A New Identification Algorithm of Voltage Perturbations for a Three Phase Series Active Power Filter

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Abstract— A Parallel Active Power Filters (PAPF) have been recognized as valid solution for the compensation of the current perturbations (harmonic, unbalanced currents and reactive power). Their dual circuits; the Series Active Power Filters (SAPF) are usually based on Pulse-with Modulated (PWM) Voltage Source Inverter (VSI), and are able to compensate all voltages perturbations (voltage harmonics, voltage unbalance and voltage sag). In this paper we propose a new algorithm of voltage reference calculation, based on the instantaneous real and imaginary auxiliary powers, for separating positive and negative sequence components of the supply voltage. The perturbations compensation using the SAPF has been studied and validated through Matlab simulation.

Keywords: Compensation, Harmonic perturbation, Matlab – Simulink, Series Active Power Filters, Voltage sag, Voltage unbalance.

I. INTRODUCTION

The PAPF’s, established by Kataoka [12] and Akagi [3], were used to compensate the current perturbations, current harmonics, unbalanced current and reactive power in the load side. Concerning the voltage quantity, other types of perturbation: voltage harmonics, voltage unbalance and voltage sags are frequently met on the electrical supply network and have harmful effects on the electric equipments [2] and [8]. Recently, the SAPF’s are applied to compensate these voltage perturbations in the grid side as well as the load side [1]-[12].

Voltage sags, voltage unbalance and voltage harmonics are considered a major perturbations concern in industrial power systems due to the increasing presence of sensitive loads [2] and [8]. The SAPF’s are an appropriate solution to protect sensitive loads against voltage perturbations. The SAPF injects by means of three single-phase transformers three voltages in the grid, synchronized in such a way that the load voltage magnitude and phase are constant at any instant to guarantee a maintained operation for the load. The dynamic performance of the SAPF is significant. Thus, the response time of the voltage detection algorithm and voltage compensation must be short; consequently, the bandwidth should be high.

The SAPF’s are based on PWM-VSI. The basic configuration of the SAPF for voltage compensation is described in Fig. 1, its PWM-VSI is inserted in series with two electric subsystems interconnected by a power line. Three single-phase transformers are used to perform the series connection.

The PWM-VSI behaves as a controlled, non-sinusoidal voltage source. The SAPF works in closed-loop manner, sensing continuously the phase voltages V_{abc}, and calculating the instantaneous values of the compensating voltage references V_{abref} for the PWM-VSI. It compensates the voltage V_{abc}, such that V_{abc} becomes balanced and free of harmonics. As done for the PAPF, the SAPF has no dc power supply. The SAPF has to take energy from the ac network, through a three phase rectifier diodes.

In this paper, the detection of the voltage perturbations, as well as its compensation, performed by applying the proposed algorithm (instantaneous real and imaginary auxiliary powers) has been studied and validated through Matlab simulation.

II. GENERAL DESCRIPTION, AND POWER CIRCUIT OF THE SERIES ACTIVE POWER FILTER

Fig. 1: Basic configuration and power circuit of the SAPF

The Fig. 1 shows the power circuit and configuration of system, the SAPF is inserted between the perturbed voltage source and a protected load. The SAPF is based on the split capacitor inverter topology and a second order LRC passive output filter is used to connect the VSI to the grid through a voltage injection single phase transformers. The SAPF has to take energy from the ac network, through a three phase
rectifier diodes, for covering the losses in the VSI and regulating the dc bus voltage. The block of voltage references identification and a PWM voltage control are used to control the inner closed loop.

III. SERIES ACTIVE POWER FILTER CONTROLLER

Theoretically, the SAPF should compensate all voltage perturbations and work together with a PAPF in a combined device, and several simplifications, not only in the control circuit, but also in the power circuit, can be made the SAPF approach. Our aim in this work is limited to compensate the sags, harmonics and unbalances in the voltages of electrical power supply.

A. Identification algorithm for voltage compensation

The phase voltages \( v_a, v_b \) and \( v_c \) at load terminal are mainly composed of positive sequence component, but can be unbalanced and contain harmonics. The voltage references identification uses a Phase-Locked-Loop (PLL) circuit locked to the fundamental frequency of the system voltage [6].

In steady state, the pulse signal output of the voltage controlled oscillator (VCO) is proportional to the fundamental frequency of the positive sequence voltage and is used in a sine wave generator as an angular frequency reference \( \omega_t \) which produces two sinusoidal signals expressed in a stationary reference \( \alpha \beta \):

\[
\begin{align*}
\alpha & = \sin(\omega t) \\
\beta & = -\cos(\omega t)
\end{align*}
\] (1)

The output of the PLL circuit corresponds to the \( \alpha \beta \) reference transformation of some auxiliary fundamental positive sequence currents, considering only the fundamental positive sequence components.

There are used in the mains circuit of the voltage references identification detector as auxiliary source currents \( i_\alpha \) and \( i_\beta \).

The source voltages are transformed, considering for simplicity a null value for zero sequences voltage, into the \( \alpha \beta \) frame as given by equation (2):

\[
[v]_{\alpha \beta} = C_{\alpha \beta}^{abc} [v]_{abc}
\] (2)

where the Concordia transformation is given by

\[
C_{\alpha \beta}^{abc} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & \sqrt{3}/2 \end{bmatrix}
\]

\( v_\alpha \) and \( v_\beta \) are used together with auxiliary source currents \( i_\alpha \) and \( i_\beta \) to calculate the auxiliary powers \( p \) and \( q \) through expression (3).

\[
\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} + \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \begin{bmatrix} i_\alpha \\ -i_\beta \end{bmatrix}
\] (3)

The influence of the fundamental negative sequence and the harmonics will appear only in the high frequency components of \( p \) and \( q \). Two 5th order Butterworth low-pass filters are used to obtain the real oscillatory power value \( \bar{p} \) and imaginary oscillatory power value \( \bar{q} \).

