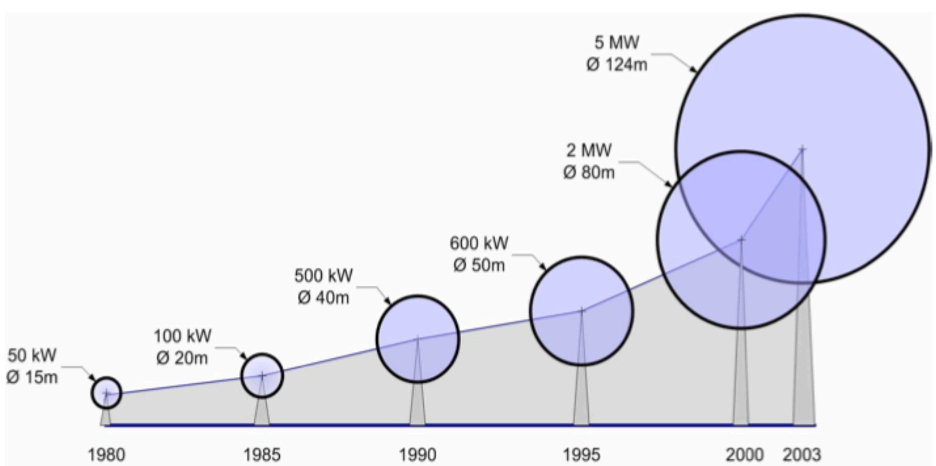

Figure 1.2 Development of the wind turbines at the end of 2003 [2]

1.2 Control Objectives in Renewable Energy Systems

Considering the generation scale and characteristics of these renewable energy resources, the concept of distributed generation has been proposed. To transform this abstract concept into a practical application, distributed generation systems such micro-grids and smart-grids have been developed. A general structure for a DGS is illustrated in Figure 1.3. The input power is transformed into electricity by means of a power conversion unit whose configuration is closely related to the input power nature [4]-[8]. The generated electricity can be delivered to the local loads or to the utility network, depending on where the generation system is connected.

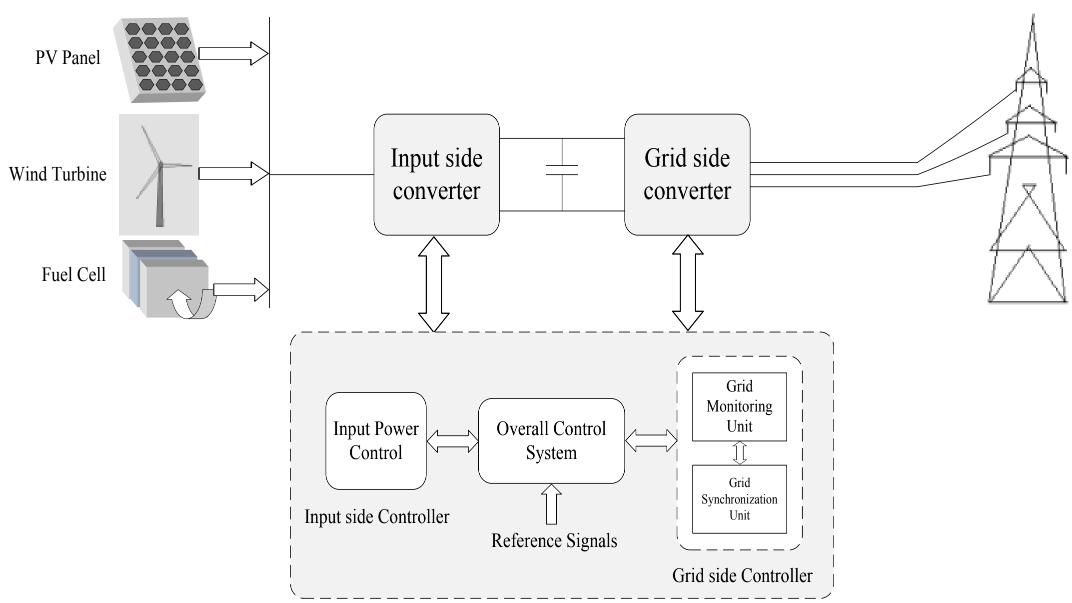

Figure 1.3 General structure for distributed power system

The main part of this distributed generation system is its control system. In this structure, there are basically two controllers; an input side controller that controls the input side converter and a grid side controller that deals with the DGS interaction with the utility grid.

The input side controller extracts the maximum power from the input power source and transmits this power to the grid side controller. Furthermore, this controller is responsible for protection of the input power source. The grid side controller normally regulates the dc-link voltage to maintain the power balance, and controls the output current to insert quality power to the grid. The dc links decouples the input and output converters. Therefore, the grid side converter is mainly responsible for the fault tolerance of such a power generation system [12].

The grid side controller consists of two major units: grid synchronization and grid monitoring units. The grid synchronization synchronizes the converter-interfaced DG units with the utility system, and the grid monitoring monitors grid side parameters and based on those parameters generates appropriate reference control signals [9]-[14].

Grid synchronization is a challenging task especially when the utility signal is polluted with harmonics and disturbances. 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, unbalance, voltage sags, and other types of pollutions that exist in the grid signal [5], [13]. Another important part of the grid side controller is the grid- monitoring unit, which plays a vital task in power quality and protection of grid connected converters. This unit is also responsible for harmonics detection and active/reactive current (power) extraction from the load/grid.

1.3 Basic Control Methods

The implementation of the control strategy for a distributed generation system can be done in different reference frames such as synchronous rotating (dq), stationary ($\alpha\beta$), or natural (abc) frame. Traditional control structures for the grid-connected converters are discussed in this section.

1.3.1 Synchronous Reference Frame Control

Synchronous reference frame control, also called dq control, uses a reference frame transformation module, (i.e. $abc \rightarrow dq$), to transform the grid current and voltage waveforms into a rotating reference frame that rotates synchronously with the grid voltage. By using the synchronous reference frame, the control variables become dc values; thus, filtering and controlling can be easily achieved [15].

A schematic of the dq control is represented in Figure 1.4. In this structure, the dc-link voltage is controlled in accordance to the necessary output power. Its output is the reference for the active current controller, whereas the reference for the reactive current is usually set to zero. The dq control structure is normally associated with proportional–integral (PI) controllers since they have a satisfactory behaviour when regulating dc variables. The matrix transfer function of the controller in dq coordinates can be written as:

$$G_{PI}^{(dq)}(s) = \begin{bmatrix} K_p + \frac{K_i}{s} & 0 \\ 0 & K_p + \frac{K_i}{s} \end{bmatrix} \tag{1.1}$$

Where Kp is the proportional gain and K_i is the integral gain of the controller. Since the controlled current has to be in phase with the grid voltage, the phase angle of the grid voltage must be extracted. Filtering the grid voltages and using arctangent function to extract the phase angle is a possibility [16]–[18]. The state of the art for the extracting the phase angle of the grid voltages is employment of the phase-locked loop (PLL) technique [5], [19]-[21]. The PLL algorithm provides a better rejection of grid harmonics, notches, and any other kind of disturbances. However, one drawback is in case of unsymmetrical voltage faults where the second harmonics produced by the negative sequence will propagate through the PLL system and will be reflected in the extracted phase angle. To overcome this, the negative sequence should be filtered out, and during unbalanced conditions, the three-phase dq PLL structure should estimate the phase angle of the positive sequence of the grid voltages. For improving the performance of PI controller in such a structure as depicted in Figure 1.4, cross-coupling terms and voltage feed-forward are usually used [22]-[27]. Even in improved PLL-based structures equipped with PI controllers, acceptable low-order harmonic rejection/compensation is not achieved, which is a major drawback when using them in grid- connected systems [5].

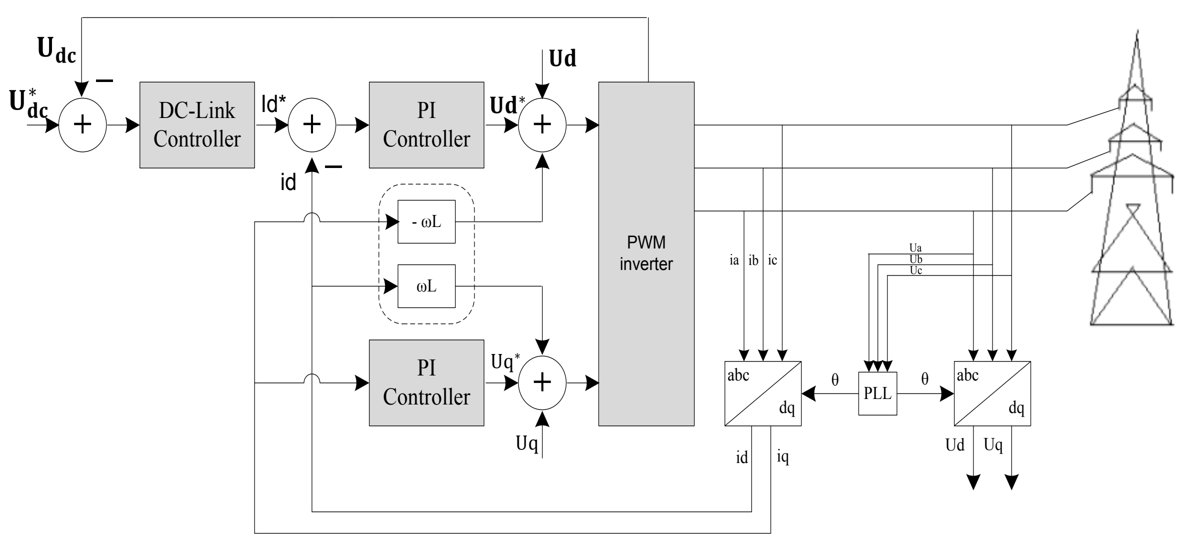

Figure 1.4 Synchronous rotating frame control structure

1.3.2 Stationary Reference Frame Control

In stationary reference frame control shown in Figure 1.5, the control variables, (i.e. grid currents), are time-varying waveforms; therefore, PI controllers encounter difficulties in removing the steady-state error. As a consequence, another type of controller should be used in this situation. The proportional-resonant (PR) controller [28]–[29] gained a large popularity in the last decade due to its capability of eliminating the steady-state error when regulating sinusoidal signals, as is the case of αβ or abc control structures. Moreover, easy implementation of a harmonic compensator for low-order harmonics without influencing the controller dynamics makes this controller suitable for grid-connected systems [12], [30]. The controller matrix in the stationary reference frame is given by

$$G_{PR}^{(\alpha\beta)}(s) = \begin{bmatrix} K_p + \frac{K_i s}{s^2+\omega^2} & 0 \\ 0 & K_p + \frac{K_i s}{s^2+\omega^2} \end{bmatrix} \quad (1.2)$$

Where ω is the resonance frequency of the controller, Kp is the proportional gain, and K_i is the integral gain of the controller. This controller achieves a very high gain around the resonance frequency, which makes it capable of eliminating the steady-state error between the controlled signal and its reference [31]. The width of the frequency band around the resonance point depends on the integral time constant, K_i. A low K_i leads to a very narrow band, whereas a high K_i leads to a wider band.

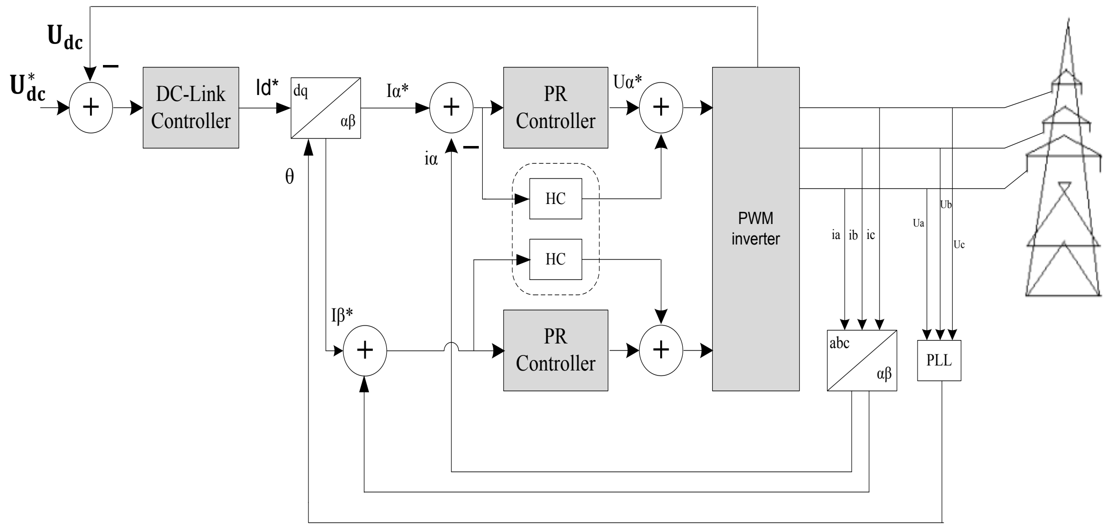

Figure 1.5 Stationary reference frame control structure

1.3.3 Natural Frame Control

In the abc control is an individual controller is used for each grid current; however, different ways of connecting the three-phase systems (i.e., delta, star with or without isolated neutral, etc.), are issues to be considered when designing the controller [5].

The abc control is a structure in which nonlinear controllers like hysteresis or dead-beat are usually preferred due to their responsiveness. The performance of these controllers is proportional to the sampling frequency. An implementation of abc control is depicted in Figure 1.6, where the output of dc-link voltage controller sets the active current reference. Using the phase angles of the grid voltages provided by a PLL system, the controller generates three current references. Each of them is compared with the corresponding measured current, and the error goes into the controller. When hysteresis or dead-beat controllers are employed in the current loop, the modulator is not anymore necessary. The output of these controllers is the switching states for the switches in the power converter. In the case that three PI or PR controllers are used, a modulator is necessary to generate the PWM pattern [12]. PI controller is widely used, and its performance in the abc frame is described in [27]. The implementation of PR controller in abc is straightforward since the controller is already in the stationary frame. Therefore, complexity of this controller is considerably less than a PI controller. Furthermore, to implement hysteresis control, an adaptive band of the controller has to be designed to obtain fixed switching frequency. Dead-band (DB) controller is widely employed for sinusoidal current regulation of different applications due to its responsiveness [15]-[18], [32]–[35]. Two different PLL schemes are possible in the abc frame control. In the first approach, three single-phase PLL systems [20] are employed to independently extract the three phase angles of the grid voltages. In this case, the transformation module $dq \rightarrow abc$ is not necessary anymore, with the active current reference being multiplied with the sine of the phase angles. In the second approach, one three-phase PLL [13], [42]-[44] is used and the current references are created as shown in Figure 1.6 [5].

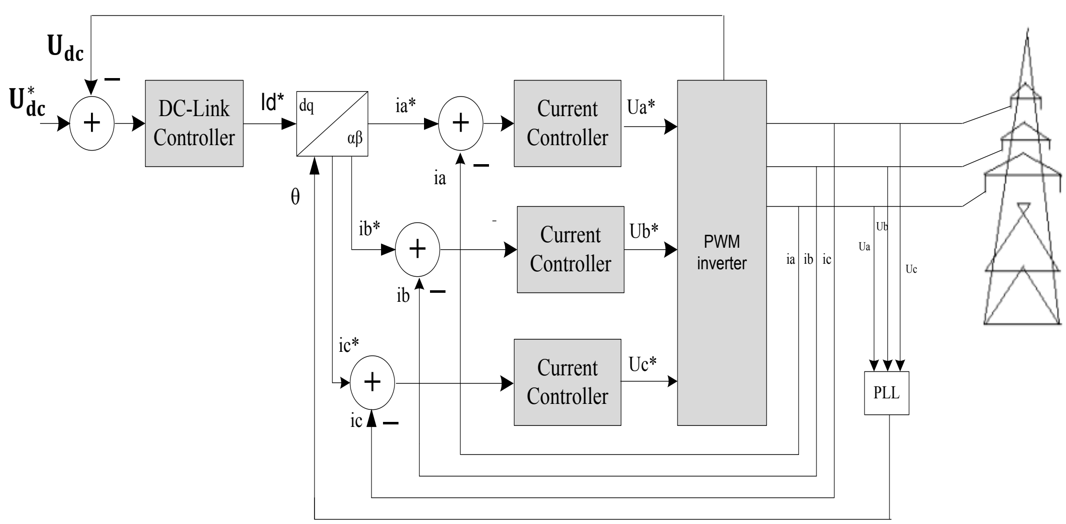

Figure 1.6 Natural reference frame control structure

1.4 Evaluation of Different Controllers

Dependence on voltage feed-forward and cross-coupling blocks are the major drawbacks of the control structure implemented in synchronous reference frame. The phase angle of the grid voltage should be extracted in this implementation. In the stationary reference frame, if PR controllers are used for current regulation, the complexity of the control becomes less compared to the structure implemented in the dq frame. Additionally, the phase angle information is not necessary and filtered grid voltages can be used as templates for the reference current waveform. In the natural frame, the control system complexity will be increased if an adaptive hysteresis band controller is used for current regulation. A simpler control scheme can be achieved by implementing a dead-beat controller instead. Note that for this control structure, each phase can be controlled independently if three single-phase PLLs are used to generate the current reference [45].

1.6 Research Motivation

Distributed energy sources equipped with power electronic interfaces can provide flexibility while working as an aggregated system and maintain the desired power quality and energy output in a power network. However, despite the significant benefits of distributed generation, the submission of a DG system can cause many problems such as lots of protection coordination and interference with grid`s transient response. To solve these problems, distributed generation systems are integrated to form micro-grids and smart-grids. Most of the power electronics-based distributed generation systems are interconnected to the utility grid; hence, switching harmonics will directly influence the quality of the output currents. If this problem is not properly addressed, connection of the DES to the utility network will create problems on the grid side. Therefore, power quality, control and harmonic compensation are considered as an important operation characteristics. There are different methods such as using passive and active filters and using appropriate control schemes like PI controller, PR controller and nonlinear controller for reducing harmonics in power electronic converters. Grid synchronization unit is a crucial subsystem regarding to harmonic compensation. Among different methods introduced for grid synchronization such as zero-crossing, filtering method, and the PLL-based method, the later one perfectly rejects harmonics and other disturbances. However, the PLL-based method needs further improvements to handle the unbalanced situations. To alleviate the aforementioned problems and improve the power quality and dynamic performance of the power network, a *modified reduced-order* digital adaptive notch filter (ANF) that extracts harmonic contents of the voltage and the injected current at the point of common coupling is introduced in this thesis.

1.7 Research Objectives

The objective of this research is to incorporate an adoptive power processor in a closed loop control scheme of renewable energy systems for power quality enhancement of the emerging micro-grids. This power processor enables the system to extract harmonics, and allows for compensation of particular unwanted frequency components, or a wide range of spectral contents of the injected current. Current harmonics of non-linear local loads have been therefore compensated by the distributed generation (DG) source and quality electric power is injected to the grid. Moreover, the proposed scheme is able to deal with unbalanced harmonic contents. The theoretical analysis is presented and Simulation results verify the accuracy of the proposed technique.

1.8 Thesis Layout

This thesis is organized as follows. Chapter 2 presents an extensive literature review on existing techniques for power quality improvement in terms of harmonic compensation. Control schemes for harmonic compensation in various reference frames will be discussed. And finally, among all grid synchronization techniques, ANF method is discussed for achieving better results compared to PLL techniques.

Chapter 3 reviews a single-phase and three-phase synchronization technique for harmonic extraction of the grid signal. The three-phase ANF based approach is extended for the extraction of individual harmonics of the load current. Finally, a digital power processor based on a modified reduced-order ANF will be presented and discussed.

In chapter 4, the unique multi-purpose modified ANF-based power processor technique, will be used for the power quality enhancement of DG systems in micro-grids. All this, nominate the technique as a simple and powerful "power processor". The operating principles of such a power signal analyzer are presented and the simulation results confirm the validity of the analytical work.

Chapter 5 presents the thesis summary and its contributions as well as directions for future work.

Chapter 2

Literature Review

Renewable energy resources such as wind and solar are considered clean and suitable choices for electric power generation compared to conventional energy resources such as oil, coal and natural gas. Nowadays, it is a general trend to deploy renewables in the electricity production in the form of distributed generation systems (DGSs). Most of the DGSs are interconnected to the utility grid, therefore, distortions in detected phase due to the distorted grid voltage, harmonic content and reactive current, directly influence the power factor and quality of output current. The harmonics not only increase losses in the power system, but also generate noise on regulating devices and control systems. Thus, if these systems are not properly controlled, their connection to the utility network can generate problems on the grid side. In this regard, power quality, control and grid synchronization are discussed due to significant importance. This chapter gives an overview on various aspects of the power quality as a challenging issue in renewable energy systems, summarizes some existing methods for power quality enhancement, discusses the state-of-the-art techniques for grid synchronization, and reviews the most popular control methods.

2.1 Power Quality

From the customer's point of view, the electric power has to be received without interference or interruption. On the other hand, from the grid's point of view the power quality deals with the waveforms of current and voltage in an ac system, harmonic components in bus voltages and load currents, spikes and momentary low voltages, and other types of distortion. A broad definition of power quality borders on system reliability, long-term outages, voltage unbalance in three-phase systems, operation of power electronics and their interface with the electric power supply, and many other areas [36].

