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Advanced nonlinear control of three phase series active power filter

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Abstract. The problem of controlling three-phase series active power filter (TPSAPF) is addressed in this paper in presence of the perturbations in the voltages of the electrical supply network. The control objective of the TPSAPF is twofold: (i) compensation of all voltage perturbations (voltage harmonics, voltage unbalance and voltage sags), (ii) regulation of the DC bus voltage of the inverter. A controller formed by two nonlinear regulators is designed, using the Backstepping technique, to provide the above compensation. The regulation of the DC bus voltage of the inverter is ensured by the use of a diode bridge rectifier which its output is in parallel with the DC bus capacitor. The Analysis of controller performances is illustrated by numerical simulation in Matlab/Simulink environment.

1 Introduction

The harmonic contamination is a harmful problem in Electric Power System. Indeed, the increasing use of rectifiers, thyristor power converters, UPS (Uninterruptible Power Supply), switching power supplies and other nonlinear loads are known to cause serious problems in electric power systems. These devices are responsible for the contamination of the line currents with the harmonics of various orders. The harmonics of the current circulating through the line impedance produce distortion in the voltages of power system. Indeed, the distortion, the unbalance and sags of the power system voltages cause several power quality problems, including the incorrect operation of some sensitive loads [1]. The TPSAPF's are an appropriate solution to protect the sensitive load against voltage perturbations.

In most papers, the researchers often use, for the control of the TPSAPF, the method of the instantaneous power [2]. In this paper, the work focuses on the advanced nonlinear control of three-phase series active power filter in the presence of disturbances in the power system voltages by using a method based on the calculation of the references of the series voltages. A controller that is formed by two nonlinear regulators is designed, using the Backstepping technique, to ensure compensation of voltage perturbations (voltage harmonics, voltage unbalances and voltage sags) at the terminals of the sensitive loads. The regulation of DC bus voltage of the inverter is provided by the use of a diode bridge rectifier which its output is connected in parallel with the DC bus capacitor. This theoretical result is confirmed by numerical simulation.

The paper is organized as follows: the system includes the electric network and the DC/AC converter is modeled in Section 2, the control problem is formulated in Section 3 which also includes the design. Performances of controller are illustrated by simulation in Section 4. A general conclusion ends the paper.

2 Series active power filter

2.1 Series active power filter topology

Three-phase series active power filter under study has the structure of figure 1. In the AC side, the TPSAPF is inserted between the perturbed voltage source and a sensitive load, a second order $\left(R_f,\ L_f,\ C_f\right)$ passive output filter used to connect the inverter to grid through voltages injected by three current transformers. In the DC side it has a capacitor of energy storage C_{dc}. The circuit operates according to the well known Pulse Width Modulation principle (PWM) [3,4,5]. The switching function μ_i of the inverter is defined by:

$$\mu_i = \begin{cases} +1 & \text{if } S_i \text{ is ON and } S_{i+3} \text{ is OFF} \\ -1 & \text{if } S_i \text{ is OFF and } S_{i+3} \text{ is ON} \end{cases} \quad (\text{for } i = 1,2,3)$$

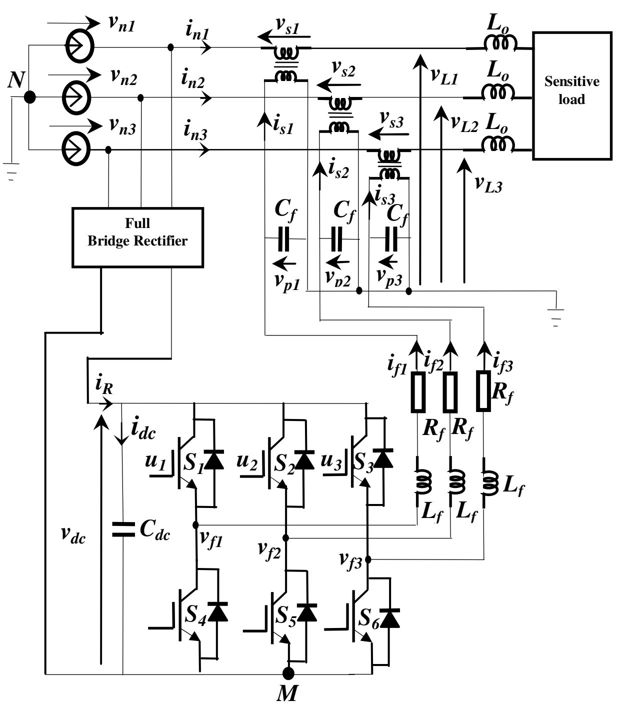

Fig. 1. Three- phase series active power filter.

