Application of Backstepping to the Virtual Flux Oriented Control for Three- Phase Shunt Active Power Filter

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Abstract ‒

The present paper proposes to combine the virtual flux oriented control with backstepping control to increase the filtering performance of three-phase shunt active power filter. This work is motivated by the limited ability of the conventional controller to perform effectively the dynamic performance of active filter when load variations or line voltage distortions are considered. The resulting control system based on backstepping approach is aimed to compensate reactive power and harmonic distortion, operate at unit power factor and maintain the DC voltage at the desired level. Computer simulations are presented to confirm the performance and effectiveness of the proposed control strategy.
Keywords: virtual flux oriented control; backstepping control; three-phase shunt active filter; space vector modulation.

INTRODUCTION

The increasing use of power electronic loads in industry and by consumers results in a considerable amount of harmonic injection, and lower power factor [1]. Conventionally, passive filters have been used to eliminate current harmonics and to increase the power factor. However, the use of passive filter has many disadvantages [2]. Recently, because of the rapid progress in modern power electronic technology, the previous works were oriented mostly on the active filters instead of passive filters [3]. The basic difference between passive and active filters is that the active filters have the capability to compensate random varying currents [4].

One of the most popular active filters is the shunt active power filter (SAF). The SAF has been researched and developed, They have gradually been recognized as a feasible solution to the problems created by nonlinear loads. They are used to eliminate the unwanted harmonics and compensate fundamental reactive power consumed by nonlinear loads through injecting the compensation currents into the AC lines. In addition, to eliminatingharmonic currents and improving the power factor, SAF can keep the power system

balance under the condition of unbalanced and nonlinear loads [5, 15]. Various control strategies have been proposed to control the shunt active power filter, such as hysteresis band current control [6], Voltage Oriented Control (VOC) [7], and Direct Power Control (DPC) [7]. Particularly the Voltage Oriented Control guarantees fast transient response and high performance in steady state operatio. However, the VOC uses an internal current control loops and the final performance of the system strongly depends on applied current control techniques [7].

Recent developments have popularized the Virtual Flux (VF) concept, which assumes that both the grid and converter's line filter behave as an AC motor [8]. One of the main advantages of this approach is that it is less sensitive to line-voltage variations than other approaches. The virtual flux oriented control (VFOC) is an adaptation of the VOC to a VF reference frame [8].

To improve the performances of VOC, a nonlinear control strategy based on the backstepping control is proposed. It is well known that the backstepping technique is a control method to eliminate the nonlinearity of the system by using the inverse dynamics [9]. It has been applied to control permanent.
magnet synchronous motor [10], induction motor [11], and linear DC Brushless motor [12], which gives good performances, robustness to disturbances as well as fast transient responses [14].

The backstepping design recursively selects some appropriate functions of state variables as pseudo control inputs for lower dimension subsystems of the overall system. Each backstepping stage results in a new pseudo control design, expressed in terms of the pseudo control designs from preceding design stages. The final control input is derived from final Lyapunov function formed by summing up the Lyapunov functions associated with each individual design stage [9]. This method is a recursive procedure that skill fully interlaces the choice of a

Lyapunov function with the control. Indeed, backstepping control can guarantee global stability, tracking and transient performance for abroad class of strict-feedback systems.

In this paper, a backstepping associated to VFOC is applied to three-phase shunt active filter. It is shown via simulation results that the proposed controller has high performance both in the transient and in the steady state operations. The line currents are very close to sinusoidal waveforms, a good control of the DC-bus voltage is obtained, and unity power factor (UPF) operation is achieved.

2.2 Mathematical model of three-phase PWM inverter

The differential equations describing the dynamic model of the inverter are defined in d-q reference frame, as given in equation (1).