Over the past few years, the growth in employment of nonlinear loads (such as adjustable speed drives, power converters, arc furnaces and transformers) has caused many power quality problems like high harmonic content, low power factor and excessive neutral current. The harmonics in the load current can sometimes result in overheated transformers, overheated neutrals, blown fuses and tripped circuit breakers (or breakers failing to trip in some cases) [37]. Nonlinear loads appear to be current sources injecting harmonic currents into the supply network through the utility's Point of Common Coupling (PCC). This results in distorted voltage drop across the source impedance, which causes voltage distortion at the PCC. Other customers at the same PCC will receive distorted supply voltage, which may cause overheating of power factor correction capacitors, motors, transformers and cables, and mal-operation of some protection devices. Therefore, it is important to deploy compensating devices to eliminate the harmonic currents produced by the nonlinear loads [19],[77].

2.1.1 Harmonic Distortion and Definitions

Electricity generation is normally produced at constant frequencies of 50 Hz or 60 Hz and the generators voltages can be considered sinusoidal waveforms. However, when a source of sinusoidal voltage is applied to a nonlinear device or load, the resulting current is not perfectly sinusoidal. In the presence of system impedance this current causes a non-sinusoidal voltage drop and therefore, produces voltage distortion at the load terminals, which is called harmonics.

In other words, a harmonic is a sinusoidal component of a periodic waveform having a frequency that is an integer multiple of the fundamental power frequency of 60 Hz. Harmonic distortion of the power waveform occurs when the fundamental component and harmonics are combined. It results voltage (or current) contamination on the sinusoidal waveform.

Unlike transient events such as lightning that last for a few microseconds, or voltage sags that last from a few milliseconds to several cycles, harmonics are steady-state periodic phenomena that produce continuous distortion of voltage and current waveforms. These periodic non-sinusoidal waveforms are described in terms of their harmonics, whose magnitudes and phase angles are computed using Fourier analysis. The analysis permits a periodic distorted waveform to be decomposed into an infinite series containing dc, fundamental frequency (e.g. 60Hz), and harmonics.

2.1.2 Harmonic Sources

There are two general categories of harmonic sources: saturable devices and power electronic devices. Saturable devices produce harmonics due mainly to iron saturation, as is the case for transformers, machines, and fluorescent lamps (with magnetic ballasts). The resulting magnetizing currents are peaked and rich in the third harmonic. Their current distortion is due to the arc and to the ballast. Power electronic loads draw power only during portions of the applied voltage waveform. These loads include switch-mode power supplies, fluorescent lights (with electronic ballasts), voltage source converters, pulse-width modulated converters, to mention just a few desktop computers, video monitors, and televisions have similar waveforms [46].

2.1.3 Harmonic Standards

Standardization is one of the most effective issues to influence equipment design and to control distortion in power systems. Power system engineers in the United States and in European Communities have turned to legislation and regulation to use of lower-harmonic electronic power supply designs. Their common objective is to preserve the sinusoidal nature of the power system voltage while protecting power system components from added harmonic current loading. However, the Americans and Europeans choose two completely different contrasting standards, IEEE and IEC. IEEE Standard 519 (recommended Practices and Requirements for Harmonic Control in Electrical Power Systems), suggests limitations for voltage and current harmonic distortion included individual harmonic limits and total harmonic distortion limits. IEEE 519-1992 provides separate harmonic voltage and current limits. As a part of the shared responsibility concept, the utility is generally concerned with meeting the voltage harmonic limits of Table 2.1 while all customers are responsible for meeting the (appropriate) current limits in Tables 2.2-2.4. Customers connected at higher voltages and customers that are larger with respect to the capacity of the system are more strictly limited [38].

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
69 kV and below	3.0	5.0
69.001 kV through 161 kV	1.5	2.5
161.001 kV and above	1.0	1.5

Table 2.1 IEEE 519-1992 Voltage Harmonic Limits [47]

I_{SC}/I_L	< 11	11≤ h< 17	17≤ h< 23	23≤ h< 35	35≤ h	TDD
< 20	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0
50 < 100	10.0	4.5	4.0	1.5	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

Table 2.2 IEEE 519-1992 Current Harmonic Limits (<69 kV) [47].

I_{SC}/I_L	< 11	11≤ h< 17	17≤ h< 23	23≤ h< 35	35≤ h	TDD
< 20	2.0	1.0	0.75	0.3	0.15	2.5
20 < 50	3.5	1.75	1.25	0.5	0.25	4.0
50 < 100	5.0	2.25	2.0	0.75	0.35	6.0
100 < 1000	6.0	2.75	2.5	1.0	0.5	7.5
> 1000	7.5	3.5	3.0	1.25	0.7	10.0

Table 2.3 IEEE 519-1992 Current Harmonic Limits (69-161) [47]

I_{SC}/I_L	< 11	11≤ h< 17	17≤ h< 23	23≤ h< 35	35≤ h	TDD
< 50	2.0	1.0	0.75	0.3	0.15	2.5
≥ 50	3.0	1.5	1.15	0.45	0.22	3.75

Table 2.4 IEEE 519-1992 Current Harmonic Limits (>161 kV) [47]

The IEEE 519-1992 current limits in Tables 2.2-2.4 can be related to the voltage harmonic limits in Table 1 through a system impedance which can be derived from the short-circuit to load ratio assuming the load current is 1.0 per unit. If followed, this derivation will show that multiple customers, each injecting their allowable current harmonics, are required to produce the voltage harmonic limit. IEEE 519-1992 accounts for load diversity, harmonic cancellation, and network resonance conditions by insuring that multiple customers are always required to produce the limiting amount of voltage harmonic distortion. The voltage quality management process embedded in IEEE 519-1992 is achieved indirectly through end-user current harmonic injection control. In the event that all end-users are within their permissible limits and voltage quality is not acceptable (i.e., the voltage harmonic limits are exceeded), the utility is responsible for whatever further actions are required in order to meet the voltage quality (harmonic) targets. The IEC has developed harmonic limits with a more direct focus on voltage quality. Planning levels, which are system-wide design targets at medium voltage (MV), high voltage (HV), and extra-high voltage (EHV), for voltage harmonics are established based on electromagnetic compatibility requirements for end-use equipment [51]-[54]. These planning levels are shown in Table 2.5.

Odd harmonics Non-multiple of 3			Odd harmonics Multiple of 3			Even harmonics		
Harmonic Order h	Harmonic Voltage %		Harmonic Order h	Harmonic Voltage %		Harmonic Order h	Harmonic Voltage %	
	MV	HV-EHV		MV	HV-EHV		MV	HV-EHV
5	5	2	3	4	2	2	1.8	1.4
7	4	2	9	1.2	1	4	1	0.8
11	3	1.5	15	0.3	0.3	6	0.5	0.4
13	2.5	1.5	21	0.2	0.2	8	0.5	0.4
$17 \leq h \leq 49$	$1.9.\frac{17}{h} - 0.2$	$1.2.\frac{17}{h}$	$21 < h \leq 45$	0.2	0.2	$10 \leq h \leq 50$	$0.25.\frac{10}{h} + 0.22$	$0.19.\frac{10}{h} + 0.16$

Table 2.5 IEC 61000-3-6 Voltage Harmonic Planning level [47]

2.2 Improving Power Quality by Means of Reducing Harmonics

There are different methods of reducing harmonics such as filtering techniques and control schemes in power electronics converters. In the former, harmonics can be mitigated with passive and active methods. In the latter, harmonic compensation can be achieved by using appropriate control schemes. PI and PR controllers in dq and $\alpha\beta$ reference frames, are examples for harmonic compensation by control techniques.

2.2.1 Active and Passive Filters

Filter is an electrical network that alters the amplitude and/or phase characteristics of a signal with respect to frequency. Ideally, a filter does not add new frequency components to the input signal however; it changes the relative amplitudes of the particular frequency components and/or their phase relationships.

Filters can be classified based on their operational frequency range. There are five basic filter types accordingly, which are referred to as band-pass, notch, low-pass, high-pass, and all-pass. Band-pass filters are used in electronic systems to separate a signal at one frequency or within a band of frequencies from signals at other frequencies. This filter could also reject unwanted signals at other frequencies outside of the pass-band, so it could be useful in situations where the signal of interest has been contaminated by signals at a number of different frequencies. Filters that affect conversely with regards to the band-pass are called band-rejection or notch filters. Notch filters are used to remove an unwanted frequency from a signal, while affecting all other frequencies as little as possible. The third type is a low-pass filter. A low-pass filter passes low frequency signals, and rejects signals at frequencies above the filter's cut-off frequency. Low-pass filters are used whenever high frequency components must be removed from a signal. The opposite of the low-pass is the high-pass filter, which rejects signals below its cut-off frequency. High-pass filters are used in applications requiring the rejection of low-frequency signals. The fifth and final filter type has no effect on the amplitude of the signal at different frequencies. Instead, its function is to change the phase of the signal without affecting its amplitude. This type of filter is called an all-pass or phase-shift filter. All-pass filters are typically used to introduce phase shifts into signals in order to cancel or partially cancel any unwanted phase shifts previously imposed upon the signals by other circuitry or transmission media.

In another classification based on the nature of components, a filter can be passive or active. A passive filter is simply a filter that uses all passive components. Passive filters have some advantages. Because they have no active components, passive filters require no power supplies. Since they are not restricted by the bandwidth limitations of controllers, they can work well at very high frequencies. They can be used in applications involving larger current or voltage levels than cannot be handled by active devices. Passive filters also generate little noise when compared with circuits using active elements. The noise that they produce is simply the thermal noise from the resistive components, and, with careful design, the amplitude of this noise can be very low. Passive filters have some important disadvantages in certain applications. The compensation characteristics heavily depend on the operating point, such as the system impedance because the filter impedance has to be smaller than the source impedance in order to eliminate source current harmonics. Overloads can happen in the passive filter due to the circulation of harmonics coming from nonlinear loads connected near the connection point of the passive filter. They are not suitable for variable loads, since, on one hand, they are designed for a specific reactive power, and on the other hand, the variation of the load impedance can detune the filter. Series and/or parallel resonances with the rest of the system can appear which is another disadvantage of passive filters.

Conventionally passive filters were used to reduce harmonics in various applications such as capacitors that employed for improving the power factor of the ac loads. However, passive filters have the demerits of fixed compensation, large size, and resonance. The increased severity of harmonic pollution in power networks has attracted the attention of power electronics and power system engineers to develop dynamic and adjustable solutions to the power quality problems. Such equipment, generally are known as active filters. Active filters use switching elements, especially MOSFETS and IGBTs, with respective control loops, to synthesize the desired filter characteristics. Possibly their most important attribute is wide range of operation, thereby reducing the problems associated with certain operating point in passive filters. The active filter technology is now mature for providing compensation for harmonics, reactive power, and/or neutral current in ac networks, eliminate voltage harmonics, regulate terminal voltage, suppress voltage flicker, and to improve voltage balance in three-phase systems [48]-[49]. These filters are costly and relatively new and a number of different topologies are being proposed. In the next section, few solutions are described to reduce harmonic effects and also improving power quality [39].

2.2.2 Using Active Filters for Harmonic Compensation

Active filters are a means to improve the power quality in distribution networks. In order to reduce the injection of non-sinusoidal load currents shunt active filters are connected in parallel to disturbing loads. Its main component is a voltage source inverter (VSI) with dc link capacitors. The VSI is connected to the point of common coupling (PCC) via a decoupling inductor that is usually the leakage inductance of a transformer. The purpose of the active filter is to compensate transient and harmonic components of the load current so that only fundamental frequency components remain in the grid current. The control principle for the active filter is rather straightforward: The load current is measured, the fundamental active component is removed from the measurement, and the result is used as the reference for the VSI output current. In [50], a control structure for the compensation of selected stationary harmonics in active filters has been presented. The high power active filter investigated is based on a pulse-width modulation (PWM) controlled voltage source inverter. Its inner current control is realized with a dead-beat controller that allows fast tracking of stochastically fluctuating load currents. For the mitigation of stationary load current harmonics, an outer control loop is required that compensates for the persistent phase error caused by the delay of the inner loop. The outer loop developed is based on integrating oscillators tuned to the major load current harmonics. A distinguishing feature from conventional control concepts is the direct path, which allows the fast compensation of transient harmonics. With conventional concepts, it takes one period of fundamental frequency to eliminate the harmonics after the load current has changed. Here, the harmonics are filtered immediately with the full speed of the inner dead-beat control loop. The initial phase error is corrected within the first period. This control structure is illustrated in Figure 2.1.

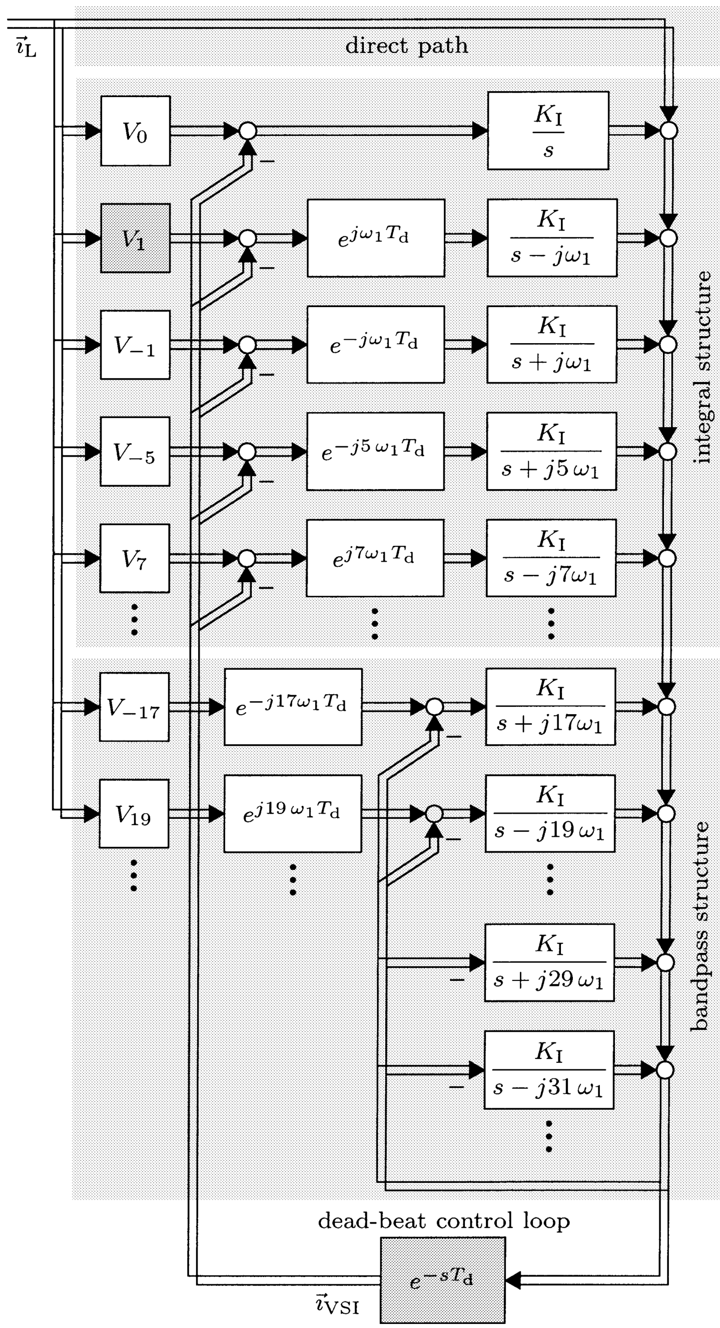

Figure 2.1 Control structure for the complete compensation of stationary harmonics [50]

Furthermore, in [19], the use of artificial neural network (ANN) technique for the shunt active filter is proposed. The extraction circuit uses ANN algorithm to compute the harmonic currents and reactive power for the nonlinear load. With the use of this ANN extraction circuit, the shunt active filter can be made adaptive to variations in nonlinear load currents. It can also compensate for unbalanced nonlinear load currents and correct the power factor of the supply-side near to unity. It also has the capability to regulate the dc capacitor voltage at the desired level. The application of ANN in active filters makes the extraction of harmonics faster resulting in faster adaptation of the active filters to any variation in the operating condition. Besides that, it also makes alternation in the designs of control circuit easier and more flexible for active filters. Furthermore, the modification of the conventional ANN weights updating algorithm to extract the harmonics greatly enhances the speed of the algorithm and extraction. Besides all of these advantages, stability of the system as an important issue has not been considered. Moreover, according to existing literature, combination of active and passive filters in series and parallel has better results in harmonics compensation. In [31] a control algorithm for a hybrid power filter constituted by a series active filter and a passive filter connected in parallel with the load is proposed. The control strategy is based on the dual vectorial theory of electric power. The new control approach shows that the compensation characteristics of the hybrid compensator do not depend on the system impedance, and the set of hybrid filter and load presents a resistive behaviour. The method in [31] eliminates the risk of overload due to the current harmonics of nonlinear loads close to the compensated system. And the compensator can be applied to loads with random power variation, as it is not affected by changes in the tuning frequency of the passive filter. Furthermore, the reactive power variation is compensated by the active filter.

Series and/or parallel resonances with the rest of the system are avoided because compensating equipment and load presents resistive behaviour. Therefore, the active filter improves the harmonic compensation features of the passive filter and the power factor of the load [31]. Another example of integration of active filters is proposed in [41]. This paper deals with unified power quality conditioners (UPQC's), which aims at the integration of series-active [56]–[58] and shunt-active filters. The main purpose of a UPQC is to compensate for supply voltage flicker/imbalance, reactive power, negative-sequence current, and harmonics. In other words, the UPQC has the capability of improving power quality at the point of installation on power distribution systems or industrial power systems. The UPQC, therefore, is expected to be one of the most powerful solutions to large capacity loads sensitive to supply voltage flicker/imbalance.

2.2.3 Using PI Controller for Harmonics Compensation

Synchronous reference frame control, dq control, uses a reference frame transformation module to transform the grid current and voltage into a reference frame. Since, the dq control structure is normally considered with proportional – integral (PI) controller, the possibilities for harmonic compensation are based on low-pass and high-pass filters. But in this case, under unbalanced conditions, more compensators are necessary to compensate for both positive and negative sequence of each harmonics. Figure 2.2 shows the dq control structure having a harmonic compensator for the positive sequence of the fifth harmonic.

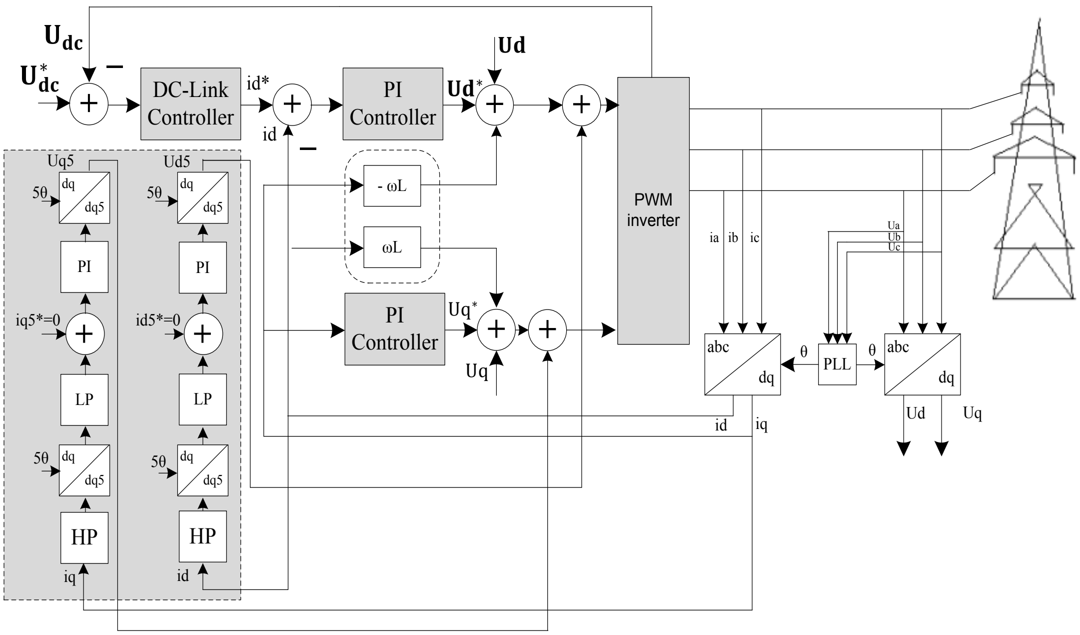

Figure 2.2 Compensating method for the positive sequence of the fifth harmonic in dq control system

This control algorithm is more complex. On the other hand, the controlled current should be in phase with the grid voltage, so the phase angle has to be extracted from the grid voltage. As a solution, the phase-locked loop (PLL) technique is used to extract the phase angle in the case of distributed generation systems. Considering all these improvements, very poor capability in rejection of low-order harmonics is a major drawback of the PI controllers [5]. The PI controlled active power filter (APF) scheme proposed in [24] is based on sensing the line currents. This approach is different from conventional ones, which are based on sensing harmonics and reactive power requirements of the nonlinear load. The three phase current/voltages are detected using only two current/ voltage sensors. This PI controller is used for the generation of a reference current template. It gives better performance in terms of time response and system stability, when compared to traditional PI ones.