According to equation (4) \( v_{\alpha \beta \text{ref}} \) and \( v_{\beta \alpha \text{ref}} \) are calculated, which correspond to the perturbation components of the system voltage transformed into the \( \alpha \beta \) frame.

\[
\begin{bmatrix} v_{\alpha \beta \text{ref}} \\ v_{\beta \alpha \text{ref}} \end{bmatrix} = \frac{1}{i_\beta} \begin{bmatrix} i_\alpha & i_\beta \\ i_\beta & -i_\alpha \end{bmatrix} \begin{bmatrix} \bar{p} \\ -\bar{q} \end{bmatrix}
\] (4)

Finally, the three phase voltages references \( v_{\alpha \beta \text{ref}} \), \( v_{\beta \alpha \text{ref}} \) and \( v_{\beta \alpha \text{ref}} \) can be calculated applying the inverse transformation given by equation (5).

\[
[v]_{\alpha \beta \text{ref}} = (C_{\alpha \beta}^{abc})^T [v]_{\alpha \beta \text{ref}}
\] (5)

The diagram of voltage references identification is represented in Fig. 2.

Fig. 2: Block diagram of identification voltage references.

B. Output filter of the SAPF

The output filter of the SAPF is a second order passive filter (RLC); it is used to connect the VSI to the grid and permits the reduction of the high frequency switching ripple caused by switching operation of the power transistors. The Fig. 3 shows the diagram of the output filter model.

Fig. 3: Diagram of output filter model.

\( V_x, V_o \) and \( I_c \) represent respectively the output voltage of the VSI, the output voltage of the SAPF, and the load current. The model equation of the SAPF is given in (6):

\[
V_o = G_{so}(s)V_{ref} + G_p(s)I_c
\] (6)

Where \( G_{so}(s) \) and \( G_p(s) \) represent respectively the original transfer function and the perturbations model function.
C. Filter output voltage regulation

From the Fig. 3, the voltage closed loop transfer function of the SAPF is given by the Fig. 4. The inverter is controlled by a modulator (PWM) and the nominal switching frequency is 10 kHz. $H_{ref}(s)$ and $H_i(s)$ represent respectively the PI function transfer and VSI function transfer.

$$G_{s_0}(s)=\frac{V_o}{V_{ref}}=\frac{K_i}{V_{ref}}=\frac{1+\left(\frac{K_i}{K_r}\right)s}{LCs^2+(R/L)s^2+\left(\frac{K_i}{K_r}\right)s+K_r/LC}$$ \hspace{1cm} (7)

$$G_p(s)=\frac{V_o}{I_c}=\frac{(Ls+R)}{LC(s^2+(R/L)s+1/LC)}$$ \hspace{1cm} (8)

The parameters $K_i$ and $K_r$ are fixed with an empirical method in order to regulate a third order system with only two parameters.

IV. SIMULATION RESULTS

A several voltages perturbations in an electrical network (voltage harmonics, voltage unbalanced and sags) are modulated and compensated using a SAPF in the aim to validate the robustness of the proposed voltage identification algorithm.

A. Voltage harmonic compensation

The three phase source voltages are balanced, but contain the $5^{th}$ and $7^{th}$ harmonic components. Their expressions are given in equation (7).

$$v_a(t)=V_i\sin(\omega t)+V_i\sin(5\omega t)+V_i\sin(7\omega t)$$

$$v_b(t)=V_i\sin(\omega t-\frac{2\pi}{3})+V_i\sin(5\omega t+\frac{2\pi}{3})+V_i\sin(7\omega t-\frac{2\pi}{3})$$

$$v_c(t)=V_i\sin(\omega t+\frac{2\pi}{3})-V_i\sin(5\omega t-\frac{2\pi}{3})+V_i\sin(7\omega t+\frac{2\pi}{3})$$

where $V_s=V_i/5$ and $V_s=V_i/7$

The parameters were calculated in order to regulate a third order system with only two parameters.

B. Voltage unbalance compensation

The three phase source voltages are unbalanced, but do not contain harmonic components. Their expressions are given in equation (8).

$$v_a(t)=V_i\sin(\omega t+0.13)V_i\sin(\omega t+0.13)$$

$$v_b(t)=V_i\sin(\omega t+\frac{2\pi}{3})+0.13V_i\sin(\omega t+\frac{2\pi}{3})$$

$$v_c(t)=V_i\sin(\omega t+\frac{2\pi}{3})+0.13V_i\sin(\omega t+\frac{2\pi}{3})$$

where $V_i=\sqrt{220}$
C. Voltage sag compensation

A single phase voltage dip of 33% of the rated grid voltage is considered which modeled as magnitude of phase voltage ‘a’ decreases to \( V/3 \). The model expressions of voltage are given in equation (9).

\[
v_a(t) = \left( V/3 \right) \sin(\alpha t - \frac{2\pi}{3})
\]

\[
v_b(t) = \left( V/3 \right) \sin(\alpha t + \frac{2\pi}{3})
\]

During the dip, the grid voltage decreases on the phase ‘a’ and the capacitor voltage, in corresponding phase, increases to keep the load voltage at the nominal value.

V. CONCLUSION

In this paper, a new voltage references algorithm identification for series active power filter has been presented and tested for several perturbations in an electrical network (voltage harmonics, voltage unbalanced and voltage dip), which have been modulated and successfully compensated.

In a near future, a performed controller algorithm of the inner and outer loop will be studied and applied to SAPF. Which validated by using Power System Blockset Toolbox (PSB) of Matlab from a complete structure of SAPF.

VI. REFERENCES