Where, e_{fd} and e_{fq} are voltages of (PCC) in the d, q coordinates, i_{fd} and i_{fq} are the d-q axis AC current of APF, u_{cd} and u_{cq} are the AC side voltages of SAF.

$$\begin{cases} \dfrac{di_{fd}}{dt} = \dfrac{1}{L}(u_{cd} - e_{fd} - Ri_{fd}) - \omega i_{fq} \\ \dfrac{di_{fq}}{dt} = \dfrac{1}{L}(u_{cq} - e_{fq} - Ri_{fq}) + \omega i_{fd} \quad (1) \\ \dfrac{dv_{dc}}{dt} = -\dfrac{e_{fd}i_{fd} + e_{fq}i_{fq}}{Cv_{dc}} \end{cases}$$

3 VFOC-Bacsteppingcontrol

The basic operation of the VFOC-backstepping control method is shown in Fig. 1. The capacitor voltage is compared with its reference value, v_{dcref}, in order to maintain the energy stored in the capacitor constant. The backstepping controller is applied to regulate the error between the capacitor voltage and its reference. The output of backstepping controller presents the reference of reactive current, while the reference active current value is set to zero for unity power factor.

The compensating currents are derived based on instantaneous p-q theory [7], the instantaneous active and reactive power can be computed in terms of transformed current signals and PCC virtual flux estimator [7]. The alternate value of active power is extracted using high-pass filters. The α-β harmonic

components are computed using harmonic active and reactive powers. After that, using reverse α-β transformation, the d-q compensating currents are derived in terms of α-β currents [7]. Then higher harmonics compensating signals $\tilde{i}_{Ld}$ and $\tilde{i}_{Lq}$ are added with an opposite sign to the standard VFOC reference signals $i_{fd\ ref}$ and $i_{fq\ ref}$ as follow:

$$\begin{aligned} i_{d\_err} &= i_{fd\ ref} - \tilde{i}_{Ld} - i_{fd} \\ i_{q\_err} &= i_{fq\ ref} - \tilde{i}_{Lq} - i_{fq} \end{aligned} \quad (2)$$

The output signals from backstepping currents controllers are used for switching signals generation by Space Vector Modulator (SVM) [10].

3.1 Backstepping controller synthesis

From equations (1), it is obvious that the converter is a nonlinear and coupled system. So a nonlinear controller based on the backstepping method is developed in this section.

The system (1) is subdivided in three subsystems as follows:

Subsystem 1:

$$\frac{dv_{dc}}{dt} = -\frac{e_{fd}i_{fd} + e_{fq}i_{fq}}{Cv_{dc}} \quad (3)$$

The first subsystem is characterized by only one state $x = v_{dc}$ and only one control input $u = i_{fq}$.

The equation (3) can be written as follow:

$$\begin{cases} \dot{x}_1 = L_f h_1 + L_g h_1 u \\ y_1 = h_1(x) = v_{dc}, \quad y_{1d} = v_{dcref} \end{cases} \quad (4)$$

Where:

$$x_1 = v_{dc}, \quad u = i_{fq}, \quad L_f h_1 = -\frac{e_{fd}i_{fd}}{Cv_{dc}}, \quad L_g h_1 = -\frac{e_{fq}}{Cv_{dc}}$$

Subsystem 2:

$$\frac{di_{fd}}{dt} = \frac{1}{L}(u_{cd} - e_{fd} - Ri_{fd}) - \omega i_{fq} \quad (5)$$