2.2.4 Using PR Controller for Harmonics Compensation

In this case, harmonic compensation can be achieved by cascading several generalized integrators adjusted to resonate at the ideal frequency. In this controller, only one harmonic compensation is necessary for a harmonic order, cause, the harmonic compensator works on both positive and negative sequences of the elected harmonic; and this is the main advantage of this controller. A significant feature of this harmonic compensator is that it does not affect the dynamics of the PR controller, as it only reacts to the frequencies very close to the resonance frequency. This characteristic makes the PR controller an effective solution in applications where high dynamics and harmonic compensation, especially low-order harmonics, are required, as in distributed generation systems. In [30], the transfer function of a typical harmonic compensator (HC) designed to compensate the third, fifth, and seventh harmonics is given:

$$G_h(s) = \sum_{h=3,5,7} K_{ih} \frac{s}{s^2 + (\omega . h)^2} \tag{2.1}$$

In this case, it is easy to extend the capabilities of the scheme by adding harmonic compensation features simply with more resonant controllers in parallel with the main controller, as illustrated in Figure 2.3.

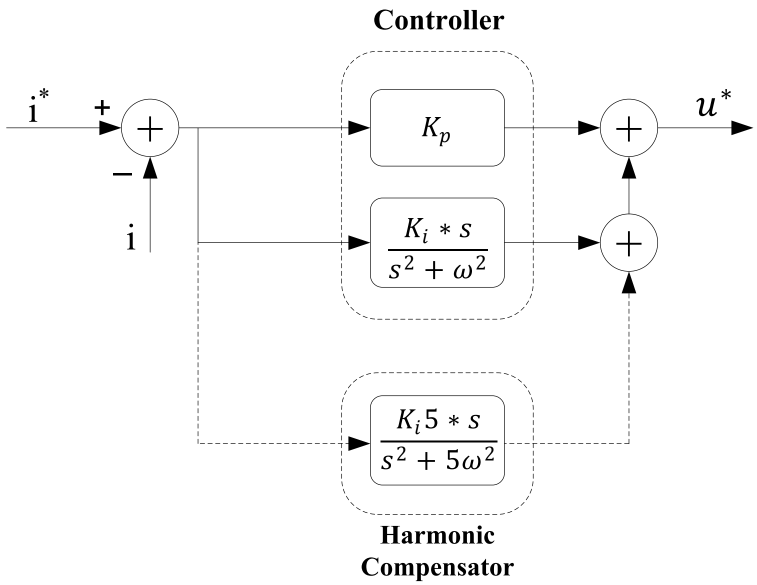

Figure 2.3 Harmonic compensator attached to the resonant controller of the main controller

2.2.5 Using Nonlinear Controllers for Harmonics Compensation

The basic implementation of the hysteresis current controller derives the switching signals from the comparison of the current error with a fixed hysteresis band. Although simple and extremely robust, this control technique exhibits several unsatisfactory features such as producing a varying modulation frequency for the power converter. Another negative aspect of the basic hysteresis control is that its performance is negatively affected by the phase currents' interaction, which is typical of three-phase systems with, insulated neutral. However, since both hysteresis and dead-beat controller are very fast, there is no concern about the low-order harmonics when the implemented control structure uses such controllers. Another issue is the need for the hardware with fast sampling capabilities of the hardware used [5].

2.3 Grid Synchronization

One of the most important issues of the distributed power generation systems (DPGS) connected to the utility network is the synchronization with the grid voltage. The synchronization algorithm mainly outputs the phase of the grid voltage. The phase angle of the utility voltage is a critical piece of information for grid-connected systems.

Therefore, a synchronization technique is essential in all grid-connected power converters providing a reference phase signal synchronized with the grid voltage to control and meet the power quality standards [13].

2.3.1 Grid Synchronization Methods

- **Zero-Crossing Method**

One of the simplest methods for obtaining the phase information is to detect the zero crossing of the utility voltages. However, the zero crossing points occur only at every half cycle of the utility voltage frequency; thus the dynamic performance of this technique is quite slow. The principle of operation of zero-crossing method is shown in Figure 2.4. Disturbances in the input signal, such as voltage sags and harmonics, influence the accuracy of the method, Figure 2.5 [13].

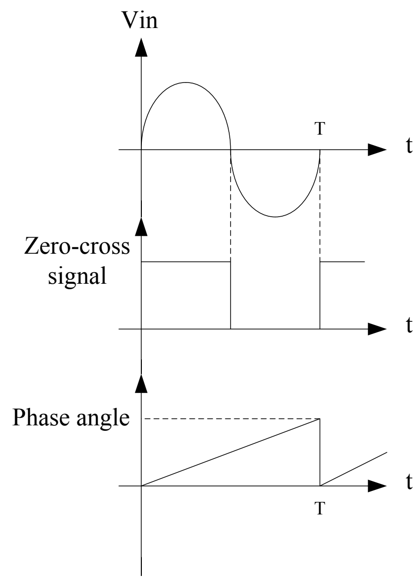

Figure 2.4 Principle of operation of zero-crossing method

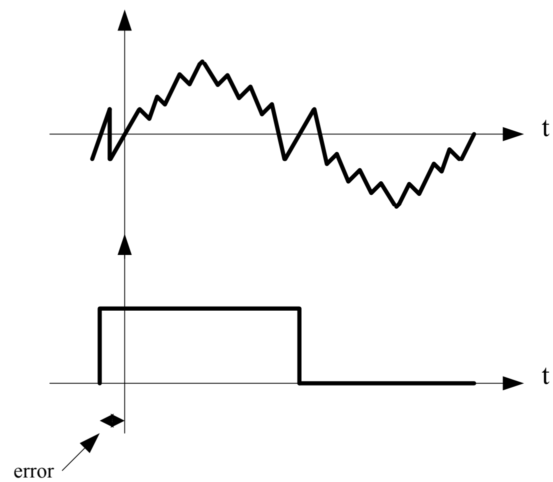

Figure 2.5 Error in zero-crossing detection due to distortion

- **Filtering Method**

The phase angle of the utility grid voltage can also simply be obtained by filtering the input signals, i.e. the three phase voltages (Ua, Ub, Uc). Depending on the reference frame where the filtering is applied, two schemes are possible, first, filtering in $\alpha\beta$ stationary reference frame and second, filtering in dq synchronous rotating reference frame.

- Filtering in $\alpha\beta$ stationary reference frame

Figure 2.6 depicts one of such filtering approaches in α-β stationary reference frame [55]. Three phase voltages are transformed to the αβ reference frame, and filtering is applied to both α and β components of the grid voltage [18]. In [16], different filters such as low pass filter (LPF), notch filter, space vector filter, etc. are investigated and their effectiveness is discussed. It is well known that using filtering, delays will be introduced in the signal, which is unacceptable in the case of grid voltage angle; therefore a proper filter design has to be made. Another alternative, as suggested in [59], is to compensate for the filter delay. A PI controller, monitoring the q component of the voltage can be used to correct the displacement introduced by the filter. Another techniques is to take advantage of band-pass filters as explained in [17]-[18]. In order to obtain satisfactory results under the unbalanced grid conditions, the authors implemented a "wave shaping and normalization module" which keeps the α and β components of the voltage sinusoidal and in quadrature. Similar to this method, in [13], a resonant filter is proposed to filter the $\alpha\beta$ voltages. The resonant filter has a similar characteristic as a band-pass filter but is not introducing delay.

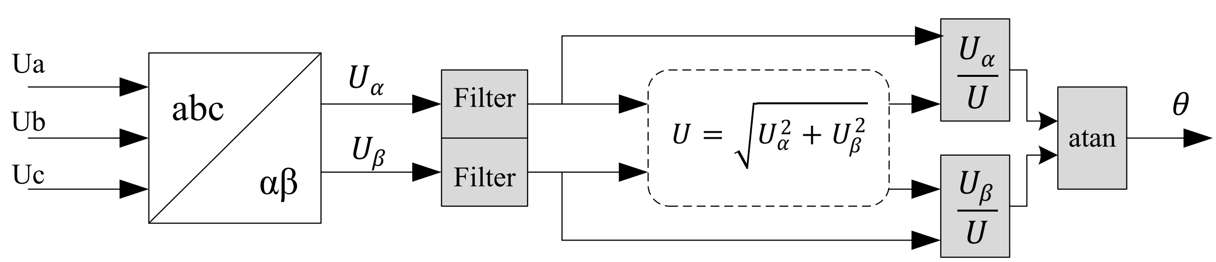

Figure 2.6 Synchronization method using filtering on $\alpha\beta$ stationary frame

➢ Filtering in dq synchronous rotating reference frame

Filtering techniques in the dq reference frame are easier to design, since voltage components are dc variables, Figure 2.7 various filtering techniques including notch filter, LPF, band-stop filter, etc. have been introduced in the rotating dq reference frame. Major deficiencies of filtering methods include their bad performance in case of grid frequency deviations, or voltage unbalance situation [5].

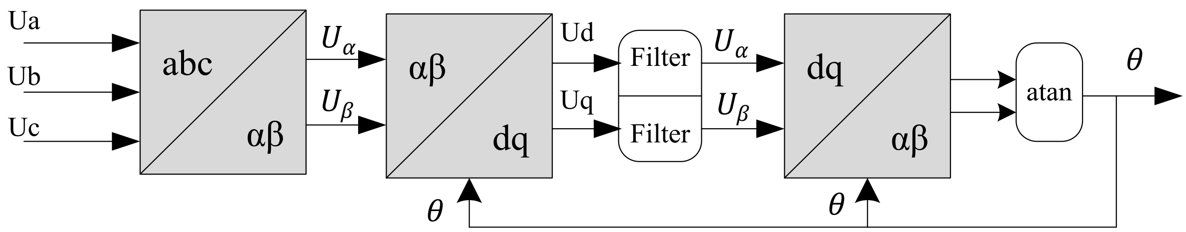

Figure 2.7 Synchronization method using filtering on dq synchronous reference frame

- **PLL Based Techniques**

➢ Single Phase Structures

The third method for synchronization is the phase locked loop (PLL) technique. The phase-locked loop (PLL) is a fundamental tool that has been used in different systems of electrical technology. The PLL can be defined as a device, which causes one signal to track another. In other words, it is known as the state-of-the-art technique in detecting the phase angle of the grid voltages. It keeps an output signal synchronizing with a reference input signal in frequency as well as in phase. In other words, the PLL system controls the phase of its output signal in such a way that the phase error between output phase and reference phase drives to zero by means of a control loop. A block diagram of a single-phase PLL is shown in Figure 2.8 the phase difference between the input and the output signals is measured using a phase detector. The error signal is then passed through a loop filter. The output of the filter drives a voltage-controlled oscillator (VCO), which generates the output signal. This technique can perfectly reject harmonics, voltage sags, notches and other kinds of disturbances. But, this tool needs additional improvements to overcome the unbalanced situations.

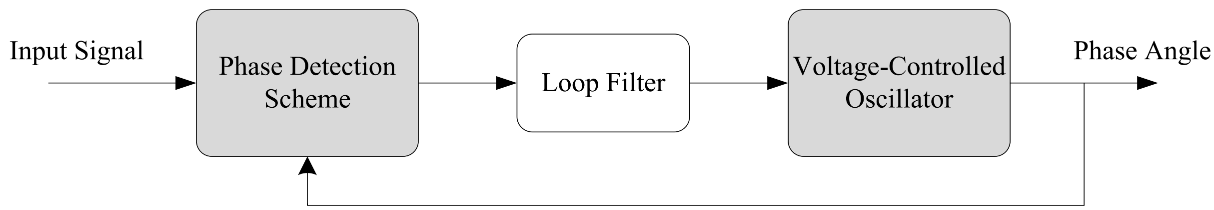

Figure 2.8 PLL Structure

- Three phase Structures

A common structure for grid synchronization in three-phase systems is a phase locked loop implemented in the dq synchronous reference frame [43]-[44]. This structure uses a abc/dq coordinate transformation and the lock is realized by setting the U_d^* to zero. A regulator, usually a PI regulator, regulates the error to zero. The VCO integrates the grid frequency and outputs the utility voltage angle that is fed back into the $\alpha\beta$ to dq transformation module.

This structure of PLL consists of two major parts, the transformation module and the PLL controller. The transformation module has no dynamics. In fact, the PLL controller determines the system dynamics. Therefore, the bandwidth of the loop filter determines the filter's filtering performance and its time response. As a consequence, the loop filter parameters have a significant influence on the lock quality and the overall PLL dynamics.

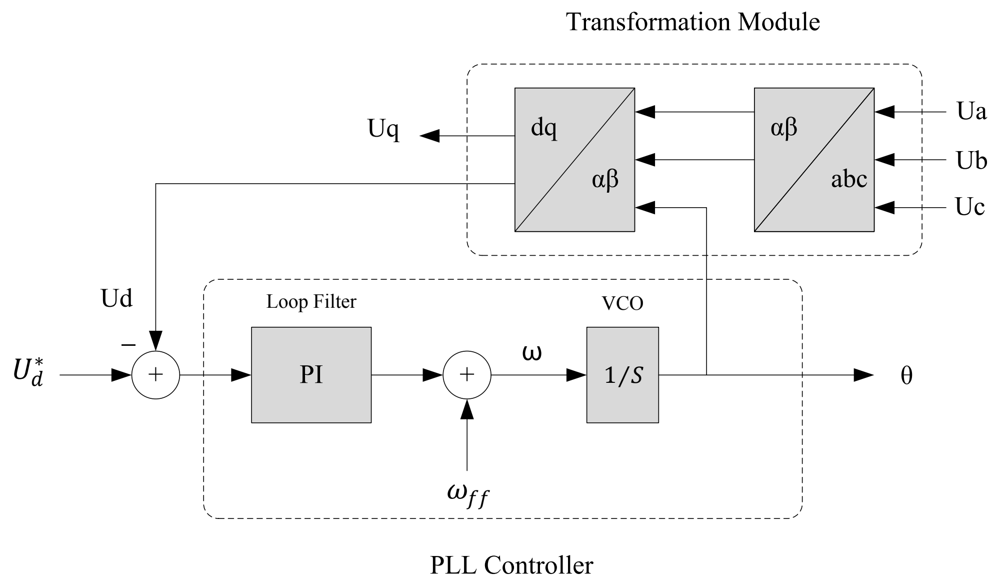

Figure 2.9 General structure of dq PLL method

The method in Figure 2.9 is also called the synchronous reference frame PLL (SRF–PLL) [5], [60]. Under ideal utility conditions, i.e., balanced system with no distortion, a loop filter of a wide bandwidth yields a fast and precise detection of the phase angle and the amplitude of the utility voltage vector. This method will not operate satisfactory if the utility voltage is unbalanced, distorted by harmonics or frequency variations.

Several works have been published based on the SRF-PLL of Figure 2.9 to improve its performance [28], [60]-[66]. In general, improved versions of the SRF-PLL use specific "filtering" techniques to deliver a non-distorted signal to the conventional SRF-PLL structure. An adaptive SRF-PLL filtering method proposed in [40], is another solution with a high rejection of the disturbances introduced by the voltage imbalance and by the voltage harmonic distortion, regardless of the grid frequency variation. On one hand, the adaptive nature of the filtering process makes the rejection insensitive to the grid frequency variation. On the other hand, the Schur-lattice IIR structure used to implement the filter stage makes the stability of the phase estimator independent of the adaptive process. In fact, the filter is inherently stable and does need neither any reference to be properly tuned nor added filtering stage to avoid swinging. Moreover, the used IIR structure makes this technique a suitable choice for fixed-point DSPs, or even for cheap fixed-point dsPICs, due to its low round-off noise and its ease to remove quantization limit cycles.

- **Adaptive Notch Filter (ANF) Method**

As mentioned before, PLL technique is not strong enough to handle the unbalanced situations and harmonic disturbances. So, to alleviate the aforementioned problems, a synchronization method based on adaptive notch filtering (ANF) is presented.

ANF is a basic adaptive structure that can be used to extract the desired sinusoidal component of a given periodic signal by tracking its frequency and amplitude of the fundamental component of the input signal. This structure guarantees a fast and accurate estimation of the phase angle when the distorted input signal contains low order harmonics. The power of this tool is that it outputs useful signal information such as the fundamental component, its 90° phase-shift, amplitude, frequency, sin/cos functions of its phase angle, harmonics and symmetrical components.

2.4 Summary

This chapter provides a quick overview of the existing techniques for power quality improvement in terms of harmonic compensation. Various methods for harmonic compensation and different classes of methods have been reviewed.

Control schemes for harmonic compensation in various reference frames have been discussed. State-of-the-art grid synchronization techniques have also briefly reviewed. Important existing methods and highlights both the merits and shortcomings of each method have been addressed. It has been addressed that among all grid synchronization techniques, the PLL-based algorithms show a better performance. However, PLL-based algorithms also suffer from situations such as grid voltage unbalance. Therefore, ANF method is discussed for achieving better results compare to PLL techniques. In the next chapter, a power quality enhancement method using a synchronization scheme based on an adaptive notch filtering approach is presented.

Chapter 3

Harmonic Extraction in Renewable Energy

In the single-phase systems, the imaginary stationary reference frame PLL using all pass filter (APF) is widely used. However, this conventional method is not robust enough to the harmonics, and consequently some errors in Zero-crossing can be occurred. For grid synchronization in three-phase systems, the dq synchronous reference frame PLL method has been widely used. Modified grid synchronization techniques are developed to improve the dynamic performance of the system during the transient due to the voltage amplitude and/or frequency variations, instability in phase detection, and harmonic/disturbance injection, etc. However, adaptive notch filter based grid synchronization method is developed for the estimation of errors due to the harmonics and noise. When the low order harmonics exist in the grid voltage, there is a trade-off between the response time and its harmonic rejection capability in the ANF-based method. Input signal harmonics are eliminated and an almost sinusoidal signal can be achieved at the output of the ANF.

In this chapter a single-phase and a three-phase synchronization scheme based on an adaptive notch filtering approach are discussed and implemented in PSCAD. Simulation results confirm the accuracy of harmonic extraction drawn from single-phase and three-phase ANFs. The simulation platform is employed in next chapter for closed loop operation.

3.1 Single-Phase Adaptive Notch Filter Unit

3.1.1 Adaptive Notch Filter (ANF) Characteristics (Basics)

As mentioned in chapter 1, one important part of the grid side power processor in converter-interfaced DG units is the grid synchronization unit. In grid-connected converters, the input signal to the synchronization tool is usually a periodic signal and is in the form defined in equation (3.1).

$$u(t) = \sum_{i=1}^{n} A_i \sin \emptyset_i \qquad where \qquad \emptyset_i = \omega_i t + \varphi_i \tag{3.1}$$

Nonzero amplitudes A_i, the nonzero frequencies ω_i, (for i=1,2...n), and the phases φ_i, (for i=1,2...n), are typically unknown parameters. Estimating unknown parameters especially unknown frequencies, are a required task in many applications, and are a fundamental issue in systems theory and signal processing. Fast and precise detection of the phase angle of such a polluted grid signal is the main task that a good synchronization technique must provide. Existing synchronization schemes, as mentioned in chapter 2, have some advantages and disadvantages.

Most of low power DG systems are single-phase, Grid-synchronization techniques for single-phase applications differ from those developed for three-phase systems. The synchronization scheme discussed in this chapter is simpler than existing schemes, overcomes their drawbacks, and is able to be extended for three-phase systems.

The adaptive notch filter is a basic adaptive structure that can be used to extract the desired sinusoidal component of a given single phase periodic signal by tracking its frequency variations. The dynamic behaviour of the modified ANF [68]-[76], is characterized by the following set of differential equations:

$$\ddot{x} + \theta^2 x = 2\zeta\theta e(t)$$
$$\dot{\theta} = -\gamma x \theta e(t) \tag{3.2}$$
$$e(t) = u(t) - \dot{x}$$

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

$$O = \begin{pmatrix} x \\ \dot{x} \\ \theta \end{pmatrix} = \begin{pmatrix} -\frac{A_1}{\omega_1}\cos(\omega_1 t + \varphi_1) \\ A_1 \sin(\omega_1 t + \varphi_1) \\ \omega_1 \end{pmatrix} \tag{3.3}$$

The third entry of O is the estimated frequency, which is identical to its correct value, ω_1. Figure 3.1 shows the schematic structure of an ANF unit, where the ANF is functioning as the main cell. The input is a distorted sinusoidal signal or in general a periodic signal. The power of the this structure is that it outputs useful signal information such as the fundamental component, its 90 degrees phase-shift, its amplitude, its frequency, sine/cosine functions of its phase angle, and harmonics.