2.2 Series active power filter modeling

The average model of the TPSAPF in dq frame is the following:

$$\frac{d}{dt}\begin{pmatrix} x_{sd} \\ x_{sq} \end{pmatrix} = \begin{pmatrix} 0 & \omega \\ -\omega & 0 \end{pmatrix}\begin{pmatrix} x_{sd} \\ x_{sq} \end{pmatrix} + \frac{m_s}{C_f}\begin{pmatrix} x_{fd} \\ x_{fq} \end{pmatrix} + \frac{m_s^2}{C_f}\begin{pmatrix} i_{nd} \\ i_{nq} \end{pmatrix} \quad \text{(1a)}$$

$$\frac{d}{dt}\begin{pmatrix} x_{fd} \\ x_{fq} \end{pmatrix} = \begin{pmatrix} -R_f/L_f & \omega \\ -\omega & -R_f/L_f \end{pmatrix}\begin{pmatrix} x_{fd} \\ x_{fq} \end{pmatrix} + \frac{x_{dc}}{2L_f}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}\begin{pmatrix} u_d \\ u_q \end{pmatrix} - \frac{1}{m_s L_f}\begin{pmatrix} x_{sd} \\ x_{sq} \end{pmatrix} \quad \text{(1b)}$$

$$\frac{dx_{dc}}{dt} = \frac{1}{C_{dc}}\left(i_R - \frac{1}{2}\left(u_d x_{fd} + u_q x_{fq} \right) \right) \quad \text{(1c)}$$

where x_{sd}, x_{sq}, x_{fd}, x_{fq}, x_{dc}, u_d and u_q respectively denote the average values over cutting periods of the signals v_{sd}, v_{sq}, i_{fd}, i_{fq}, v_{dc}, μ_d and μ_q. m_s is the transformation ratio of current transformers

3 Controller design

The controller synthesis is carried out by two stages. First, a voltage loop is designed to compensate all voltage perturbations. Second, a diode bridge rectifier is used to ensure the regulation of DC bus voltage.

3.1 Voltages series loop design

In order to compensate the voltage disturbances in the power system, the voltages v_{s1}, v_{s2} and v_{s3} injected by three-phase series active power filter should respectively follow their references v_{s1}^*, v_{s2}^* and v_{s3}^* which are defined by:

$$\left[v_{s123} \right] \longrightarrow \left[v_{s123} \right]^* = \left[v_{n123} \right] - \left[v_{L123} \right]^* \quad (2)$$

where the voltages v_{L1}, v_{L2} and v_{L3} at the terminals of the load must be sinusoidal and form a balanced three-phase system. Expressing the references voltages from equation (2) in the dq frame, it comes:

$$\begin{pmatrix} x_{sd}^* \\ x_{sq}^* \end{pmatrix} = \begin{pmatrix} v_{nd} \\ v_{nq} \end{pmatrix} - \begin{pmatrix} v_{Ld}^* = \sqrt{3/2}E\, sin(\omega t - \theta) \\ v_{Lq}^* = -\sqrt{3/2}E\, cos(\omega t - \theta) \end{pmatrix} \quad (3)$$

To force the voltages x_{sd} and x_{sq} in order to respectively follow the references x_{sd}^* and x_{sq}^*, a controller formed by two nonlinear regulators, using the Backstepping technique [6], is proposed in the follow:

Step 1 Stabilization of the subsystem $e_1 = \begin{pmatrix} e_{1d} \\ e_{1q} \end{pmatrix}$

Let's introduce the tracking error e_1

$$e_1 = \begin{pmatrix} e_{1d} \\ e_{1q} \end{pmatrix} = \begin{pmatrix} x_{sd} - x_{sd}^* \\ x_{sq} - x_{sq}^* \end{pmatrix} \quad (4)$$

Given (1a), the time derivative of error e_1 is:

$$\begin{pmatrix} \dot{e}_{1d} \\ \dot{e}_{1q} \end{pmatrix} = \begin{pmatrix} \omega x_{sq} + \left(m_s x_{fd} \right)/C_f + \left(m_s^2 i_{nd} \right)/C_f - \dot{x}_{sd}^* \\ -\omega x_{sd} + \left(m_s x_{fq} \right)/C_f + \left(m_s^2 i_{nq} \right)/C_f - \dot{x}_{sq}^* \end{pmatrix} \quad (5)$$

Introduce the candidate Lyapunov function

$$V_1 = \frac{1}{2} e_1^T e_1 = \frac{1}{2}\left(e_{1d}^2 + e_{1q}^2 \right) \quad (6)$$