The second subsystem is also characterized by only one state $x = i_{fd}$ and only one control input $u = u_{cd}$. The equation (5) can also be written as follow:
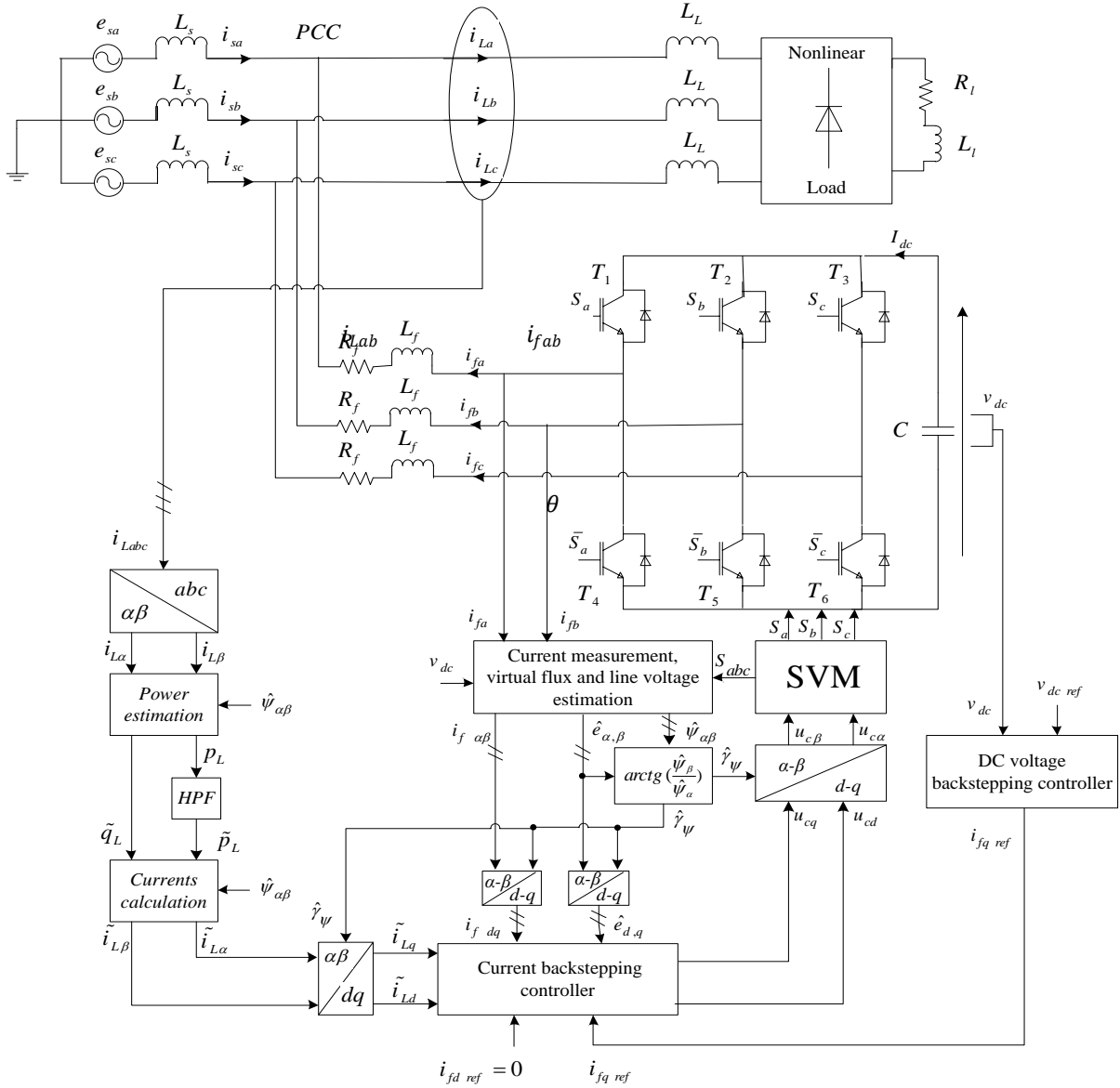
Figure 1 Three phase shunt active power filter with VFOC-backstepping control

$$\begin{cases} \dot{x}_2 = L_f\, h_2 + \bar{u}_{cd} \\ y_2 = h_2 = i_d \end{cases} \quad (6)$$

Where:

$$x_2 = i_{fd}, \quad L_f h_2(x) = -\frac{R}{L} i_{fd} - \omega\, i_{fq} - \frac{1}{L} e_{fd}, \quad \bar{u}_{cd} = \frac{1}{L} u_{cd}$$

Subsystem 3:

$$\frac{di_{fq}}{dt} = \frac{1}{L}(u_{cq} - e_{fq} - R i_{fq}) + \omega i_{fd}$$

The third subsystem is characterized by one state $x = i_{fq}$ and one control input $u = u_{cq}$.

