Connection of Shunt Active Power Filters in Multibus Industrial Power Systems for Harmonic Voltage Mitigation

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Abstract. The bus voltage and branch current detection control strategies of the active power filters used in multibus power systems for harmonic voltage mitigation are analysed in terms of the harmonic bus voltage mitigation and of the demanded current spectrum injected by the active power filters.

Key words

Active power filter, industrial power system, harmonic voltage mitigation, optimum location, control strategies.

1. Introduction

Active power filters have been analyzed mainly in terms of operation principles, control algorithms, and performance characteristics [1]. Some analyses have been related with active filter compensation performance in power distribution systems [2]-[4],[5]. The performance and effectiveness of the active power filter depends on the point of its connection.

The problem of an optimal location of active power filters and of current spectra injected by them and demanded for minimum harmonic voltage distortion has been formulated either as unconstrained or constrain optimization problem solved by analytical procedures [2], graphic methods [3] or by using some techniques suitable for very large scale optimization problems [4]. A strategy enabling us to exactly determine the most effective points of connections of active power filters in multibus power systems with distributed harmonic sources bas been presented in [5]. Nevertheless, the question how to control active power filters to attain desirable effects of harmonic voltage mitigation remains still open.

The bus voltage and branch current detection control strategies of the active power filters used in multibus power systems for harmonic voltage mitigation are analysed and compared in the paper. The steady state analysis of a power system configuration composed of a large number of buses where active current harmonics compensation performance should be optimized is done in the frequency domain. The analysis of basic principles of both the control methods applied in a multibus industrial power system is focused on the effectiveness of the methods in terms of the harmonic bus voltage mitigation and of the demanded current spectrum injected by the active power filters.

2. Circuit representation

Let us suppose that a circuit has n nodes and b branches. The voltages $V_\mathrm{N}(i)$ at nodes are related to a reference node 0, which voltage $V_\mathrm{N}(0)$ is set to zero ($V_\mathrm{N}(0) = 0$). The vectors $\boldsymbol{V}_\mathrm{I}$, $\boldsymbol{I}_\mathrm{I}$ represent voltage and current sources (injected voltages and currents).

We will analyse steady states in the frequency domain, so the following equations will be algebraic equations for voltage and current vectors (phasors) with frequency dependent matrix elements.

The whole circuit may be described by:

- $(n-1)$ equations (1st Kirchhof's law) for $(n-1)$ nodes
$$\boldsymbol{A}^\mathrm{T}\boldsymbol{I} + \boldsymbol{A}_\mathrm{I}^\mathrm{T}\boldsymbol{I}_\mathrm{I} = 0 \tag{1}$$
- b equations (Ohm's law) for b branches
$$\boldsymbol{I} = \boldsymbol{Y}\left(\boldsymbol{V} - \boldsymbol{V}_\mathrm{I}\right) \tag{2}$$
- b equations reflecting the incidence among the branch and node voltages
$$\boldsymbol{V} = \boldsymbol{A}\boldsymbol{V}_\mathrm{N} \tag{3}$$

where $\boldsymbol{V}$, $\boldsymbol{I}$ are vectors of the branch voltages and currents, $\boldsymbol{V}_\mathrm{N}$ is the vectors of the node voltages, $\boldsymbol{Y}$ is the branch admittance matrix and $\boldsymbol{A}$, $\boldsymbol{A}_\mathrm{I}$ are the incidence matrices. The matrix $\boldsymbol{A}_\mathrm{I}^\mathrm{T}$ describes the distribution of the m currents $\boldsymbol{I}_\mathrm{I}$ injected into individual nodes.

On the basis of equations (1) – (3) we can obtain the matrix relation between $\boldsymbol{V}_\mathrm{N}$ and the injected voltages $\boldsymbol{V}_\mathrm{I}$ and currents $\boldsymbol{I}_\mathrm{I}$. Let us suppose that the vector $\boldsymbol{I}_\mathrm{I}$ of the m currents injected consists of the vector $\boldsymbol{I}_\mathrm{IL}$ of m_L load currents and the vector $\boldsymbol{I}_\mathrm{IF}$ of m_F APF currents. The APF currents should compensate the node voltages $V_\mathrm{N}(i)$, $i = 1, ..., n$ induced by the injected currents $\boldsymbol{I}_\mathrm{IL}$ and voltages $\boldsymbol{V}_\mathrm{I}$
$$\boldsymbol{V}_\mathrm{N} = \boldsymbol{Z}_\mathrm{NIL}\boldsymbol{I}_\mathrm{IL} + \boldsymbol{Z}_\mathrm{NIF}\boldsymbol{I}_\mathrm{IF} + \boldsymbol{H}_\mathrm{NI}\boldsymbol{V}_\mathrm{I} \tag{4}$$
where $\boldsymbol{H}_\mathrm{NI}$, $\boldsymbol{Z}_\mathrm{NI}$ are the transfer matrices of the injected voltages and currents, $\boldsymbol{I}_\mathrm{I} = (\boldsymbol{I}_\mathrm{IL}, \boldsymbol{I}_\mathrm{IF})^\mathrm{T}$, $\boldsymbol{Z}_\mathrm{NI} = (\boldsymbol{Z}_\mathrm{NIL}, \boldsymbol{Z}_\mathrm{NIF})$, $m_\mathrm{L} + m_\mathrm{F} = m$.