Its dynamic is given by:

$$\dot{V}_1 = \dot{e}_{1d} e_{1d} + \dot{e}_{1q} e_{1q} \quad (7)$$

The choice $\dot{V}_1 = -c_{1d} e_{1d}^2 - c_{1q} e_{1q}^2$ ensuring the asymptotic stability of (5) with respect to the Lyapunov function (6) where $c_{1d} \succ 0$ and $c_{1q} \succ 0$ are a design parameters. Indeed, this choice would imply:

$$\begin{pmatrix} \dot{e}_{1d} \\ \dot{e}_{1q} \end{pmatrix} = \begin{pmatrix} -c_{1d} e_{1d} \\ -c_{1q} e_{1q} \end{pmatrix} = \begin{pmatrix} \omega x_{sq} + \left(m_s x_{fd} \right)/C_f + \left(m_s^2 i_{nd} \right)/C_f - \dot{x}_{sd}^* \\ -\omega x_{sd} + \left(m_s x_{fq} \right)/C_f + \left(m_s^2 i_{nq} \right)/C_f - \dot{x}_{sq}^* \end{pmatrix} \quad (8)$$

If we consider that $m_s x_{fd}/C_f$ and $m_s x_{fq}/C_f$ are, respectively, the actual commands in the preceding equation (8), then the error $e_1 = \begin{pmatrix} e_{1d} \\ e_{1q} \end{pmatrix}$ will be regulated to zero if:

$$\begin{pmatrix} m_s x_{fd}/C_f \\ m_s x_{fq}/C_f \end{pmatrix} = \begin{pmatrix} \sigma_d \\ \sigma_q \end{pmatrix} \tag{9}$$

where $\begin{pmatrix} \sigma_d \\ \sigma_q \end{pmatrix}$ are the stabilizing functions defined by:

$$\begin{pmatrix} \sigma_d \\ \sigma_q \end{pmatrix} = \begin{pmatrix} -c_{1d}e_{1d} - \omega x_{sq} - \left(m_s^2 i_{nd}\right)/C_f + \dot{x}_{sd}^* \\ -c_{1q}e_{1q} + \omega x_{sd} - \left(m_s^2 i_{nq}\right)/C_f + \dot{x}_{sq}^* \end{pmatrix} \tag{10}$$

As $m_s x_{fd}/C_f$ and $m_s x_{fq}/C_f$ are not the actual controls, then new variable error $e_2 = \begin{pmatrix} e_{2d} \\ e_{2q} \end{pmatrix}$ between the virtual controls and their desired values $\begin{pmatrix} \sigma_d \\ \sigma_q \end{pmatrix}$ are defined as follow:

$$e_2 = \begin{pmatrix} e_{2d} \\ e_{2q} \end{pmatrix} = \begin{pmatrix} m_s x_{fd}/C_f - \sigma_d \\ m_s x_{fq}/C_f - \sigma_q \end{pmatrix} \tag{11}$$

Then, by using (10) and (11), equation (5) becomes:

$$\begin{pmatrix} \dot{e}_{1d} \\ \dot{e}_{1q} \end{pmatrix} = \begin{pmatrix} -c_{1d}e_{1d} + e_{2d} \\ -c_{1q}e_{1q} + e_{2q} \end{pmatrix} \tag{12}$$

Thereafter, the derivative of equation (6) becomes:

$$\dot{V}_1 = -c_{1d}e_{1d}^2 - c_{1q}e_{1q}^2 + e_{1d}e_{2d} + e_{1q}e_{2q} \tag{13}$$

end of step 1.

Step 2 Stabilization of the subsystem (e_1, e_2)

To achieve the above objective, the controller forcing the errors (e_1, e_2) to tend to zero, one needs the dynamics of $e_2 = \begin{pmatrix} e_{2d} \\ e_{2q} \end{pmatrix}$. We derive (11), using (1b) we obtain:

$$\begin{pmatrix} \dot{e}_{2d} \\ \dot{e}_{2q} \end{pmatrix} = \begin{pmatrix} -\dfrac{m_s R_f}{C_f L_f} x_{fd} + \dfrac{m_s \omega}{C_f} x_{fq} + \dfrac{m_s x_{dc}}{2C_f L_f} u_d - \dfrac{1}{C_f L_f} x_{sd} - \dot{\sigma}_d \\ -\dfrac{m_s \omega}{C_f} x_{fd} - \dfrac{m_s R_f}{C_f L_f} x_{fq} + \dfrac{m_s x_{dc}}{2C_f L_f} u_q - \dfrac{1}{C_f L_f} x_{sq} - \dot{\sigma}_q \end{pmatrix} \tag{14}$$