The equation (7) can also be written as follow:

$$\begin{cases} \dot{x}_3 = L_f\, h_3 + \bar{u}_{cq} \\ y_3 = h_3 = i_q \end{cases} \quad (8)$$

Where:

$$x_3 = i_{fq}, \quad L_f h_3(x) = -\frac{R}{L} i_{fq} + \omega\, i_{fd} - \frac{1}{L} e_{fq}, \quad \bar{u}_{cq} = \frac{1}{L} u_{cq}$$

3.1.1 DC voltage controller synthesis

The synthesis of the DC voltage controller is based on the first subsystem.

The first tracking error is defined as:

$$z_1 = x_1 - y_{1d} \quad (9)$$

Its derivative is:

$$\dot{z}_1 = L_f h_1 + L_g h_1 u - \dot{y}_{1d} \quad (10)$$

The Lyapunov function is chosen as:

$$V_1 = \frac{1}{2} z_1^2 \quad (11)$$

The derivative of (11) is given by:

$$\dot{V}_1 = z_1 \dot{z}_1 = z_1 (L_f h_1 + L_g h_1 u - \dot{y}_{1d}) \quad (12)$$

The current component $i_{q\,ref}$ represent the control law of the first subsystem. It is selected such as the Lyapunov function $\dot{V}_1$ should be definite negative [13], as follow:

$$i_{fq\,ref} = \frac{-k_1 z_1 - L_f h_1 + y_{1d}}{L_g h_1} \quad (13)$$

Where: k_1 is positive constant.

3.1.2 Current controller synthesis

The active and reactive power can be indirectly controlled via the control of the both outputs $y_2 = i_{fd}$ and $y_3 = i_{fq}$. To achieve unity power factor operation, the active current command is set to zero. The active current command is delivered from the outer DC voltage controller (13).

The errors z_2 and z_3 are defined as:

$$\begin{cases} z_2 = x_2 - y_{2d} \\ z_3 = x_3 - y_{3d} \end{cases} \quad (14)$$

The Lyapunov functions are given by the following expression: $\begin{cases} V_2 = \dfrac{1}{2} z_2^2 \\ V_3 = \dfrac{1}{2} z_3^2 \end{cases} \quad (15)$

And consequently, their derivatives are given by:

$$\begin{cases} \dot{V}_2 = z_2 \dot{z}_2 = z_2 (L_f h_2 + \bar{u}_{cd} - \dot{y}_{2d}) \\ \dot{V}_3 = z_3 \dot{z}_3 = z_3 (L_f h_3 + \bar{u}_{cq} - \dot{y}_{3d}) \end{cases} \quad (16)$$

To make $\dot{V}_2 < 0$ and $\dot{V}_3 < 0$, [13] we must choose:

$$\begin{cases} \bar{u}_{cd} = -k_2 z_2 - L_f h_2 + \dot{y}_{2d} \\ \bar{u}_{cq} = -k_3 z_3 - L_f h_3 + \dot{y}_{3d} \end{cases} \quad (17)$$

Where: k_2 and k_3 are positive constants.

We also have:

$$\begin{bmatrix} \bar{u}_{cd} \\ \bar{u}_{cq} \end{bmatrix} = D \begin{bmatrix} u_{cd} \\ u_{cq} \end{bmatrix} \quad (18)$$

Where:

$$D = \begin{bmatrix} \dfrac{1}{L} & 0 \\ 0 & \dfrac{1}{L} \end{bmatrix}$$

The D matrix determinant is different to zero, and then the control law is given as:

$$\begin{bmatrix} u_{cd} \\ u_{cq} \end{bmatrix} = D^{-1} \begin{bmatrix} \bar{u}_{cd} \\ \bar{u}_{cq} \end{bmatrix} \quad (19)$$

4 Simulation results

To verify the validity of the proposed controller, the SAF system was simulated the parameters given in Table I.