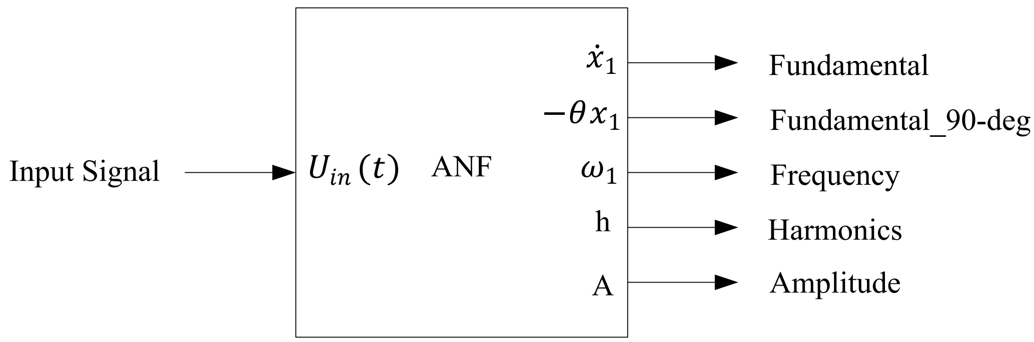

Figure 3.1 Basic structure of ANF [67]

A detailed implementation diagram of the single-phase ANF scheme is shown in Figure 3.2. The ANF is composed of simple adders, multipliers, and integrators. The output θ provides the fundamental frequency of the input signal, ω_1, and the amplitude of the fundamental component is calculated using two additional multipliers, a summer, and a square-root function. The sin/cosine functions of the phase angle are simply obtained by dividing the fundamental component and its 90 degrees phase-shift by the amplitude the fundamental component.

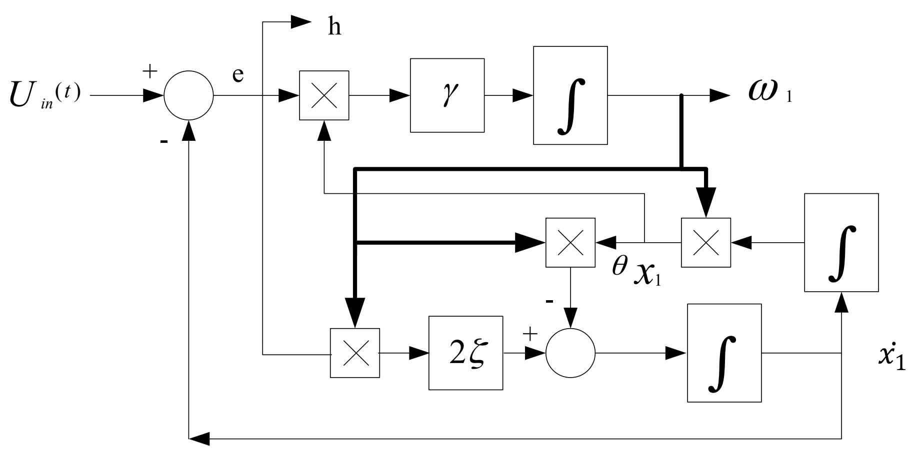

Figure 3.2 Detailed implementation of the single-phase ANF-based unit

3.1.1 Harmonic Extraction Using a Single-Phase ANF-based Unit

In some applications, it is desirable to estimate more than one frequency. In this section, it is shown how an extended structure of an adaptive notch filter can extract multiple frequencies. Consider the ANF the equations of (3.2) with the periodic orbit of the equation (3.3). The filter dynamics in the equation (3.2) is identical to a resonator (i.e. $\ddot{x} + \theta^2 x = 0$) that is forced with the error signal $e\,(t)$. The error signal incorporates the signal *x(t)* in the update law in the equation (3.2). The term θ in both equations is for scaling. In addition, the second component of the periodic orbit of the equation (3.3) (i.e. $\dot{x} = A_1 sin\,(\omega_1 t\ +\ \varphi_1)$) is equal to the fundamental component of the input signal. A structure composed of *n* parallel adaptive sub-filters has been used in [67] to directly estimate frequencies of an input signal $u\,(t)$ given by the equation (3.1). In such a structure, the i^{th} sub-filter is formulated by:

$$\begin{aligned}
&\ddot{x}_i + i^2\theta^2 x_i = 2\zeta_i \theta e(t) \\
&\dot{\theta} = -\gamma x_1 \theta e(t) \qquad\qquad (3.4) \\
&e(t) = u(t) - \sum_{l=1}^{n} \dot{x}_1
\end{aligned}$$

Similarly, in the equation (3.4), ζ_i and γ determine the behaviour of the i^{th} sub-filter in terms of accuracy and convergence speed, are real positive numbers. The method for estimating multiple frequencies based on the concept of ANF is shown in Figure 3.3. This figure shows a schematic structure of the multi-frequency estimator that extracts the fundamental component and the 5th and 7th order harmonics of the input signal. The input signal in this figure contains the fundamental (the 1st order harmonic) and only harmonics of the order of $6k \pm 1$ (for $k = 1,2,....$).

The multi-frequency estimator shown in Figure 3.3 consists of i) a master ANF that estimates the fundamental component of the input signal and its frequency; and ii) a multiplicity of slave ANFs that use the information and extract a number of harmonic components and their frequencies. The master ANF is linked to the slave ANFs in a parallel structure and operational frequencies of the slave ANFs are dictated by the frequency estimation loop embedded in the master ANF.

The operating principles of this multi-frequency estimator can be explained as follows. At steady state, $\dot{x}_i = A_i \sin \emptyset_i(t)$ (the i^{th} component of the input signal) appears at the output of the corresponding slave filter. For instance, the 2nd filter in the proposed algorithm finds the instantaneous frequency of the *5*th harmonic of the input signal ($\dot{x}_5$) and depicts it at its output. Simultaneously, the master ANF outputs the fundamental frequency, $\theta = \omega_1$. In addition, at steady state, we can write $A_i = (i^2\theta^2 x_i^2 + \dot{x}_i^2)^{1/2}$ that is the amplitude of the i^{th} harmonic component of the input signal. This means that the algorithm can be further furnished to estimate the amplitudes of the harmonics using arithmetic units that compute the right-hand side of A_i.

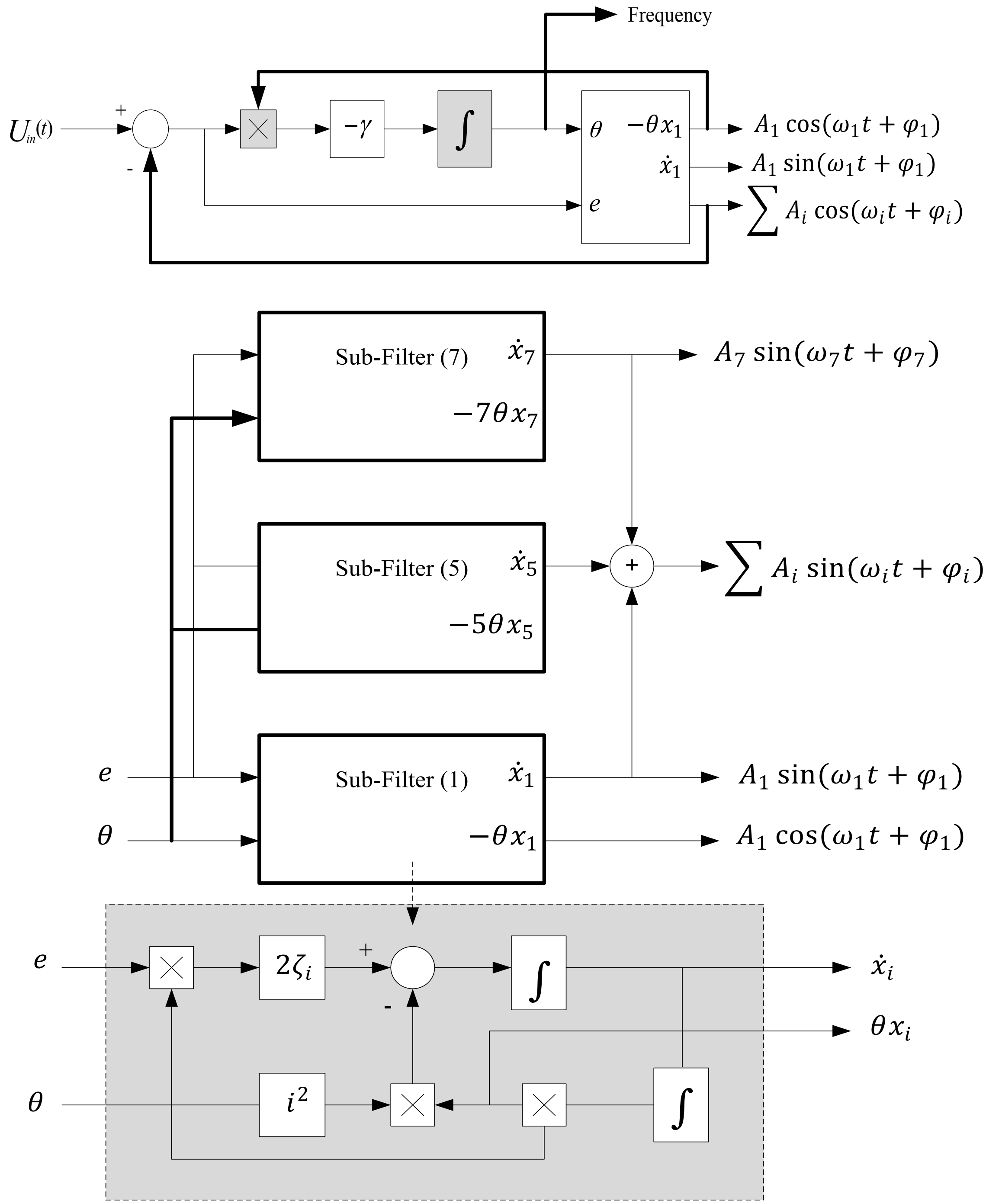

Figure 3.3 Structure for selective harmonic extraction

3.1.2 Performance Evaluation of Single-Phase ANF Unit

Extensive simulations in PSCAD evaluate performance of the ANF-based power signal processor technique. The input signal, produced by a programmable voltage source, is fed into the ANF-based power signal processor implemented in PSCAD. The parameters of the ANF are set to γ=18000 and ζ=0.7. The initial condition for the integrator that outputs the frequency, ω_1, is set to (2π)*60 rad/sec (the nominal power system frequency). The initial conditions for all other integrators are set to zero.

Accurate tracking and harmonic extraction feature of this method is investigated in this section. The input signal is composed of a fundamental (120v), a fifth harmonic, and a seventh harmonic component. Simultaneous step-changes in the fifth harmonic (from 1V maximum peak to 5V maximum peak), and the seventh harmonic (from 1V maximum peak to 8V maximum peak) are applied and the system response is recorded. Figure 3.4 shows the sum of the fifth and seventh harmonic components of the input signal. The step change occurs in the t=0.1s.

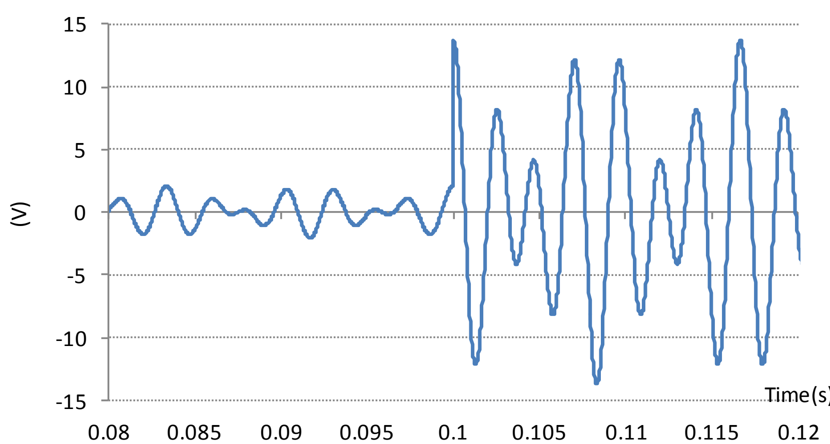

Figure 3.4 The harmonic content of the input signal for evaluation of harmonic extraction capability. Sum of the fifth and seventh harmonic component has been shown

The performance of the system for tracking the changes in magnitudes of the harmonic components are shown in Figures 3.5-3.7. Figure 3.5 shows the maximum magnitude of the fundamental component, in which the maximum amplitude of the fundamental component has remained at 171V. This has been expected, as the system is a 120V single-phase system. This figure shows that the system has properly followed the magnitude of the fundamental component even under step changes in the harmonics.

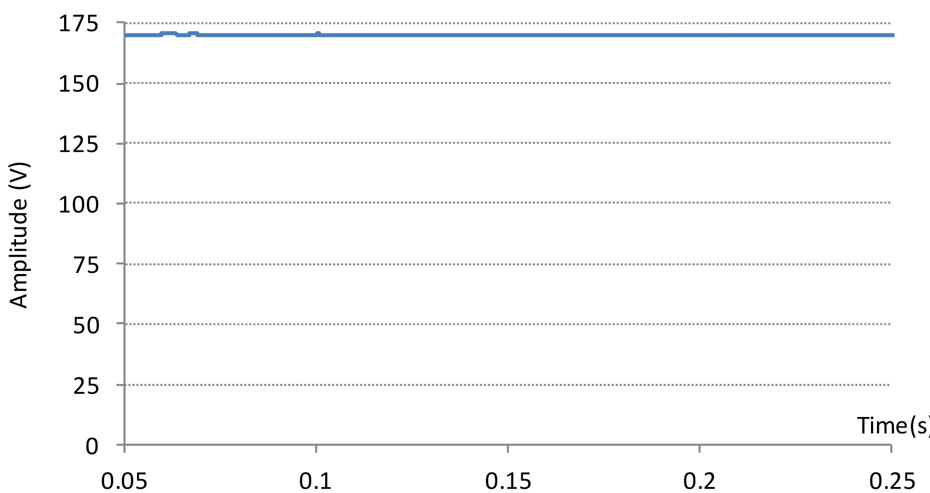

Figure 3.5 Extraction of amplitude of the fundamental component 60Hz.

Figure 3.6 illustrates the tracking capability of the system as the fifth harmonic is gone under a step change. This figure shows that the system successfully follows the changes in the magnitude of the fifth harmonic from 1V to 5V.

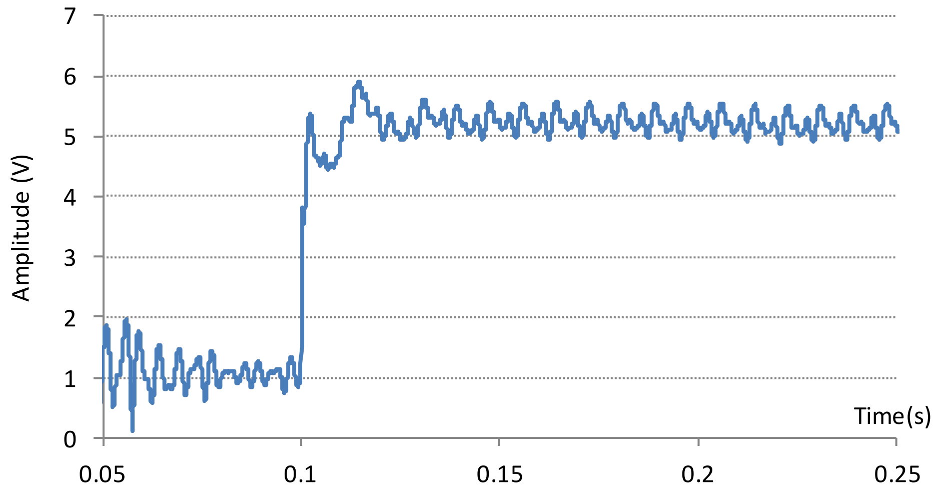

Figure 3.6 Extraction of the magnitude of 5th harmonic component

The same performance has been observed in the extraction of the seventh harmonic component, Figure 3.7. Therefore, operation of the system for following the changes in the harmonic content has been successfully verified.

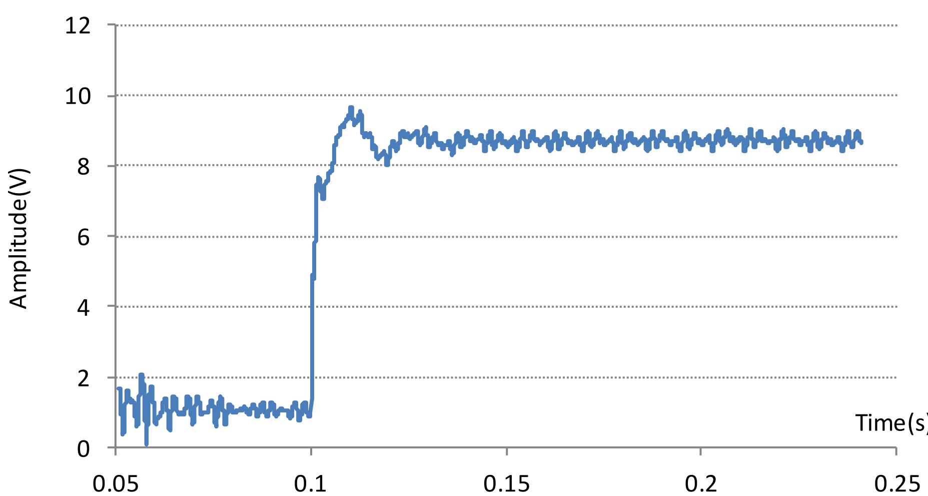

Figure 3.7 Extraction of the magnitude of 7th harmonic component

Another feature of the ANF unit is to provide the in-phase and quadrature component for each frequency component of the signal. This has been done by providing the sin and cosine functions of the phase angle of each component. Figure 3.8 illustrates the sin and cosine functions of the fundamental, 5^{th} and 7^{th} harmonics. The harmonic content has a step change in magnitude as explained above. As it can be seen in the following figures, the phase angle, or the sine and cosine functions has no variations. This has been expected since there has been no change in the phase angle of the frequency components. Accurate in-phase and quadrature components highly improve the performance of the system because of the sensitivity of control schemes to phase angle.

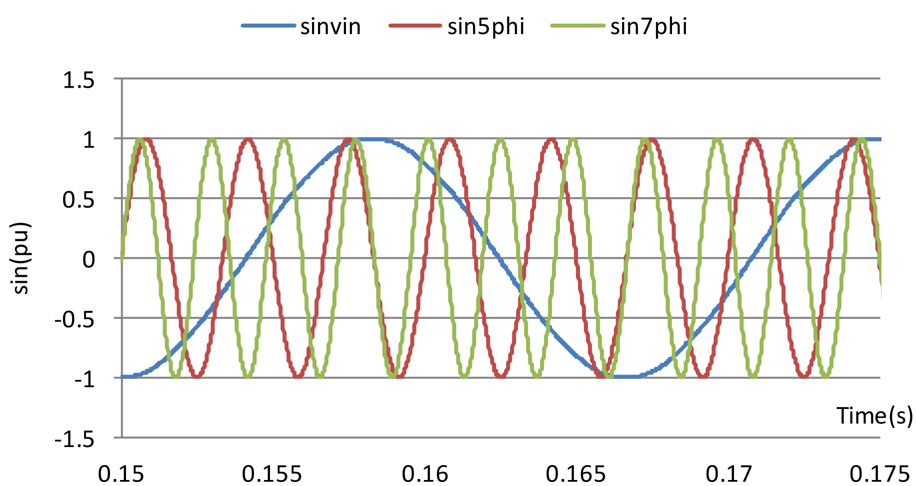

Figure 3.8 Sine of phase angle (quadrature component) of the fundamental, the fifth and the seventh harmonic components

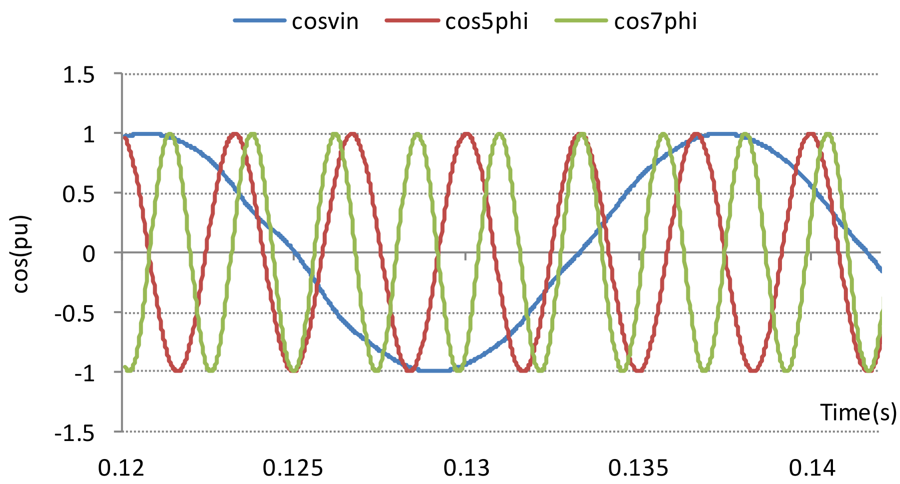

Figure 3.9 Cosine of phase angle (in-phase component) of the fundamental, the fifth and the seventh harmonic components

3.2 Three-Phase Adaptive Notch Filter Unit

This method is based on a three-phase ANF approach. Mathematical derivations of this technique are presented to describe the principles of operation and simulation results confirm the validity of the analytical work [67].

3.2.1 Three-Phase Synchronization Method

A three-phase ANF-based synchronization for three-phase systems is proposed in [67]. The three-phase based method introduced uses a seven order dynamical ANF system and provides fast and accurate estimation of the input signal's information in the presence of frequency and amplitude variations. In addition, the simplicity of the structure makes the method suitable for both software and hardware implementations.