Introduce the candidate Lyapunov function

$$V_2 = V_1 + \frac{1}{2} e_2^T e_2 \tag{15}$$

The derivative of (15) is obtained by using (13):

$$\dot{V}_2 = -c_{1d}e_{1d}^2 - c_{1q}e_{1q}^2 + e_{2d}\left(e_{1d} + \dot{e}_{2d}\right) + e_{2q}\left(e_{1q} + \dot{e}_{2q}\right) \tag{16}$$

To ensure the negativity of $\dot{V}_2$, it is necessary that:

$$\begin{pmatrix} \dot{e}_{2d} \\ \dot{e}_{2q} \end{pmatrix} = \begin{pmatrix} -e_{1d} - c_{2d}e_{2d} \\ -e_{1q} - c_{2q}e_{2q} \end{pmatrix} \tag{17}$$

where $c_{2d} \succ 0$ and $c_{2q} \succ 0$ are a design parameters then,

From the equations (14) and (17) we deduce the expressions of the laws of actual control in the dq reference

$$\begin{pmatrix} u_d \\ u_q \end{pmatrix} = \frac{1}{x_{dc}} \begin{pmatrix} \dfrac{2L_f C_f}{m_s}\left(-e_{1d} - c_{2d}e_{2d} + \dot{\sigma}_d\right) + 2R_f x_{fd} - 2L_f \omega x_{fq} + \dfrac{2}{m_s} x_{sd} \\ \dfrac{2L_f C_f}{m_s}\left(-e_{1q} - c_{2q}e_{2q} + \dot{\sigma}_q\right) + 2R_f x_{fq} + 2L_f \omega x_{fd} + \dfrac{2}{m_s} x_{sq} \end{pmatrix} \tag{18}$$

3.2 Voltage of DC bus loop design

The regulation of the DC bus voltage is provided by the use of a full bridge rectifier which its output is connected in parallel with the capacitor of the DC bus. The voltage v_{dc} of the DC bus is regulated to the average value of the output voltage of the rectifier bridge: $U_{moy} = 3\sqrt{3}E/\pi$.

4 Numerical simulations

In order to simulate the behavior of the three-phase series active power filter shown in figure 1, the chosen nonlinear load is a three-phase bridge rectifier which supplies an inductive load comprising a resistor R_L and an inductor L_L. The coil L_o is inserted to the input of three-phase bridge rectifier to limit the $di_{nk}/dt \quad k \in \{1,2,3\}$.

The performances of the proposed controller are now numerically evaluated with the following characteristics:

Table 1. Parameters simulation values

Parameters	Symbol	Value
Network	E, f	$220\sqrt{2}\ V, 50\,Hz$
DC bus	C_{dc}	$9000\,\mu F$
TPSAPF	R_f, L_f, C_f	$80m\Omega, 3mH, 1200\mu F$
Rectifier	R_L, L_L, L_o	$20\Omega, 500mH, 5mH$
Voltages regulators	$c_{1d} = c_{2d}$ $c_{1q} = c_{2q}$	$3000\ s^{-1}$ $6000\ s^{-1}$

4.1 Voltage harmonics compensation

The three-phase source voltages are balanced but contain the 5th and 7th harmonic components. Their expressions are given by:

$$v_{n1}(t) = E_1 Sin(\omega_n t) - E_5 Sin(5\omega_n t) + E_7 Sin(7\omega_n t)$$

$$v_{n2}(t) = E_1 Sin\left(\omega_n t - \frac{2\pi}{3}\right) - E_5 Sin\left(5\omega_n t + \frac{2\pi}{3}\right) + E_7 Sin\left(7\omega_n t - \frac{2\pi}{3}\right)$$

$$v_{n3}(t) = E_1 Sin\left(\omega_n t + \frac{2\pi}{3}\right) - E_5 Sin\left(5\omega_n t - \frac{2\pi}{3}\right) + E_7 Sin\left(7\omega_n t + \frac{2\pi}{3}\right)$$

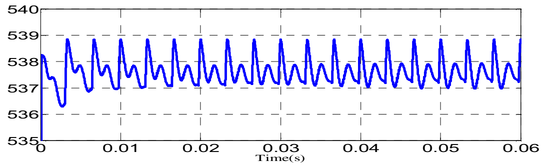

Fig. 2. Voltage of DC bus v_{dc} .

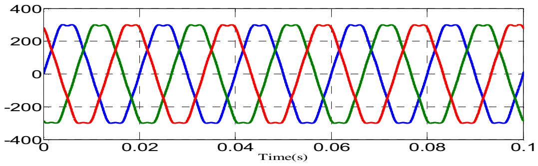

Fig. 3. Source voltages harmonics $(v_{n1}\ v_{n2}\ v_{n3})$.