The goal of the simulation is to examine the capability of the controller to fulfill the following three different aspects.

a) Current harmonic compensation
b) Dynamic response performance
c) Distorted grid phase voltage

Table I

System parameters

RMS value of phase voltage	220 V
DC-link capacitor C	4.5 mF
Source impedance R_s, L_s	100 mΩ, 10 mH
Filter impedance R_f, L_f	100 mΩ, 10 mH
Line impedance R_l, L_l	100 mΩ, 10 mH
DC-link voltage reference$v_{dc\,ref}$	600 V
Diode rectifier load R_l, L_l	200 Ω, 1mH
Switching frequency f_s	10kHz
Sampling frequency	200kHz
k_1, k_2, k_3 constants	100, 2.10^5, 2.10^5

4.1 Currentharmonic compensation

The AC supply current of the first phase and its harmonic spectrum before and after compensation are illustrated in Figs. 2, 3 and 4. It results that the active filter decreases the total harmonic distortion (THD) in the supply currents from 27.73% to 3.78% with PI controller. However, with backstepping controller, the THD is increased to 1.50% which proves the effectiveness of the proposed nonlinear controller.

(b) Fundamental (50Hz) = 2.758 , THD= 27.73%
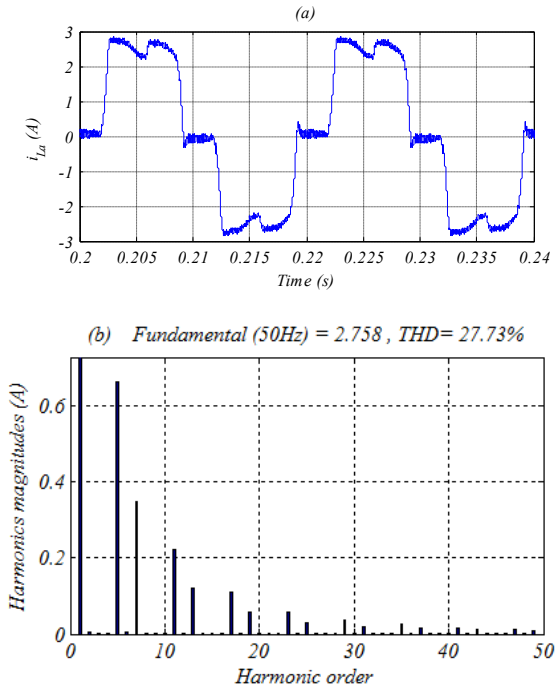
Figure 2

(a) Supply current before harmonics compensation, (b) its harmonic spectrum

(b) Fundamental (50Hz) = 2.793 , THD= 1.50%
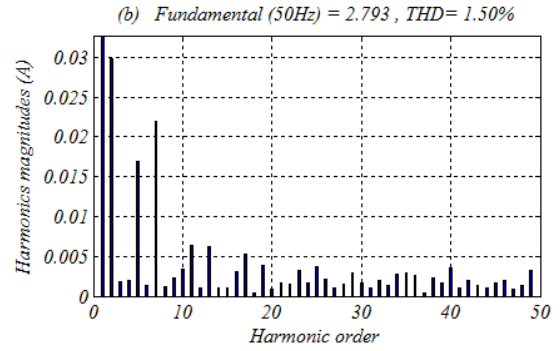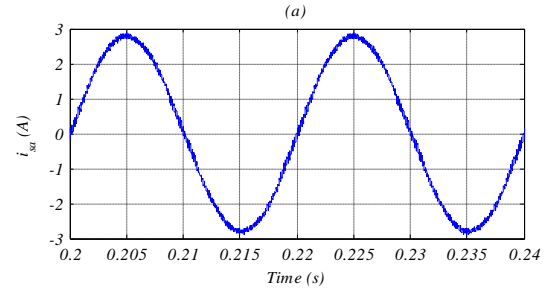
Figure 3