3.2.2 Three-Phase Frequency Estimator

For three-phase applications, three single-phase ANFs can be employed to provide the fundamental component and its frequency for each $u_a(t)$, $u_b(t)$ and, $u_c(t)$. Each ANF is a third-order dynamic system; therefore, the three- phase system in has a dynamic of order nine.

However, the three-phase signals have a common frequency, ω_o, and therefore there is no need to estimate the frequency of each phase independently. Therefore, there is a common frequency estimation law based on the output information of all three ANFs. Consider three identical ANFs:

$$\ddot{x}_\alpha = -\theta^2 x_\alpha + 2\zeta_\alpha \theta e_\alpha(t) \qquad \alpha = a, b, c \tag{3.5}$$

$$e_\alpha(t) = u_\alpha(t) - \dot{x}_\alpha$$

Where θ is an estimate for ω_o. To derive an The Equation for estimating ω_o, we note that i) ω_o is the common frequency of three-phase signals, therefore, information of all three sub-filters must be incorporated into the update law for frequency estimation, and ii) the regressed signal $x\ (t)$ and the error signal $e\ (t)$ incorporate into the θ update law in the equation (3.6). The term θ is for scaling. Therefore, the update law for frequency estimation is:

$$\dot{\theta} = -\gamma\theta \sum_{\alpha=a,b,c} x_\alpha e_\alpha\,(t) \tag{3.6}$$

For a three-phase sinusoidal signal $u\ (t)$ given by:

$$u(t) = \begin{pmatrix} u_a(t) \\ u_b(t) \\ u_c(t) \end{pmatrix} = \begin{pmatrix} k_a \sin(\omega_0 t + \delta_a) \\ k_b \sin(\omega_0 t + \delta_b) \\ k_c \sin(\omega_0 t + \delta_c) \end{pmatrix} \tag{3.7}$$

The dynamical system given by the equation (3.5) and the equation (3.6) has a unique periodic orbit located at:

$$P(t) = \begin{pmatrix} P_a(t) \\ P_b(t) \\ P_c(t) \\ \bar{\theta} \end{pmatrix} \tag{3.8}$$

Where, $P_a(t)$ is given by:

$$P_a(t) = \begin{pmatrix} \bar{x}_\alpha \\ \dot{\bar{x}}_\alpha \end{pmatrix} = \begin{pmatrix} -\dfrac{A_\alpha}{\omega_0}\cos(\omega_0 t + \delta_\alpha) \\ A_\alpha \sin(\omega_0 t + \delta_\alpha) \end{pmatrix} \tag{3.9}$$

and $\theta = \omega_0$. For the ANF$_\alpha$ in the steady state, the defined outputs $\dot{x}_\alpha$and $\theta.x_\alpha$ are:

$$\dot{\bar{x}}_\alpha = A_\alpha \sin(\omega_0 t + \delta_\alpha) \tag{3.10}$$

$$-\bar{\theta}\bar{x}_\alpha = A_\alpha \cos(\omega_0 t + \delta_\alpha)$$

which are equal to $u_a(t)$ and $S_{90°}u_a(t)$. This means that the α^{th} component of the input signal and its 90° phase shift are made available by ANFα at its outputs (i.e. $\dot{x}_\alpha$ and $-\theta.x_\alpha$).

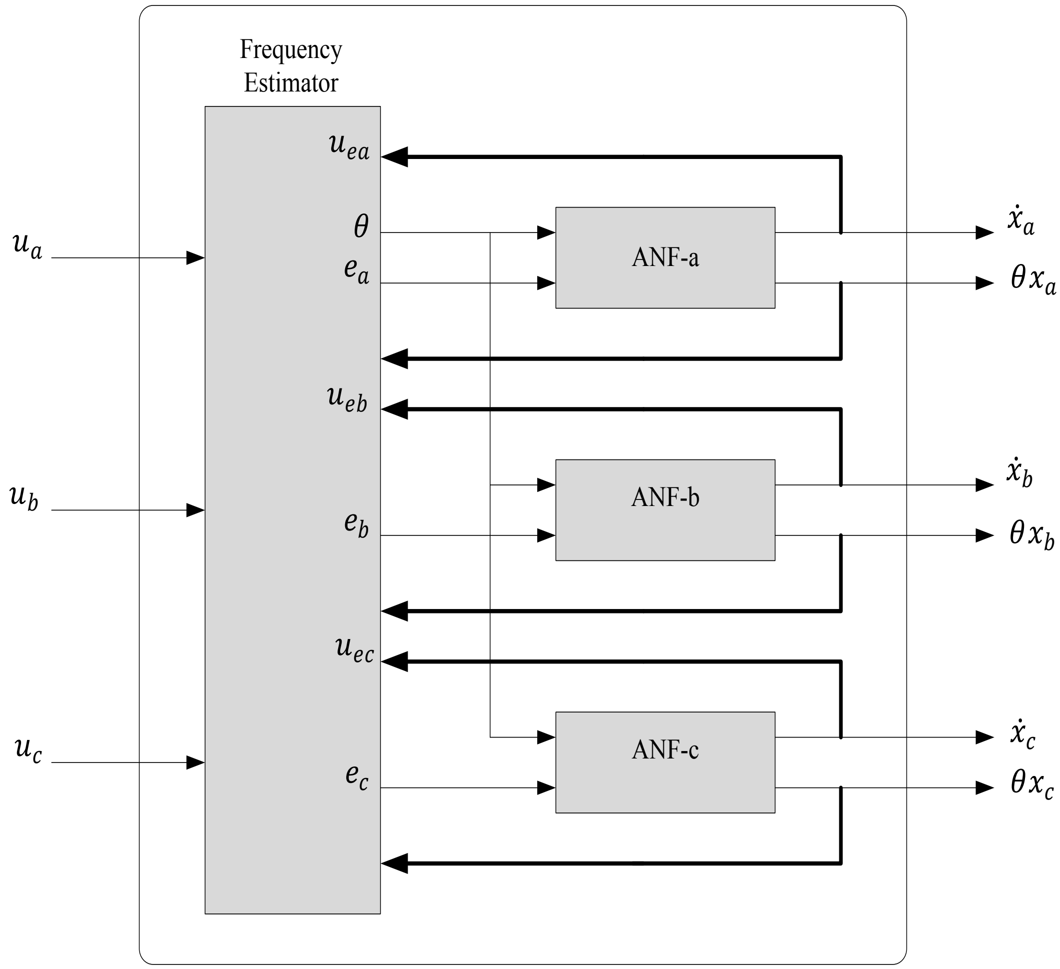

Figure 3.10 Structure for three-phase system

A structural block diagram of the first stage of this algorithm is shown in Figure 3.10. Detailed implementation block diagram of the frequency estimator and the α^{th}sub-filter (ANFα) are shown in Figures 3.11 and 3.12. The basic structure of this system has two independent design parameters, γ and ζ_α. The initial condition for the integrator in the frequency estimator block is set to the nominal power system frequency and the initial conditions for all other integrators are set to zero.

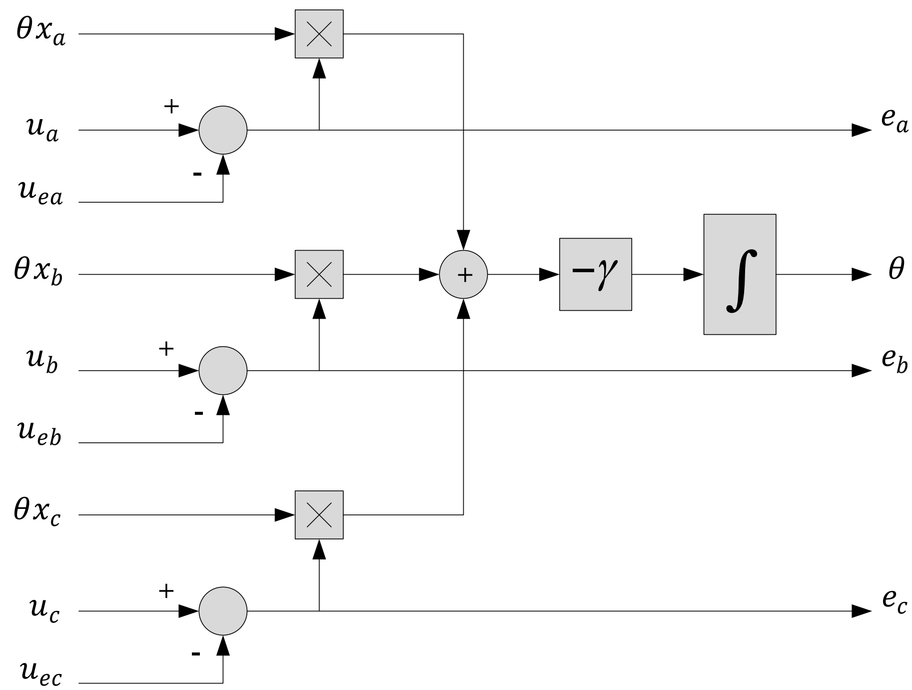

Figure 3.11 Structure of the frequency estimator unit

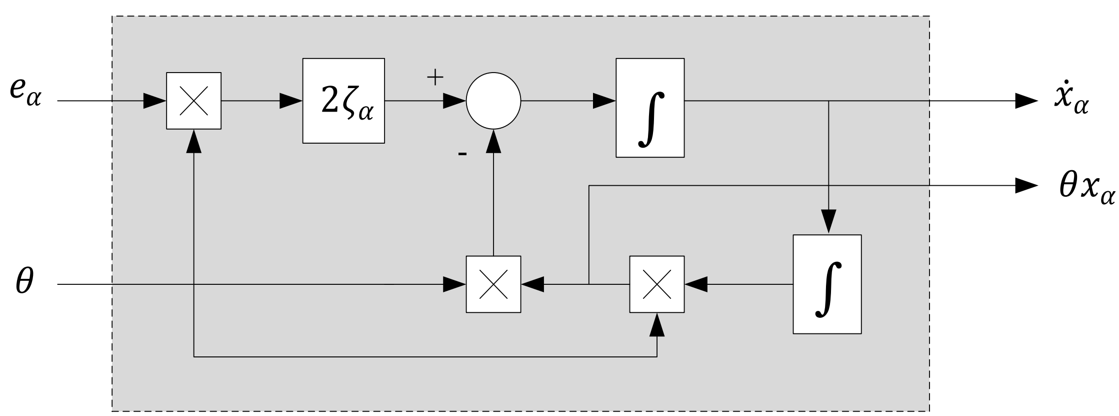

Figure 3.12 Structure of the α^{th}sub-filter

This structure receives the three-phase input signals and outputs the fundamental component and its useful information associated to each phase. In the next section, the three-phase based method is extended to estimate more than one frequency. This method has several applications in a variety of power electronics equipment, where the removal of a selected number of harmonics, especially low order harmonics, is desirable.

3.2.3 Three-Phase multiple Frequency Estimator

To extract a selective order of harmonics, the structure of the sub-filter in Figure 3.12 is modified and replaced by the multi-block ANF, as shown in Figure 3.13. In this configuration, the inputs $e_\alpha(\alpha = a, b, c)$ and θ are coming from the frequency estimator and the outputs $u_{e\alpha}(\alpha = a, b, c)$ and $\theta x_\alpha(\alpha = a, b, c)$ are fed back to the frequency estimator of Figure 3.10. When the three-phase input signal contains harmonics, the first sub-filter outputs the fundamental component of the input signal and ith sub-filter outputs the ith harmonic components of the input signal for each phase. Note that $A_\alpha = (\theta^2 . x_\alpha^2 + \dot{x}_\alpha^2)^{1/2}$ is the amplitude of the fundamental component of the α^{th} phase of the input signal.

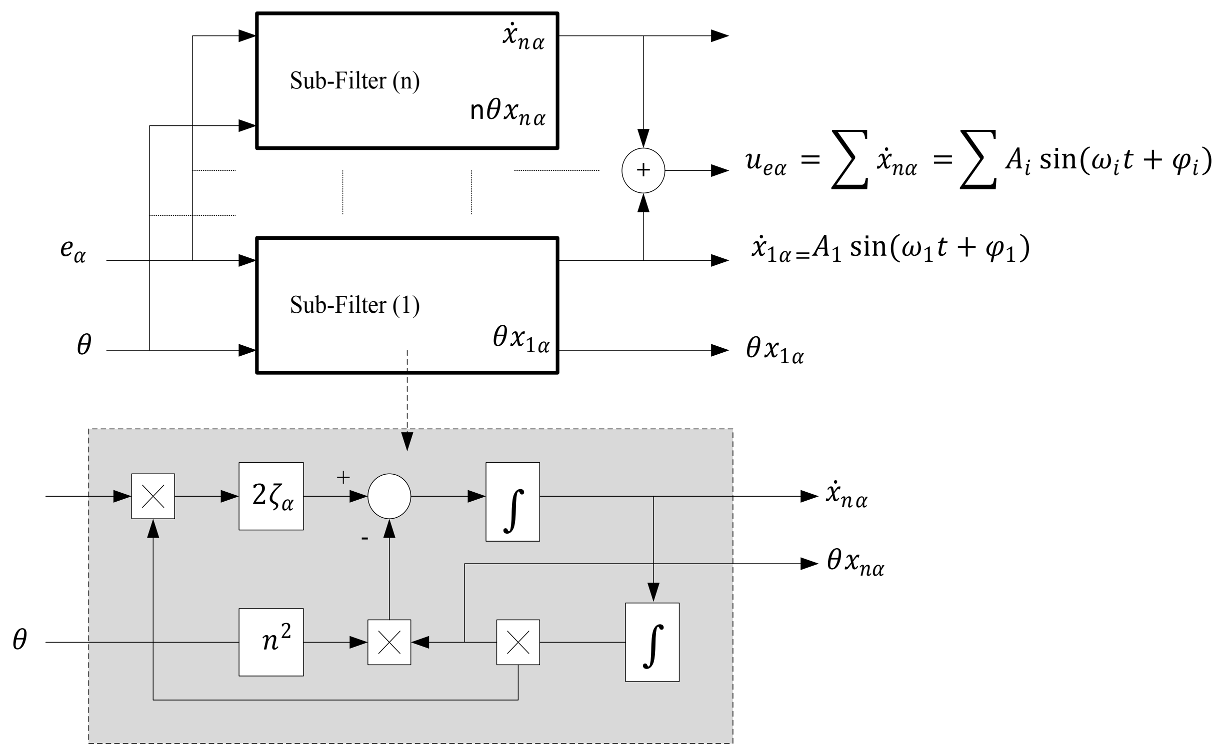

Figure 3.13 Structure of the α^{th} sub-filter; modified structure for faster time response

This configuration guarantees a fast (one cycle) and precise extraction of the individual harmonics that can be employed for further harmonic analysis or elimination purposes.

3.2.4 Performance Evaluation

Extensive simulations in PSCAD evaluate performance of the ANF-based power signal processor technique. The input signal for each phase, produced by a programmable voltage source, is fed into the ANF-based power signal processor implemented in PSCAD. The parameters of the ANF are set to γ=18000 and ζ=0.7. The initial condition for the integrator that outputs the frequency, ω_1, is set to (2π)*60 rad/sec (the nominal power system frequency). The initial conditions for all other integrators are set to zero.

The performance of the three-phase power processor has been evaluated by imposing a step change in the magnitude of the fifth and seventh harmonics in each phase. The three-phase input signal is composed of a fundamental (120v), a fifth harmonic, and a seventh harmonic component in each phase. Step-change of 1V maximum peak to 5V maximum peak in the fifth harmonic component of each phase, and from 1V maximum peak to 8V maximum peak in the seventh harmonic component of each phase are applied and the system response is illustrated in Figures 3.15-3.17. The sum of the fifth and seventh harmonic components of the input signal for each phase is illustrated in Figure 3.14. The step change occurs in the t=0.1s.

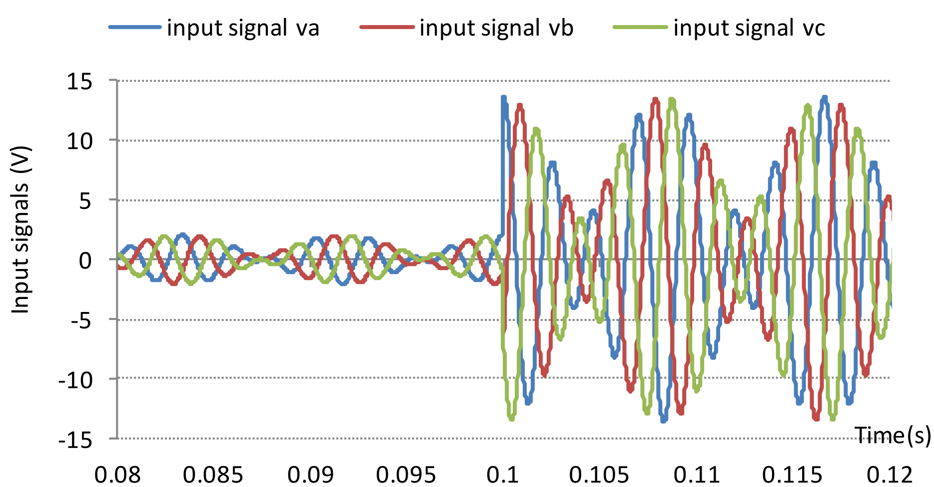

Figure 3.14 Harmonic content of the input signal for evaluation of harmonic extraction capability. The fifth and seventh harmonic component in each phase has been shown

The three-phase operation for tracking the changes in magnitudes of the harmonic components are shown in Figures 3.15-3.17. Figure 3.15 shows the maximum magnitude of the fundamental three-phase component, in which the maximum amplitude of the fundamental component for each of the phases has remained at 171V. This value is because the system under study is a three-phase 208V. Accurate tracking capability for the three-phase system has been indicated in the results.

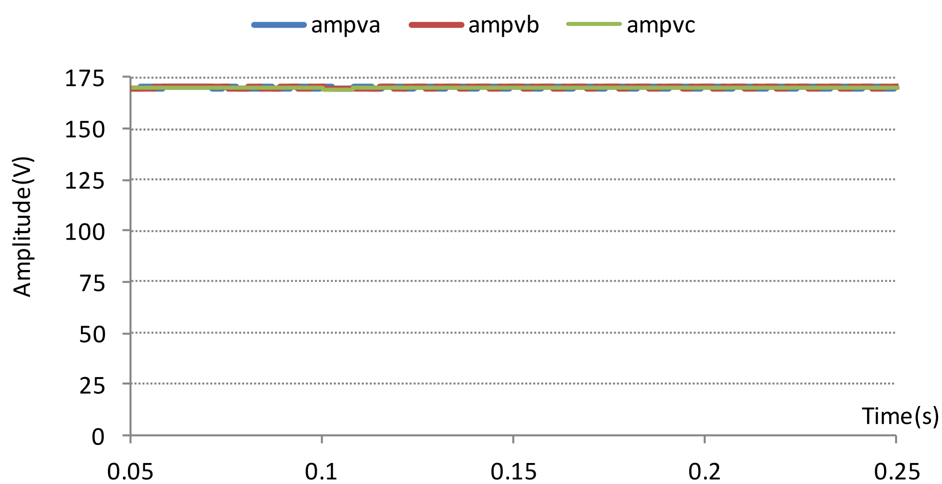

Figure 3.15 Extracted amplitude of the fundamental component 60Hz in the three-phase system

The tracking capability of the system is evaluated where the fifth harmonic has experienced a step change from 1V peak magnitude to 5V peak magnitude in each phase. Figure 3.16 show that the system perfectly follows the variations of the fifth harmonic component. Therefore, operation of the system for the changes in the three-phase system has been successfully verified.

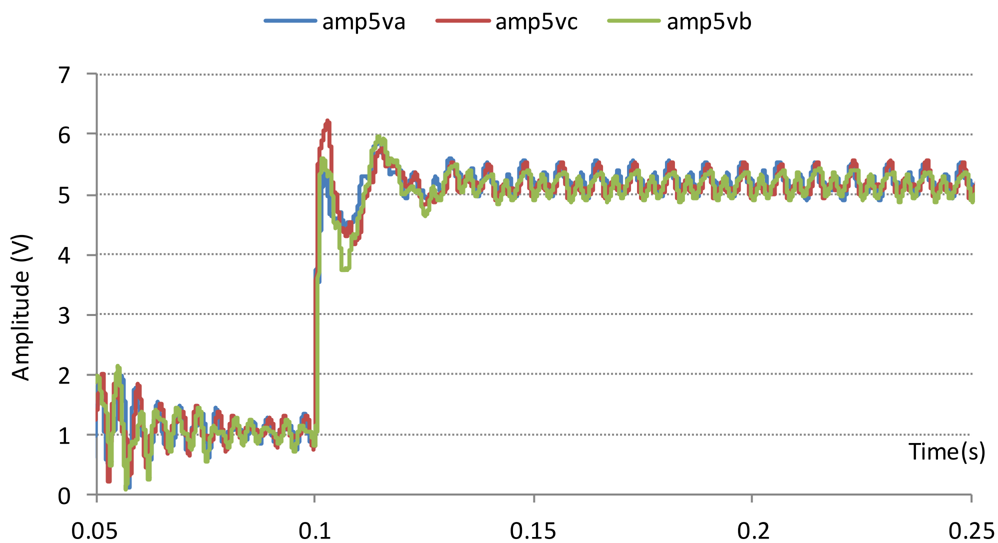

Figure 3.16 Extraction of magnitude of the 5th harmonic component in the three-phase system

The response of the system to the same step change on the 7th harmonic has been shown in Figure 3.17.