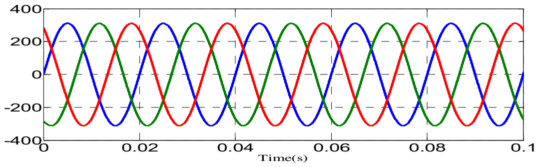

Fig. 4. Load voltages $(v_{L1}\ v_{L2}\ v_{L3})$ after compensation.

4.2 Voltage unbalance compensation

The three-phase source voltages are unbalanced, but do not contain harmonic components. Their expressions are given by:

$$v_{n1}(t) = E_1 Sin(\omega_n t) + 0.1 E_1 Sin(\omega_n t)$$

$$v_{n2}(t) = E_1 Sin\left(\omega_n t - \frac{2\pi}{3}\right) + 0.1 E_1 Sin\left(\omega_n t + \frac{2\pi}{3}\right)$$

$$v_{n3}(t) = E_1 Sin\left(\omega_n t + \frac{2\pi}{3}\right) - 0.1 E_1 Sin\left(\omega_n t - \frac{2\pi}{3}\right)$$

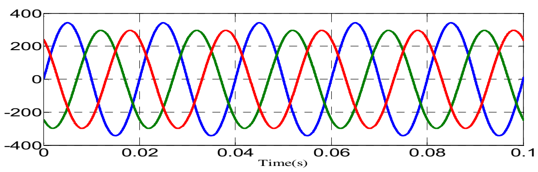

Fig. 5. Source voltages unbalanced $(v_{n1}\ v_{n2}\ v_{n3})$.

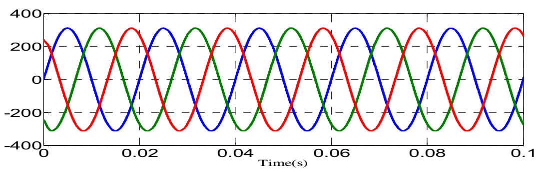

Fig. 6. Load voltages $(v_{L1}\ v_{L2}\ v_{L3})$ after compensation.

4.3 Voltage sags compensation

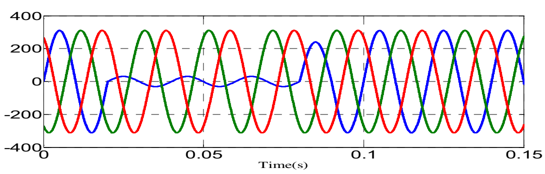

Fig. 7. Source voltages sags $(v_{n1}\ v_{n2}\ v_{n3})$.

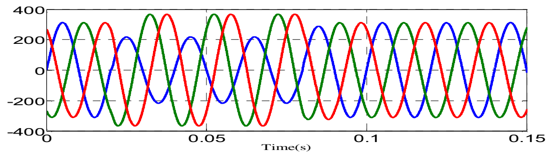

Fig. 8. Load voltages $(v_{L1}\ v_{L2}\ v_{L3})$ after compensation.

The performances of the controller are illustrated by figures 2 to 8. The figure 2 shows the voltage of DC bus v_{dc} converges, in the mean to the average value of the output voltage of the rectifier bridge: $U_{moy} = 3\sqrt{3}E/\pi$. Figure 3 shows the distortion in source voltages $(v_{n1}\ v_{n2}\ v_{n3})$. Figure 4 clearly shows that the load voltages $(v_{L1}\ v_{L2}\ v_{L3})$ after compensation are balanced and sinusoidal. Figure 5 shows source voltages unbalanced $(v_{n1}\ v_{n2}\ v_{n3})$. Figure 6 shows that the load voltages $(v_{L1}\ v_{L2}\ v_{L3})$ after compensation are balanced and sinusoidal. Figure 7 shows the sags in source voltages $(v_{n1}\ v_{n2}\ v_{n3})$. Figure 8 shows that the load voltages $(v_{L1}\ v_{L2}\ v_{L3})$ after compensation are balanced and sinusoidal after the voltages sags.

5 Conclusion

The problem of controlling three-phase series active power filter is addressed in this paper. The control objective is to compensate all voltage perturbations (voltage harmonics, voltage unbalance and voltage sags) caused by nonlinear loads. Indeed the harmonics of the current generated by the nonlinear load, cause voltage distortion of the power source. The solution of the problem is processed using a controller formed by two nonlinear regulators by using the Backstepping technique to compensate the voltages perturbations. The simulation results show that it performs perfectly the objectives.

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