(a) Supply current after harmonics compensation, (b) its harmonic spectrum
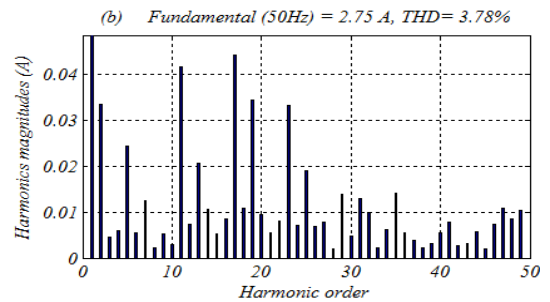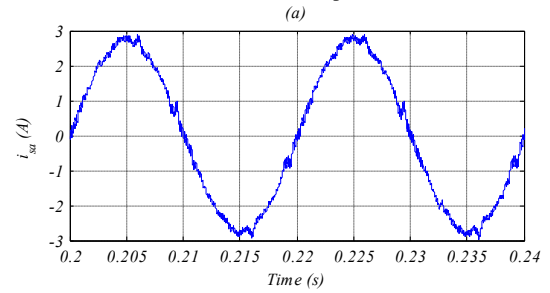

(b) Fundamental (50Hz) = 2.75 A, THD= 3.78%

Figure 4(a) Supply current after harmonics compensation, (b) its harmonic spectrum with PI controller

4.1 Dynamicresponse performance

In this section, the performance of the backstepping controller is analyzed under 100% step charge in the load resistance at t = 0.5s.
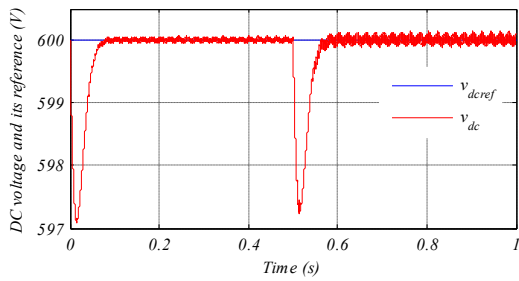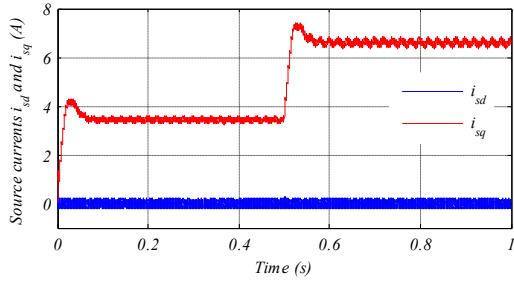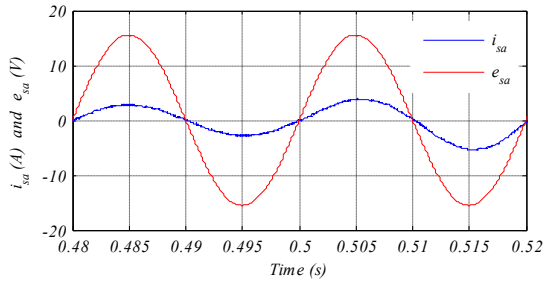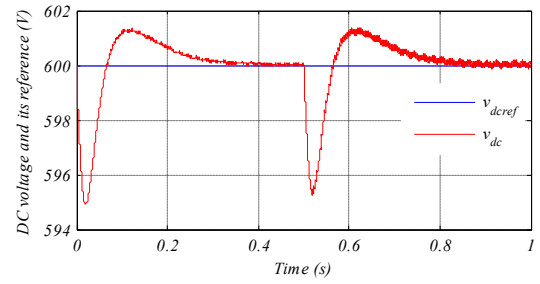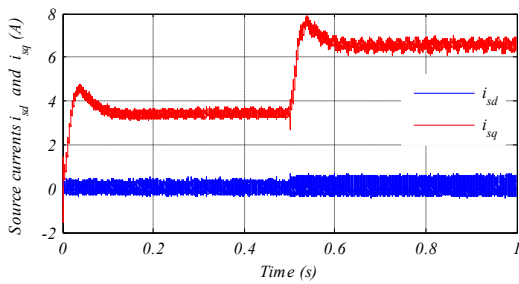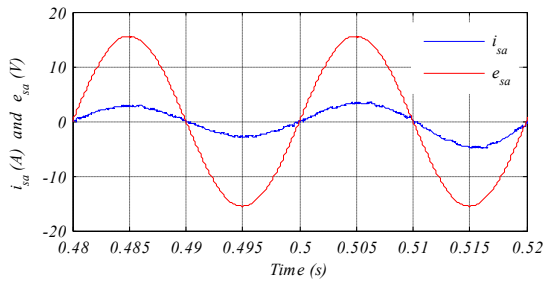
Figure 6