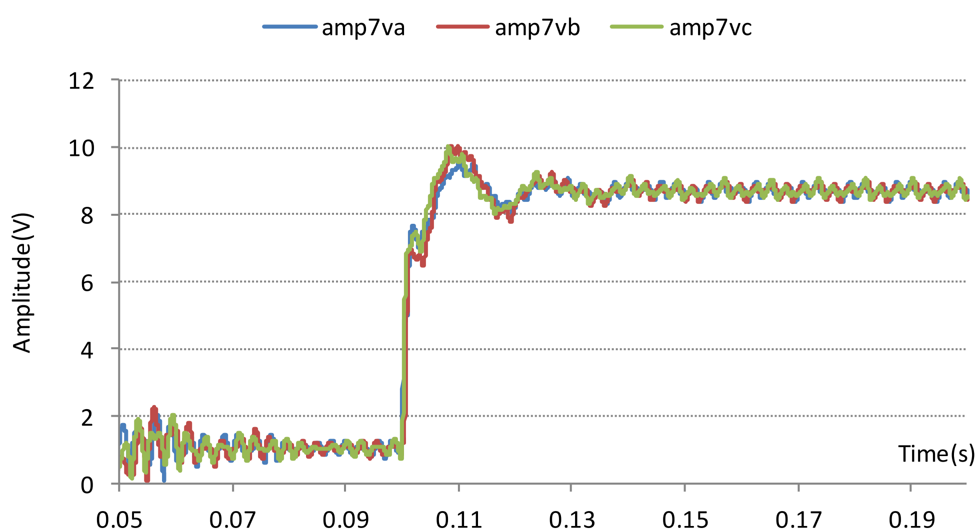

Figure 3.17 Extraction of magnitude of the 7th harmonic component in the three-phase system

For each phase the power processor has derived the sine and cosine functions of the respective phase angles when the harmonic contents experienced a step change in each phase. The sine and cosine functions for the fundamental, 5^{th} and 7^{th} harmonics have been shown in Figures 3.18-3.19. The harmonic content has a step change in magnitude as explained above. Because the step change in the amplitudes does not result in phase angle variations, it is expected that the resulting in-phase (cosine) and quadrature (sine) components does not experience significant changes. This is verified by the results shown in Figures 3.18-3.19.

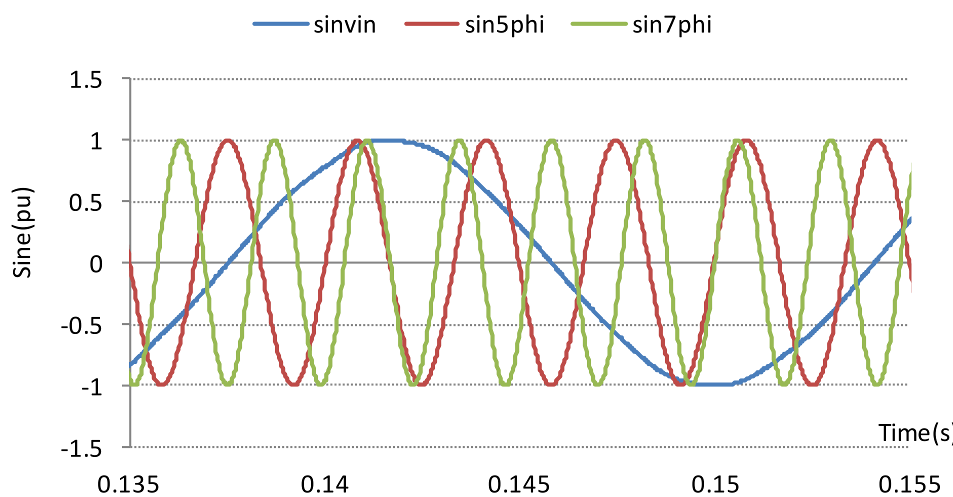

Figure 3.18 Sine of phase angle (quadrature component) of the fundamental, fifth and the seventh harmonic components of phase a

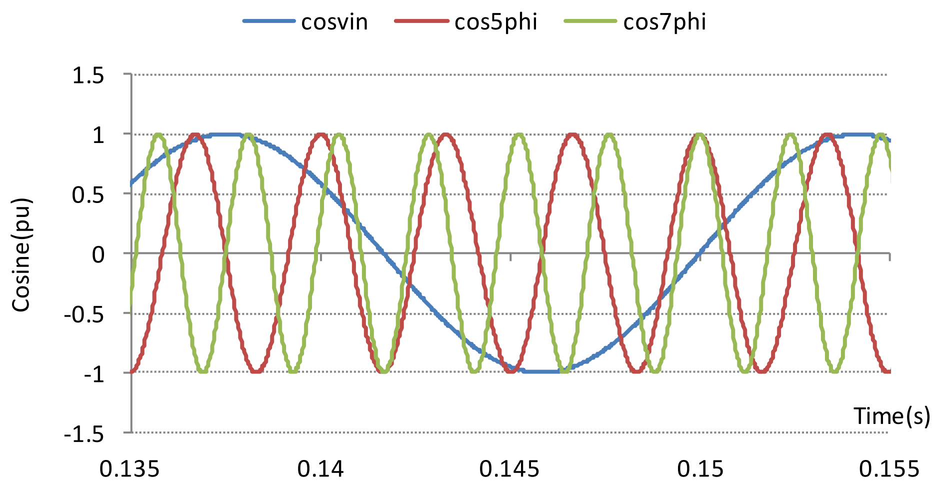

Figure 3.19 Cosine of phase angle (in-phase component) of the fundamental, the fifth and the seventh harmonic components of phase a

3.3 Proposed Modified Three-Phase Adaptive Notch Filter

A power processor based on a modified reduced-order digital adaptive notch filter (ANF) is presented in this chapter. The proposed technique is employed to extract harmonic content and symmetrical components of each harmonic of the voltage and the injected current at the point of common coupling (PCC). A universal digital power processor has been developed to improve the power quality enhancement capabilities of distributed generation systems in smart micro-grids; power quality support is one of the benefits of integration of decentralized power generation with the power grid. In other words, each distributed generation (DG) source can contribute to power quality improvement in a micro-grid by employment of proper control schemes.

The developed power processor has been employed in the control scheme of a renewable energy

DG system. It has been shown that the proposed technique is suitable for both selective and wide range current harmonic compensation. The proposed technique allows for compensation of either particular unwanted frequency components or a wide range in the spectral content of the injected current. Current harmonics of non-linear local loads have been therefore compensated by the DG source and a good quality electric power is injected to the grid. Moreover, it has been shown that the proposed scheme is able to deal with unbalanced harmonic contents. The proposed power processor also diminishes the need for extra phase extraction units such as phase-locked-loops (PLL).

The proposed scheme is simpler than PLL-based approaches, and overcomes some weaknesses of the PLL systems such as suffering from the presence of double-frequency ripples. Mathematical derivations of the proposed technique are presented to describe the principles of operation and simulation results confirm the validity and accuracy of the proposed scheme.

3.3.1 Proposed Modified ANF Dynamic and Structure

The dynamic behaviour of the newly modified ANF, which is of our interest, is characterized by the following set of differential equations:

$$u_\alpha(t) = \sum_{i=1}^{n} a_{\alpha i} \sin\left(i\omega t + \varphi_{\alpha,i}\right) \tag{3.11}$$

where i denoted the harmonic components and $\alpha = a, b, c$ represents the three phases. The set of differential the Equations are presented in the equation (3.12):

$$\ddot{x}_{\alpha,i} + i^2\theta^2 x_{\alpha,i} = 2\zeta_i \theta i e_\alpha(t) \tag{3.12}$$

$$\dot{\theta} = -\gamma \sum_{\alpha=a,b,c} x_{\alpha,1}\theta e_\alpha(t)$$

$$e_\alpha(t) = u_\alpha(t) - \sum_{i=1}^{n} \dot{x}_{\alpha,i}$$

This ANF has a unique periodic orbit located at:

$$\begin{pmatrix} x_{\alpha,i} \\ \dot{x}_{\alpha,i} \\ \theta \end{pmatrix} = \begin{pmatrix} -\frac{a_{\alpha,i}}{i\omega}\cos(i\omega t + \varphi_{\alpha,i}) \\ a_{\alpha,i}\sin(i\omega t + \varphi_{\alpha,i}) \\ \omega \end{pmatrix} \tag{3.13}$$

θ Is the estimated frequency and ζ_i and γ are positive parameters that determine the estimation accuracy and the convergence speed of the ANF. According to the equation (3.13), the in-phase and quadrature components of the input are derived using the proposed ANF, which alleviates the need for extra phase-extraction units, such as PLLs. Other useful information such as the amplitude will also be provided. To apply conventional ANFs to the three-phase power systems, considering the unbalanced conditions and harmonic content of the variables (Three-phase voltages and currents) a high-order nonlinear set of differential equations has to be solved. To simplify this, a reduced-order scheme is proposed for frequency estimation, harmonic extraction and symmetrical component extraction.

3.3.2 Three-Phase Multiple Frequency Estimator

This scheme is a power processor which is developed based on the modified ANF in (3.12) and (3.13). It consists of a frequency estimator, one or more harmonic extractor to estimate the fundamental and harmonic content of the signal and a symmetrical component extractor. Since the equations required for harmonic estimation in three phases are correlated, the reduced order set of the equations has been achieved and therefore they have been incorporated to form a set of inter-related differential equations for three-phase systems. The practical implementation of the derived set of simplified differential equations is represented in Figures 3.20 and 3.21. For a particular set of variables of interest such as a set of three-phase voltages or currents, a frequency estimator has been employed to extract the fundamental frequency of the system. The frequency estimator, as it can be seen in Figure 3.20, incorporates all the harmonic components from all the phases. This is where the modification to the set of the equations has been performed to obtain a set of the equations with reduced order. The amplitude and in-phase and quadrature components of the fundamental and any harmonic component of interest can then be estimated by including one harmonic extractor for each component of interest. The power processor also includes a symmetrical component extractor, which simply performs the necessary mathematical operations on the outputs of the harmonic extractor.

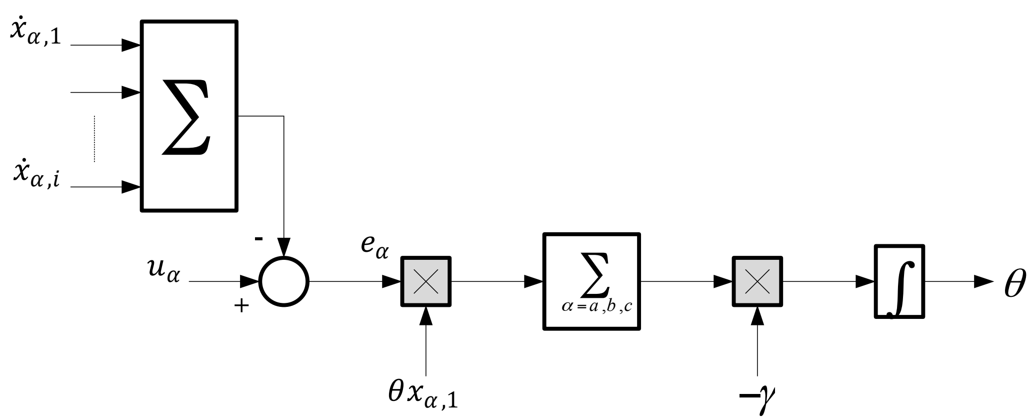

Figure 3.20 Structure of the frequency estimator

Figures 3.20-3.21 are the main blocks of the modified ANF-based power processor, where i is the harmonic order and α represents one of the three-phases a, b or c. And, the harmonic extractor is shown in Figure 3.21.

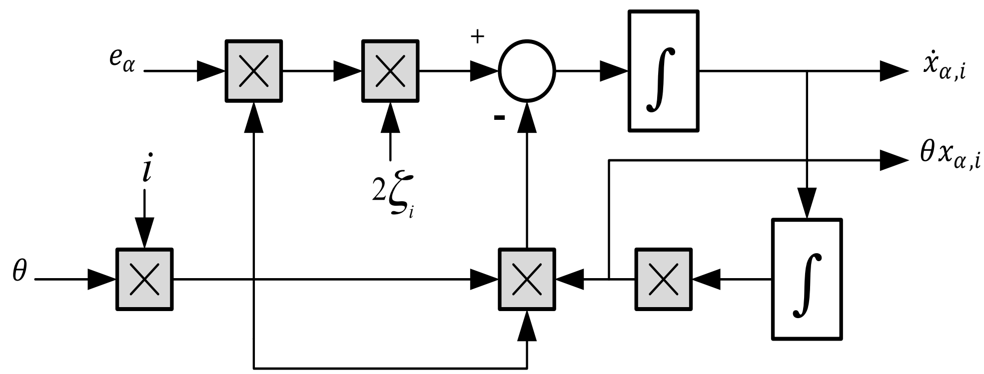

Figure 3.21 Structure of the harmonic extractor

3.4 Summary

In this chapter a single-phase and a three-phase ANF-based synchronization techniques is implemented and simulated in PSCAD for harmonic extraction of the grid signal, which both of them have several applications in power systems such as monitoring, synchronization, power quality and protection.

Compared to the PLL-based method, 1) the ANF-based scheme, since it does not require a voltage-controlled oscillator (VCO), is structurally simpler, 2) contrary to PLL-based methods; the ANF-based structure guarantees a fast and precise extraction of the frequency when the distorted input signal contains low order harmonics.

The three-phase ANF based approach is extended for the extraction of individual harmonics of a load current and was simultaneously evaluated for various load conditions. Also, the capability of the three-phase ANF in simultaneous extraction of individual harmonics and all useful information of a measured signal such as frequency, amplitude, and phase angle were verified. Unique and multi-purpose features of the modified ANF based on power processor technique, as discussed in Chapter 4, can be used for harmonic extraction, grid synchronization, sequence components decomposition, active power filtering, reactive power control, power flow control, voltage regulation, etc. All these, nominate the technique as a simple and powerful “power processor”. The operating principles of such a power signal analyzer are presented in the next chapter.

Chapter 4

Micro-grid Power Quality Enhancement

The modified reduced-order ANF has been discussed in chapter 3 is the main subsystem in the power processor introduced in this chapter. The proposed technique is employed to extract harmonic content and symmetrical components of each harmonic of the voltage and the injected current at the point of common coupling (PCC). Power quality support is one of the benefits of integration of decentralized power generation with the power grid. A digital power processor has been developed to improve the power quality enhancement capabilities of distributed generation systems in smart micro-grids. It has been shown that the proposed technique is suitable for both selective harmonic compensation, and wide range current harmonic compensation. Moreover, the proposed scheme is able to deal with unbalanced harmonic contents, and further diminishes the need for extra phase extraction units such as phase-locked-loops (PLL). The scheme is simpler than PLL-based approaches, and overcomes some weaknesses of the PLL systems such as their suffering from the presence of double-frequency ripples. An analysis of the proposed system is discussed and simulation results are provided to verify the validity of the analytical work.

4.1 Overview of the System Under Study

4.1.1 Power Circuit Configuration

The power circuit diagram of the proposed system is shown in Figure 4.1.

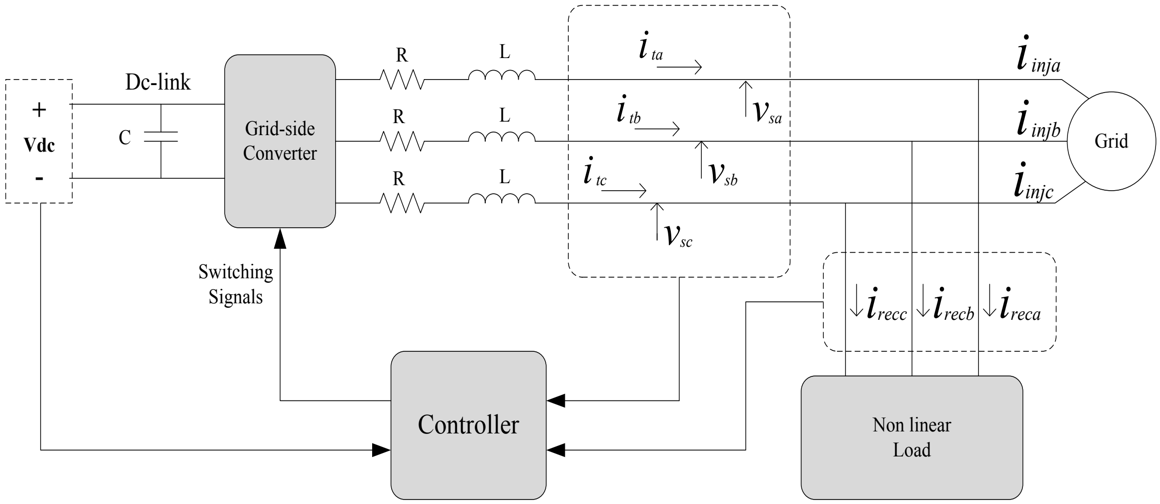

Figure 4.1 Power circuit diagram of the system under study

The structure of this system contains a dc-link connected to the grid-side converter. The power converter is a three-phase six-switch inverter, which is controlled by high frequency switching signals. The power converter in interconnected with the grid through a high frequency RL filter. In this study the DG system and its associated local loads form the micro-grid. For this purpose the local load can be a nonlinear load such as a three-phase rectifier. This rectifier is loaded with resistive-capacitive loads. The network parameters and the associated values are listed in Table 4.1.

Parameter	Value
Grid Voltage	208 v
Grid Frequency	60 Hz
Filter parameters, R	0.001Ω
Filter parameters, L	2.5 mH
DC link voltage	450 v
DC-link capacitor	470 μF
Non linear load	25 Ω
Non linear power	2.8 kw

Table 4.1 Power circuit parameters

4.1.2 Control Scheme Configuration

The purpose of the control scheme is to generate proper switching signal so that the nonlinear loads` current are compensated by the DG unit. Thus the currents injected to the grid contain only a negligible amount of harmonics. The power processor, which was explained previously, is used to derive the harmonic contents of the nonlinear load current. The negative of the low order harmonics then is used to generate reference values for the DG current (i_{acom}). The reference value for the fundamental component is determined using the power generated from the source of the renewable generation unit. The total reference current is then compared to the actual value of the DG current and the error is sent to a hysteresis controller to generate the switching signals. The hysteresis controller can be replaced by a synchronous reference frame control scheme, yet for the sake of brevity, a hysteresis controller is used in this work. Figure 4.2 illustrated the control scheme of the proposed system.

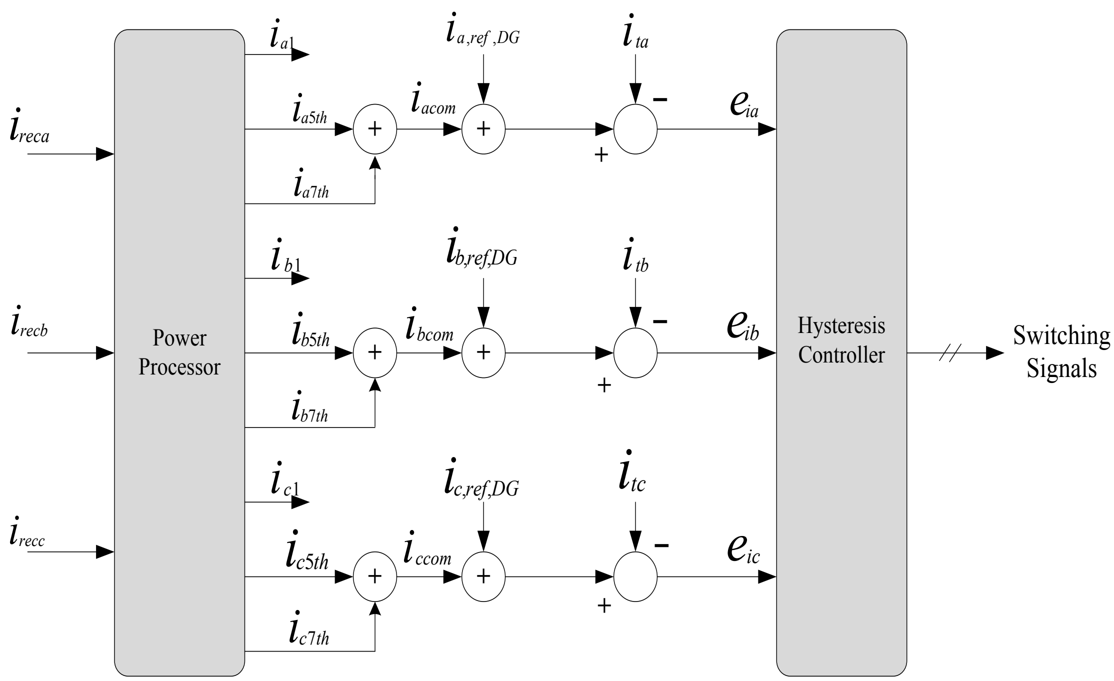

Figure 4.2 Control scheme of the proposed system

4.2 Performance Evaluation of the Proposed Power Processor

The performance of the proposed power processor for extraction of selective harmonics is evaluated by applying a 2.8kW three-phase diode rectifier as a nonlinear load. The three-phase system is a 60Hz 208V system. The goal is to extract the fundamental, 5^{th} and 7^{th} harmonics of the current using the proposed power processor. Then, the extracted harmonic components have been utilized to generate proper current references in the DG unit. The DG therefore compensates for the selected harmonics of the non-linear load.

The nonlinear load absorbs non-sinusoidal currents from the point of common coupling as it illustrated in Figure 4.3.

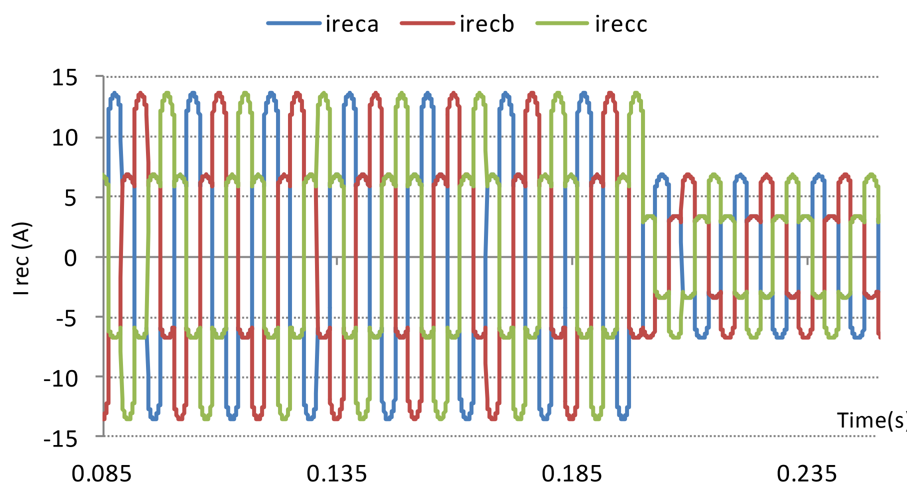

Figure 4.3 Three-phase non-linear load currents (Rectifier Currents)

As a result if the DG unit is not compensating the low-order harmonics, the currents drawn from the grid will contain considerable harmonic content. These currents are shown in Figure 4.4.

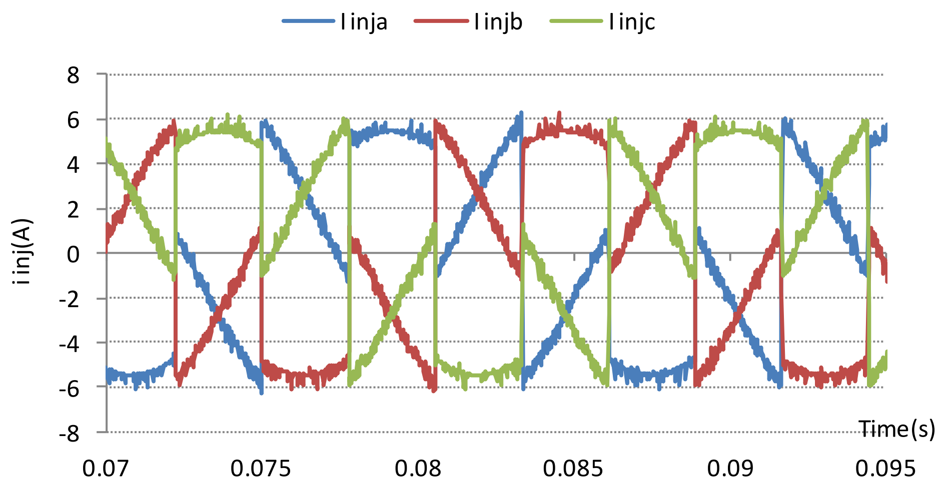

Figure 4.4 Three-phase currents drawn from the grid when the DG unit is not compensating the harmonic content of the nonlinear load

In this simulation the fifth and seventh harmonics of the currents drawn from the grid are extracted by the power processor and compensated by the DG control scheme. In this simulation, the DG unit starts compensation at t= 0.1s.

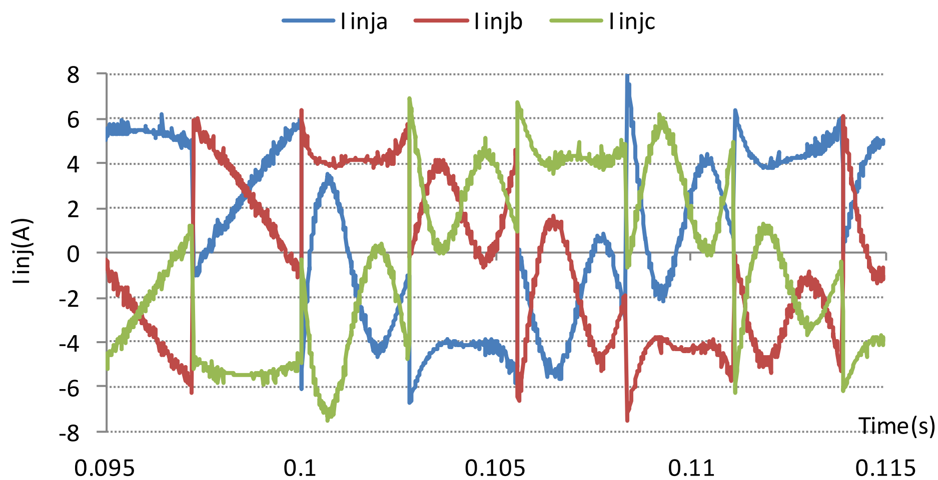

Figure 4.5 Three-phase currents drawn from the grid when the DG unit starts compensation at t=0.1s

As it is shown in Figure 4.6 the compensated currents to the grid are closer to a sinusoidal shape. It means the low order harmonics have been compensated.

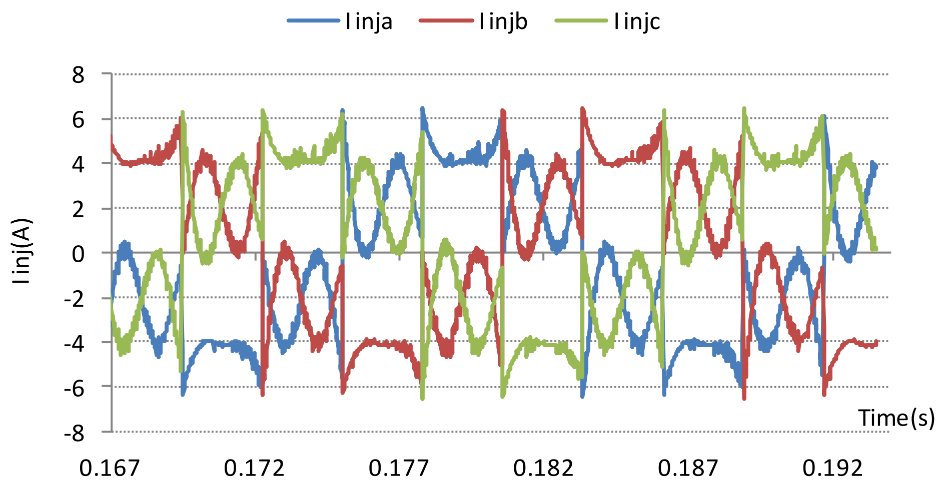

Figure 4.6 Currents drawn from the grid when the DG unit compensates the 5th and 7th harmonics

The harmonic content of the uncompensated and the compensated currents drawn from the grid are illustrated in Figures 4.7 and 4.8 respectively.

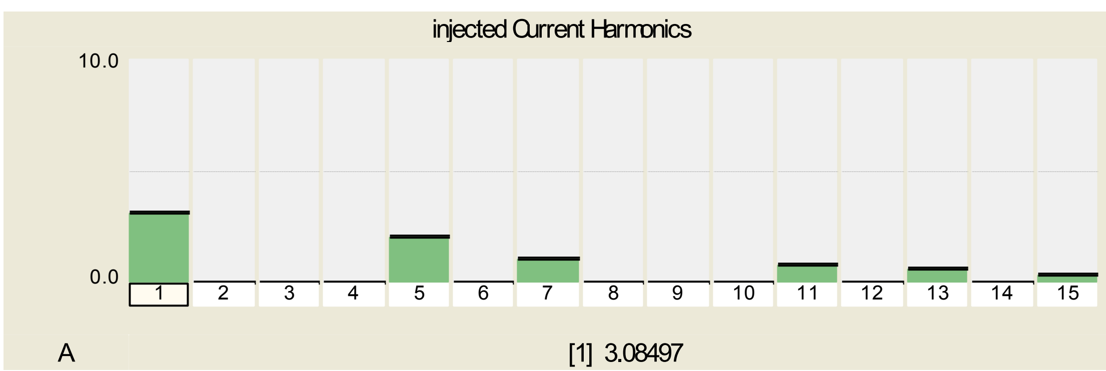

Figure 4.7 Harmonic content of the uncompensated current drawn from the grid

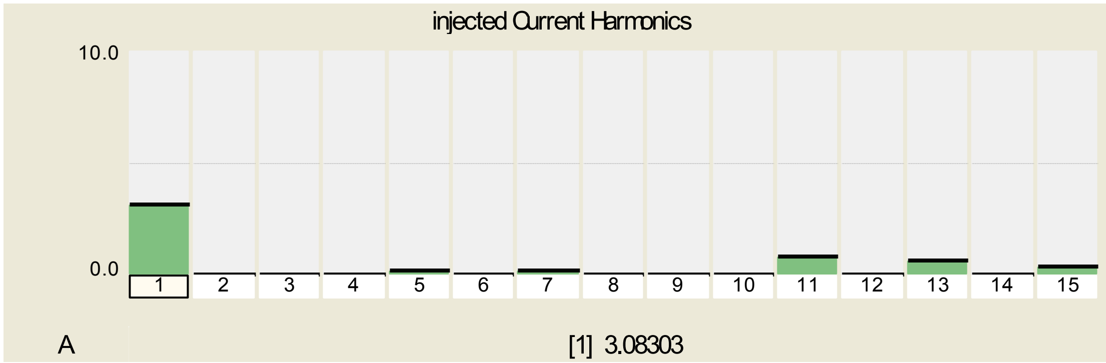

Figure 4.8 Harmonic content of the compensated current drawn from the grid

The performance of the system is evaluated when the nonlinear load is reduced by 50% in a step change. The DG continues to compensate the 5th and 7th harmonics and the resultant current drawn from the grid is illustrated in Figure 4.9.

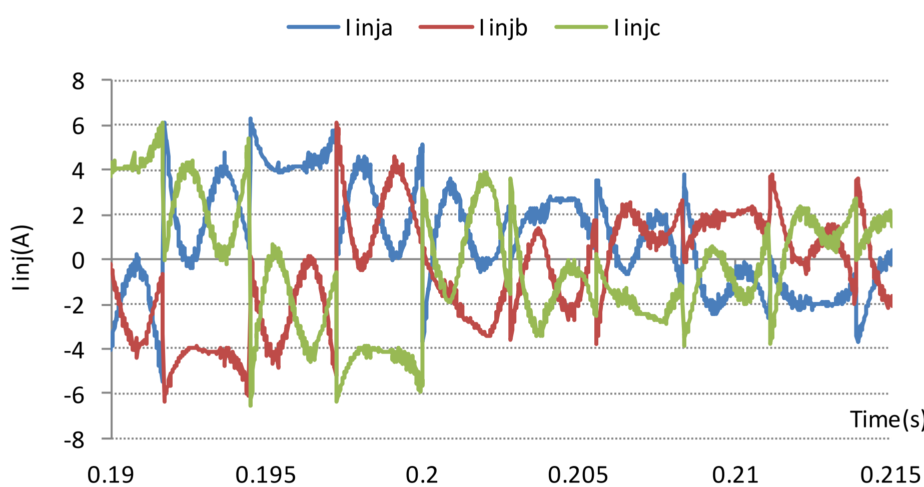

Figure 4.9 Transient response in the current drawn from the grid when the nonlinear load was reduced by 50% at t=0.2 s

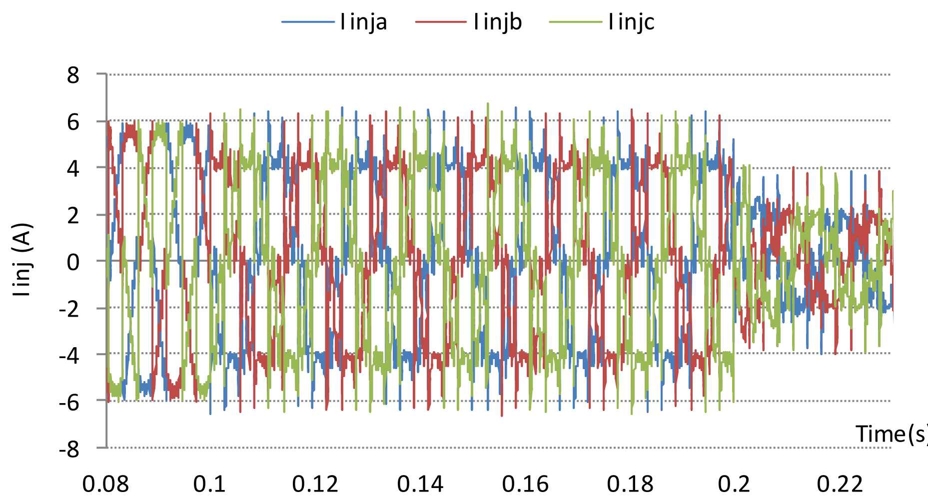

Figure 4.10 Compensated current drawn from the grid when the nonlinear was reduced by 50%

Figure 4.11 illustrated the harmonic content of the current drawn from the grid when the nonlinear load was reduced by 50%. As it was expected the fundamental component was also reduced.

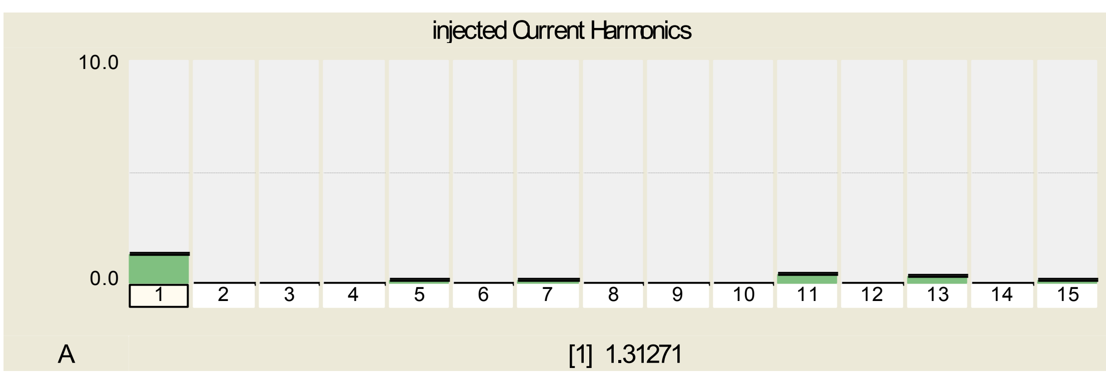

Figure 4.11 Harmonic content of the compensated current drawn from the grid, 50% of nominal load

The DG injected currents will contain low-order harmonics in order to compensate the nonlinear loads currents. So, as it is shown in Figure 4.12 when the compensation starts at t=0.1s the DG injected currents is not purely sinusoidal.

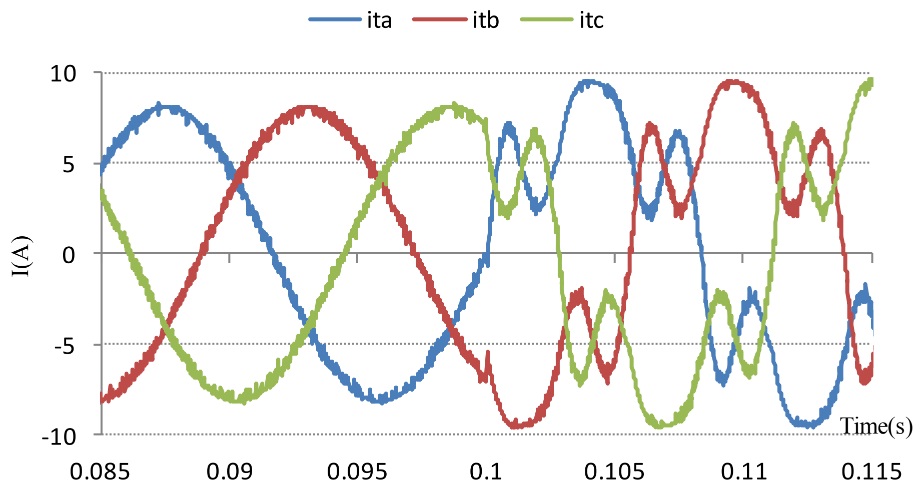

Figure 4.12 DG injected currents before and after the compensation scheme starts at t=0.1s

Upon the load change, only the harmonic content of the DG injected current varies and it is shown in Figure 4.13.

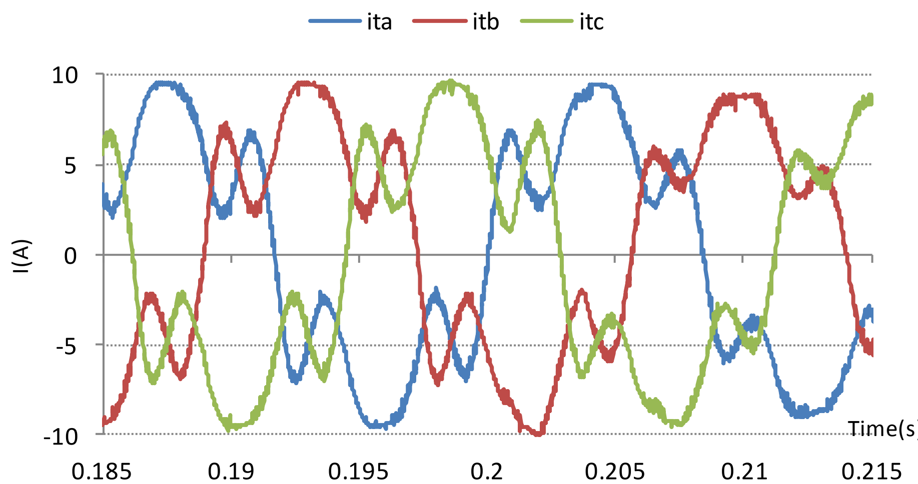

Figure 4.13 The DG currents before and after the load step change at t=0.2s

The harmonic content of the DG injected current when the nonlinear load was reduced by 50% is illustrated in Figures 4.14-4.15 respectively.

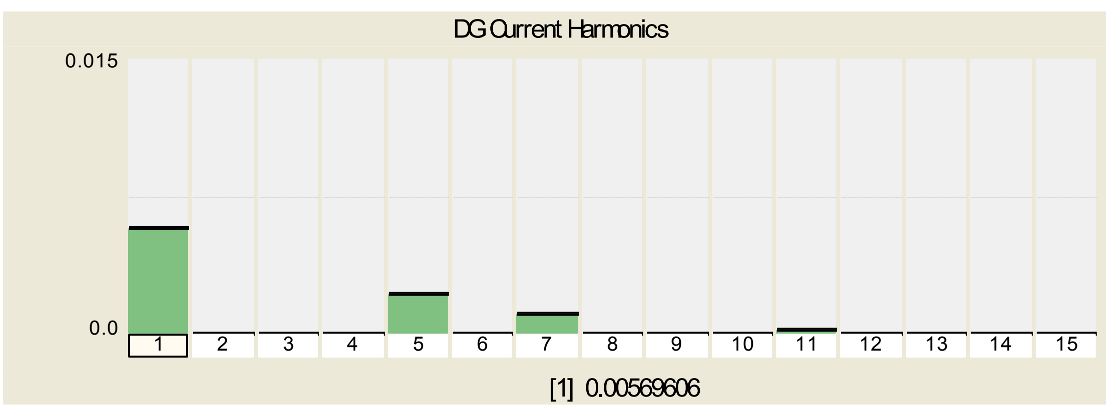

Figure 4.14 Harmonic content of the DG injected currents before the load step change (t=0.188s)

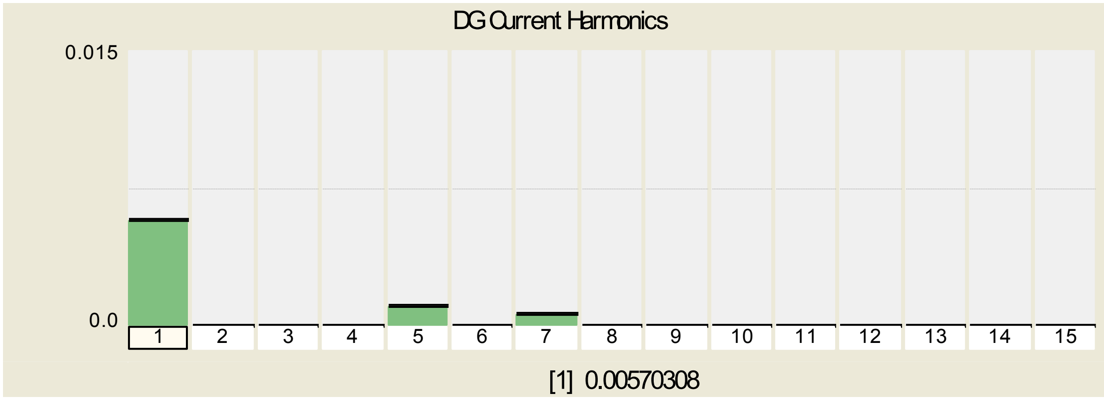

Figure 4.15 Harmonic content of the DG injected currents after the load step change (t=0.262s)

4.3 Summary

In this chapter an ANF-based digital power processor has been used to enhance the power quality capabilities of DG systems in micro-grids. The power processor has been developed based on a modified reduced-order digital adoptive notch filter (ANF) that can potentially motivate much interest in the field and provide solutions for power quality improvements in smart micro-grids. The developed power processor has been employed in the control scheme of a renewable energy DG system.