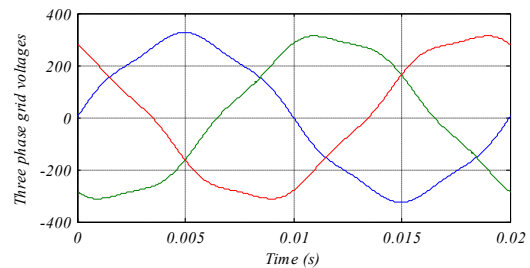Simulation results of VFOC with PI controller

The dynamic behavior under a step change of the load is presented in Figs. 5 and 6. It can be observed that the unity power factor operation is successfully achieved, even in this transient state. Notice that, after a short transient, the dc-bus voltage and reactive current are maintained close to their reference values and the active current is maintained zero.

The absence of an overshoot in DC voltage response during load change, and low current ripples, as shown in Fig. 5, demonstrates the superiority of the backstepping controller compared to its counterpart traditional PI controller.

4.1 Distortedgrid phase voltage

In this case, the grid voltage is polluted with 5% of the 5th harmonic.

The main characteristic of the proposed VFOC-backstepping method is the orientation of the line current vector towards the virtual PCC flux vector instead of the PCC voltage vector. Hence, the three-phase grid currents are nearly sinusoidal shaps (THD = 2.69%) and unity power factor operation is successfully achieved even in existence of the distorted grid voltages as shown in Fig. 7.
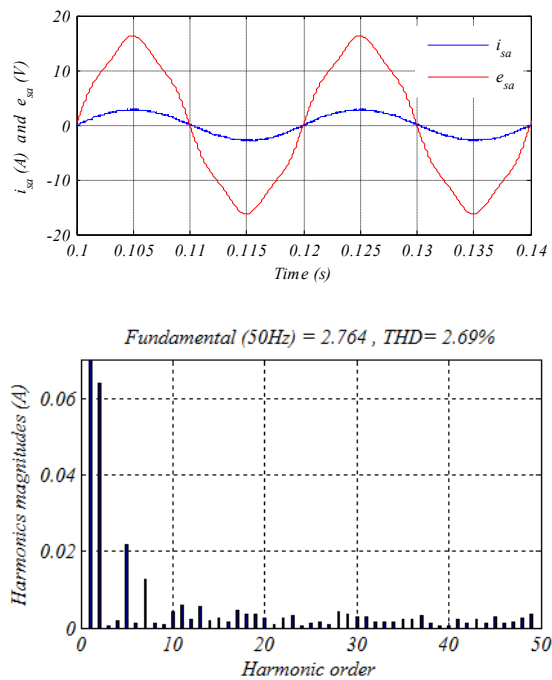
Figure 5

Simulation results of proposed VFOC-backstepping control

Figure 7

Simulation results of proposed VFOC-backstepping control with distorted grid phase voltage

5 Conclusion

This paper presents the design of virtual flux oriented control using backstepping approach for three-phase shunt active filter. The main characteristic of the proposed control method is the orientation of line filter current vector toward the PCC virtual flux vector instead of PCC voltage vector. This manner to proceed increases the robustness of active filter control system to grid voltages distortions. Simulation results show that the proposed active filter system can compensate effectively both harmonic currents and reactive power of nonlinear load. Furthermore, its performance is not much affected by the distortion of the supply. Thus, the proposed SAF system is found effective to meet IEEE 519 recommended harmonic standard limits.

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