Mathematical derivations are presented to describe the principles of operation and simulations results are obtained to confirm the validity of the work. The ability of fast and accurate harmonic extraction of the scheme is employed in a DG system to compensate the nonlinear local load current and therefore, the injected current to the grid achieved a higher quality.

Chapter 5

Conclusion

5.1 Summary and Conclusion

As mentioned before, the application of an individual distributed generation system using renewable energy sources may cause some problems and to avoid of this, the distributed generation systems and loads were considered as a subsystem called micro-grid. Since the micro-grid is usually installed in weak grids, it should offer high strength against disturbances. These disturbances might be initiated inside a micro-grid system due to load changes, harmonic disturbances, and interactions between the DG interface and the main network. Therefore, the capability of renewable energy sources to increase the power quality of DG systems in micro-grid is considered as an important issue.

In chapter 2, a quick overview of the existing techniques for power quality enhancement in terms of harmonic compensation was provided. Also, control schemes for harmonic compensation have been discussed.

In chapter 3, a power quality improvement method based on an adaptive notch filter (ANF) has been presented and excellent performance of its application in both single-phase and three-phase is depicted. And in chapter 4, a digital power processor based on a modified reduced-order ANF has been used to compensate for the load harmonic currents.

The ANF-based power processor was employed to extract of harmonic contents of a nonlinear load in a micro-grid. In this research this aforementioned power processor is employed in a closed loop control scheme to enhance the power quality of the micro-grid. This is achieved by proper reference generation in the renewable energy system control scheme to compensate for the harmonics content of the nonlinear local load.

5.2 Contributions

The main contributions of this thesis can be highlighted as follows:

A recently proposed ANF-based power processor that is simple and offers high degree of immunity to power system disturbances and harmonics is investigated in detail and its capability to extract harmonic contents of non-sinusoidal waveforms is highlighted. The most prominent feature of the proposed technique is that the power processor also lightens the need for extra phase extraction units such as phase-locked-loops (PLL). Simulation extraction of harmonics and adjustable accuracy and speed of response are another superior advantages of this proposed technique. It has been shown that the proposed technique is suitable for extraction of selective and/or wide range harmonic content of the injected current and the voltage at the point of common coupling (PCC) and also it has been shown that the proposed technique is appropriate for selective or wide range current harmonic compensation. Extensive simulations show the excellent performance this power processor for power quality enhancements in micro-grids. This powerful feature is employed in a closed loop control system to remove selected load harmonics, and thus enhance the power quality of the micro-grids.

5.3 Suggestions for Future Work

This dissertation has made major contributions to power quality enhancement in micro-grid by employing a digital power processor based on an adaptive notch filter in its control scheme.

However, it has left many open areas to be investigated. Some future research works are presented here:

- Unbalanced harmonic conditions can be further analyzed and compensated by using this technique.
- The impact of unbalanced loads on micro-grid performance.
- Investigating the performance of the power quality enhancement technique for islanded mode operation.

References

[1] N. Jungbluth, M. Stucki, and R. Frischknecht, “Photovoltaics,” *Swiss Centre for Life Cycle Inventories, Dübendorf, CH*, report No. 6-XII, 2009.

[2] F. Blaabjerg, Z. Chen, R. Teodorescu and F. Iov, “Power Electronics in Wind Turbine Systems,” *Power Electronics and Motion Control Conference,* vol.1, no., pp.1-11, 14-16 Aug. 2006.

[3] Bull, S.R., "Renewable energy today and tomorrow," *Proceedings of the IEEE* , vol.89, no.8, pp.1216,1226, Aug 2001.

[4] N. Lior, “Energy resources and use: The present situation and possible paths to the future,” *9th Conference of Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction*, PRES 2006.

[5] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. V. Timbus, “Overview of control and grid synchronization for distributed power generation systems,” *IEEE Trans. Ind. Electron.* vol. 53, no. 5, pp. 1398-1409, Oct. 2006.

[6] J. M. Carrasco, L. G. Franquelo, J. T. Bialasiewicz, E. Galvan, R. C. P. Guisado, M. A. Martin Prats, J. I. Leon and N. M. Alfonso, “Power electronic systems for grid integration of renewable energy sources: a survey,” *IEEE Trans. Industrial Electronics,* vol. 53, no. 4, pp. 1002-1016, Aug. 2006.

[7] F. Blaabjerg, Z. Chen and S.B. Kjaer, “Power electronics as efficient interface in dispersed power generation systems” *IEEE Trans. Power. Electron.* vol. 19, no. 5,pp. 1184-94, Sep. 2004.

[8] B. Kjaer, J. K Pedersen, and F. Blaabjerg, “A review of single-phase grid-connected inverters for photovoltaic modules” *IEEE Trans. On Industry Application*, vol. 41, no. 5,pp. 1292-1306, Sep-Oct. 2005.

[9] R. M. Santos Filho, P. F. Seixas, P. C. Cortizo, L. A. B. Torres, and A. F. Souza, “Comparison of three single-phase PLL algorithms for UPS applications” *IEEE Trans. on Industrial Electronics*, Vol. 55, No. 8, pp. 2923-2932, August 2008.

[10] Z. Chen and E. Spooner, “Grid power quality with variable speed wind turbines,” *Energy Conversion, IEEE Transactions on*, vol.16, no.2, pp.148, 154, Jun. 2001.

[11] M. H. Albadi and E. F. El-Saadany, “Overview of wind power intermittency impacts on power systems,” *Department of Electrical and Computer Engineering, University of Waterloo*, vol. 80, Issue. 6, Pages 627–632, Canada, June. 2010.

[12] A. Timbus, M. Liserre, R. Teodorescu, P. Rodriguez and F. Blaabjerg, “Evaluation of Current Controllers for Distributed Power Generation Systems,” *Power Electronics, IEEE Transactions on*, vol.24, no.3, pp.654,664, March. 2009.

[13] A. V. Timbus, M. Liserre, R. Teodorescu and F. Blaabjerg, “Synchronization methods for three phase distributed power generation systems. An overview and evaluation,” *Proc. IEEE PESC*, pp. 2474-2481, 2005.

[14] M. Prodanovic and T. C. Green, “Control and filter design of three-phase inverters for high power quality grid connection,” *Power Electronics, IEEE Transactions on*, vol.18, no.1, pp.373, 380, Jan. 2003.

[15] M. Kazmierkowski, R. Krishnan and F. Blaabjerg, “Control in Power Electronics, Selected Problems,” New York: Academic, 2002.

[16] J. Svensson, “Synchronisation methods for grid-connected voltage source converters,” *Generation, Transmission and Distribution, IEE Proceedings,* vol.148, no.3, pp.229,235, May. 2001.

[17] H. Kim, S. J. Lee and S. K. Sul, “Reference wave generator in dynamic voltage restorers by use of PQR power theory,” *Proc. IEEE APEC*, vol. 3, pp. 1452–1457. 2004.

[18] S. J. Lee, H. Kim, S. K. Sul and F. Blaabjerg, “A novel control algorithm for static series compensators by use of PQR instantaneous power theory,” *IEEE Trans. Power Electron*, vol. 19, no. 3, pp. 814–827, May. 2004.

[19] L. H. Tey, P. L. So and Y. C. Chu, “Improvement of power quality using adaptive shunt active filter,” *Power Delivery, IEEE Transactions on*, vol.20, no.2, pp.1558,1568, April. 2005.

[20] L. N. Arruda, S. M. Silva and B. Filho, “PLL structures for utility connected systems,” *Proc. IEEE-IAS Annu. Meeting*, vol. 4, pp. 2655–2660. 2001.

[21] M. Karimi-Ghartemani and M. Iravani, “A method for synchronization of power electronic converters in polluted and variable-frequency environments,” *IEEE Trans. Power Syst.*, vol. 19, no. 3, pp. 1263–1270, Aug. 2004.

[22] P. Rodriguez, J. Pou, J. Bergas, J. I. Candela, R. P. Burgos and D. Boroyevich, “Decoupled Double Synchronous Reference Frame PLL for Power Converters Control,” *Power Electronics, IEEE Transactions on* , vol.22, no.2, pp.584,592, March. 2007.

[23] M. C. Benhabib and S. Saadate, “A new robust experimentally validated phase-looked loop for power electronic control,” *EPE J.*, vol. 15, no. 3, pp. 36–48, Aug. 2005.

[24] A. Chaoui, JP. Gaubert, F. Krim and G. Champenos, "PI Controlled Three-phase Shunt Active Power Filter for Power Quality Improvement," *Electric Power components and systems*, vol. 35, issue. 12. 2007.

[25] J. Liang, T. C. Green, G. Weiss, G and Q. C. Zhong, "Evaluation of repetitive control for power quality improvement of distributed generation," *Power Electronics Specialists Conference, pesc 02. IEEE 33rd Annual*, vol.4, no., pp.1803,1808, 2002.

[26] R. Teodorescu, F. Iov and F. Blaabjerg, "Flexible development and test system for 11 kW wind turbine," *Proc. IEEE PESC*, vol. 1, pp. 67–72. 2003.

[27] E. Twining and D. G. Holmes, "Grid current regulation of a three-phase voltage source inverter with an LCL input filter," *IEEE Trans. Power Electron*, vol. 18, no. 3, pp. 888–895, May. 2003.

[28] X. Yuan, W. Merk, H. Stemmler and J. Allmeling, "Stationary-frame generalized integrators for current control of active power filters with zero steady-state error for current harmonics of concern under unbalanced and distorted operating conditions," *IEEE Trans. Ind. Appl.*, vol. 38, no. 2, pp. 523–532, Mar-Apr. 2002.

[29] R. Teodorescu, F. Blaabjerg, U. Borup and M. Liserre, "A new control structure for grid-connected LCL PV inverters with zero steady-state error and selective harmonic compensation," *Proc. IEEE APEC*, vol. 1, pp. 580–586. 2004.

[30] R. Teodorescu and F. Blaabjerg, "Proportional-resonant controllers. A new breed of controllers suitable for grid-connected voltage-source converters," *Proc. OPTIM*, vol. 3, pp. 9–14. 2004.

[31] P. Salmeron and S. P. Litran, "Improvement of the Electric Power Quality Using Series Active and Shunt Passive Filters," *Power Delivery, IEEE Transactions on*, vol.25, no.2, pp.1058,1067, April. 2010.

[32] D. Zmood and D. G. Holmes, "Stationary frame current regulation of PWM inverters with zero steady-state error," *IEEE Trans. Power Electron*, vol. 18, no. 3, pp. 814–822, May. 2003.

[33] M. Ciobotaru, R. Teodorescu and F. Blaabjerg, "Control of single-stage single-phase PV inverter," *Proc. PELINCEC*, CDROM. 2005.

[34] C. Ramos, A. Martins and A. Carvalho, "Current control in the grid connection of the double-output induction generator linked to a variable speed wind turbine," *Proc. IEEE IECON*, vol. 2, pp. 979–984. 2002.

[35] D. Candusso, L. Valero and A. Walter, "Modeling, control and simulation of a fuel cell based power supply system with energy management," *Proc. IEEE IECON*, vol. 2, pp. 1294–1299. 2002.

[36] G. T. Heydt, "Electric power quality: a tutorial introduction," *Computer Applications in Power, IEEE*, vol.11, no.1, pp.15,19, Jan. 1998.

[37] R. D. Henderson and P. J. Rose, "Harmonics: the effects on power quality and transformers," *Industry Applications, IEEE Transactions on*, vol.30, no.3, pp.528, 532, May-Jun. 1994.

[38] J. K. Phipps, J. P. Nelson and P. K. Sen, "Power quality and harmonic distortion on distribution systems," *Industry Applications, IEEE Transactions on*, vol.30, no.2, pp.476, 484, Mar-Apr. 1994.

[39] B. H. Chowdhury, “Power quality,” *Potentials, IEEE*, vol.20, no.2, pp.5, 11, Apr-May. 2001.

[40] F. Gonzalez-Espin, E. Figueres and G. Garcera, “An Adaptive Synchronous-Reference-Frame Phase-Locked Loop for Power Quality Improvement in a Polluted Utility Grid,” *Industrial Electronics, IEEE Transactions on*, vol.59, no.6, pp.2718,2731, June. 2012.

[41] H. Fujita and H. Akagi, “The unified power quality conditioner: the integration of series and shunt-active filters,” *Power Electronics, IEEE Transactions on*, vol.13, no.2, pp.315, 322, Mar .1998.

[42] P. Mattavelli, G. Spiazzi and P. Tenti, “Predictive digital control of power factor preregulators with input voltage estimation using disturbance observers,” *IEEE Trans. Power Electron.*, vol. 20, no. 1, pp. 140–147, Jan. 2005.

[43] S. K. Chung, “Phase-locked loop for grid-connected three-phase power conversion systems,” *Electric Power Applications, IEE Proceedings,* vol.147, no.3, pp.213, 219, May. 2000.

[44] V. Kaura and V. Blasko, “Operation of phase loop system under distorted utility conditions,” *IEEE Trans. Ind. Appl.*, vol. 33, no. 1, pp. 58–63, 1997.

[45] A. V. Timbus, R. Teodorescu, F. Blaabjerg, M. Liserre and P. Rodriguez, “Linear and Nonlinear Control of Distributed Power Generation Systems,” *Industry Applications Conference, 2006. 41st IAS Annual Meeting. Conference Record of the 2006 IEEE* , vol.2, no., pp.1015,1023, 8-12 Oct. 2006.

[46] W. M. Grady and S. Santoso, “Understanding Power System Harmonics,” *IEEE Power Engineering Review*, 2001.

[47] S. M. Halpin, "Comparison of IEEE and IEC harmonic standards," *Power Engineering Society General Meeting, IEEE* , vol., no., pp.2214,2216. Vol. 3, 12-16 June. 2005.

[48] B. Singh, K. Al-Haddad, and A. Chandra, "A review of active filters for power quality improvement," *Industrial Electronics, IEEE Transactions on*, vol.46, no.5, pp.960, 971, Oct. 1999.

[49] K. Lacanette, "A Basic Introduction to Filters Ð Active, Passive, and Switched-Capacitor," *National Semiconductor Application* Note 779, April. 1991.

[50] J. Allmeling, "A control structure for fast harmonics compensation in active filters," *Power Electronics, IEEE Transactions on*, vol.19, no.2, pp.508,514. March. 2004.

[51] *Characteristic of the Utility Interface for Photovoltaic (PV) Systems*, IEC1727, Nov. 2002.

[52] *IEEE Standard for Interconnecting Distributed Resources With Electric Power Systems*, IEEE15471, 2005.

[53] Eltra and Elkraft, *Wind Turbines Connected to Grids With Voltage Below 100 kV*, 2004. [Online]. Available: http://www.eltra.dk.

[54] E.ON-Netz, *Grid Code—High and Extra High Voltage*, 2003, Bayreuth, Germany: E.ON Netz GmbH. Tech. Rep. [Online]. Available:http://www.eon-netz.com/Ressources/downloads/enenarhseng1.pdf

[55] M. Newman, D. Zmood and D. Holmes, "Stationary frame harmonic reference generation for active filter systems," *IEEE Trans. Ind. Appl.*, vol. 38, no. 6, pp. 1591–1599, Nov-Dec. 2002.

[56] F. Z. Peng, H. Akagi and A. Nabae, "A new approach to harmonic compensation in power systems—A combined system of shunt passive and series active filters," *IEEE Trans. Ind. Applicat*, vol. 26, no. 6, pp. 983–990, 1990.

[57] H. Fujita and H. Akagi, "A practical approach to harmonic compensation in power systems—Series connection of passive and active filters," *IEEE Trans. Ind. Applicat.*, vol. 27, no. 6, pp. 1020–1025, 1991.

[58] E. H. Watanabe, "Series active filter for the DC Side of HVDC transmission systems," in *Proc. 1990 Int. Power Electronics Conf.*, pp. 1024–1030. Tokyo, Japan. 1990.

[59] C. Klumpner, M. Liserre and F. Blaabjerg, "Improved control of an active-front-end adjustable speed drive with a small DC-link capacitor under real grid conditions," in *Proc. of PESC'04*, vol. 2, no. 1156-1162, 2004.

[60] L.R. Limongi, R. Bojoi, C. Pica, F. Profumo and A. Tenconi, "Analysis and Comparison of Phase Locked Loop Techniques for Grid Utility Applications," *Proc. IEEE Power Conversion Conference PCC*, pp. 674-681. 2007.

[61] R. I. Bojoi, G. Griva, V. Bostan, M. Guerriero, F. Farina and F. Profumo, "Current control strategy for power conditioners using sinusoidal signal integrators in synchronous reference frame, " *IEEE Trans. Power Electron,* Vol. 20, n. 6, pp. 1402 - 1412. Nov. 2005.

[62] P. Rodriguez, R. Teodorescu, I. Candela, A. V. Timbus, M. Liserre and F. Blaabjerg, "New positive-sequence voltage detector for grid synchronization of power converters under faulty grid conditions, " *Conf. Rec. PESC'06,* 18-22 pp. 1 - 7. June. 2006.

[63] P. Rodríguez, A. Luna, M. Ciobotaru, R. Teodorescu and F. Blaabjerg, “Advanced grid synchronization system for power converters under unbalanced and distorted operating conditions,” *in Proc. IECON,* pp. 5173–5178, 2006.

[64] P. Rodriguez, A. V. Timbus, R. Teodorescu, M. Liserre and F. Blaabjerg, “Flexible Active Power Control of Distributed Power Generation Systems During Grid Faults,” *IEEE Trans. Power. Electron,* vol. 57, no. 5,pp. 2583-2592, Oct. 2007.

[65] A. Yazdani, R. Iravani, “A unified dynamic model and control for the voltage source converter under unbalanced grid conditions,” *IEEE Trans. Power Delivery,* vol. 21, no. 3, pp. 1620-1629, July. 2006.

[66] P. Rodriguez, J. Pou, J. Bergas, I. Candela, R. Burgos and D. Boroyevich, “Decoupled double synchronous reference frame PLL for power converters control,” *IEEE Trans. Power Electron*, vol. 22, no. 2, pp. 584-592, March. 2007.

[67] D. Yazdani, “A New Power Signal Processor For Converter- Interfaced Distributed Generation Systems,” PhD thesis, Department of Electrical and Computer Engineering, Queens University, Kingston, Canada, 2009.

[68] B. Lindgren, “A Power Converter for Photovoltaic Applications,” PhD thesis, Department of Electric Power Engineering, Chalmers University of Technology, Göteborg, Sweden, 2000.

[69] M. Halpin, “IEEE and IEC Harmonic Limits,” *Auburn University*, 21 May. 2007.

[70] M. Mojiri and A. Bakhshai, “An adaptive notch filter for frequency estimation of a periodic signal,” *IEEE Trans. Automat. Control*, vol. 49, no. 2, pp. 314–318, Feb. 2004.

[71] M. Mojiri, M. Karimi-Ghartemani and A. Bakhshai, “Time domain signal analysis using adaptive notch filter,” *IEEE Trans. Signal Processing*, vol. 55, no. 1, pp. 85-93, Jan. 2007.

[72] M. Mojiri and A. Bakhshai, “Estimation of n frequencies using adaptive notch filter,” *IEEE Trans. Circuit and Systems II: Express Briefs*, vol. 54, no. 4, pp. 338-342, April. 2007.

[73] M. Mojiri, M. Karimi-Ghartemani and A. Bakhshai, “Estimation of Power System Frequency Using Adaptive Notch Filter,” *IEEE Transactions on Instrumentation and Measurement,* Vol. 56, No. 6, pp. 2470-2477, Dec. 2007.

[74] D. Yazdani, A. Bakhshai, G. Joos and M. Mojiri, “A nonlinear adaptive synchronization technique for grid-connected distributed energy sources,” *IEEE Trans. Power Electron.,* Vol. 23, no. 4, pp. 2181-2186, July. 2008.

[75] D. Yazdani, A. Bakhshai, G. Joos and M. Mojiri, “A Nonlinear Adaptive Synchronization Technique for Single-Phase Grid-Connected Converters,”*, IEEE Power Electronics Specialists Conference, PESC 2008,* pp. 4076-4079, 2008.

[76] D. Yazdani, A. Bakhshai, G. Joos and M. Mojiri, “A Single-phase Adaptive Synchronization Tool for Grid-Connected Converters,” *IEEE IECON* 2008.

[77] M. Hassanzahraee, “Transient Droop Control Strategy for Parallel Operation of Distributed Energy Resources in an Islanded Microgrid,” Master thesis, Department of Electrical and Computer Engineering, Queens University, Kingston, Canada, 2012.