3. Control strategies

The control aim is to generate such a vector $\boldsymbol{I}_{\mathrm{IF}}$ that eliminates, or at least decreases, the node voltages $\boldsymbol{V}_{\mathrm{N}}$ at selected nodes $(\le n-1)$. For the elimination of the harmonic voltages at all $(n-1)$ nodes we should apply $m_{\mathrm{F}} = n - 1$ APF currents, which values could be found by solving (4).

A. APF currents for full elimination of harmonic voltages at selected nodes

If we want to eliminate for harmonic voltages at m_{Fr} nodes, we need to generate only m_{Fr} APF currents. The values of the APF current may be found by solving a set of equations obtained from (4) by choosing only the equations for the node voltages $\boldsymbol{V}_{\mathrm{Nr}} = 0$ that should be eliminated for. The harmonic voltages at the remaining $(n - 1 - m_{\mathrm{Fr}})$ nodes may be calculated by solving the rest set of the equations with the values $\boldsymbol{I}_{\mathrm{IFr}}$ obtained.

This procedure, suggested and analysed in [5], does not tell us nothing how to generate the calculated values of $\boldsymbol{I}_{\mathrm{IFr}}$. Additionally, we do not need usually eliminate $\boldsymbol{V}_{\mathrm{Nr}}$ fully, but only to suppress them under acceptable limits. In what follows, we will analyse APF control strategies applicable in real distribution systems.

B. Voltage detection feedback control strategy

The voltage detection feedback control strategy belongs among control strategies very often used for parallel APF applied in simple power distribution systems. We will analyse an application of this strategy in multibus power distribution systems with a few harmonic power sources.
Let the current vector $\boldsymbol{I}_{\mathrm{IF}}$ of APFs is generated by using a feedback of the node voltage vector

$$\boldsymbol{I}_{\mathrm{IF}} = \boldsymbol{Y}_{\mathrm{G}} \boldsymbol{V}_{\mathrm{N}} \tag{5}$$

where $\boldsymbol{Y}_{\mathrm{G}}$ is the feedback gain matrix.
By using (4) and (5) we can write for the APF current vector

$$\boldsymbol{I}_{\mathrm{IF}} = \left(\boldsymbol{E} - \boldsymbol{Y}_{\mathrm{G}} \boldsymbol{Z}_{\mathrm{NIF}}\right)^{-1} \boldsymbol{Y}_{\mathrm{G}} \left(\boldsymbol{Z}_{\mathrm{NIL}} \boldsymbol{I}_{\mathrm{IL}} + \boldsymbol{H}_{\mathrm{NI}} \boldsymbol{V}_{\mathrm{I}}\right) \tag{6}$$

where $\boldsymbol{E}$ is the identity matrix.

C. Current detection feedback control strategy

This method is also used in simple power distribution systems, especially for mitigation of harmonic currents. It results, effectively, to the suppression of harmonic voltages too. Now, the feedback is specified by

$$\boldsymbol{I}_{\mathrm{IF}} = \boldsymbol{G}\,\boldsymbol{I} \tag{7}$$

where $\boldsymbol{G}$ is the feedback gain matrix.
By using (2), (4) and (7) we can write for the APF current vector

$$\begin{aligned} \boldsymbol{I}_{\mathrm{IF}} &= \left(\boldsymbol{E} - \boldsymbol{G}\boldsymbol{Y}\boldsymbol{A}\boldsymbol{Z}_{\mathrm{NIF}}\right)^{-1} \cdot \\ &\cdot \boldsymbol{G}\boldsymbol{Y}\left[\boldsymbol{A}\boldsymbol{Z}_{\mathrm{NIL}}\boldsymbol{I}_{\mathrm{IL}} + \left(\boldsymbol{A}\boldsymbol{H}_{\mathrm{NI}} - \boldsymbol{E}\right)\boldsymbol{V}_{\mathrm{I}}\right] \end{aligned} \tag{8}$$

The node voltage vector $\boldsymbol{V}_{\mathrm{N}}$ is determined by the substitution of this $\boldsymbol{I}_{\mathrm{IF}}$ into (4).

D. Analysis of control strategies

Let us analyse both the feedback strategies in more detail. For simplicity, we will consider $\boldsymbol{V}_{\mathrm{I}} = 0$, and only one harmonic current I_{IL} injected into the node j. The aim is the mitigation of the voltage $V_{\mathrm{N}}(i)$ at the node i by applying the APF current I_{IF} injected into the node f.

For the <u>node voltage detection control strategy</u> the current I_{IF} is generated by amplifying the voltage $V_{\mathrm{N}}(d)$ detected at the node d, which is generally different from the node f.
We can write

$$\begin{aligned} V_{\mathrm{N}}(i) &= Z_{\mathrm{NIL}}(i) I_{\mathrm{IL}} + Z_{\mathrm{NIF}}(i) I_{\mathrm{IF}} \\ V_{\mathrm{N}}(d) &= Z_{\mathrm{NIL}}(d) I_{\mathrm{IL}} + Z_{\mathrm{NIF}}(d) I_{\mathrm{IF}} \\ I_{\mathrm{IF}} &= Y_{\mathrm{G}}(d) V_{\mathrm{N}}(d) \end{aligned} \tag{9}$$

Thus, it holds for $V_{\mathrm{N}}(i)$ and I_{IF}

$$\begin{aligned} V_{\mathrm{N}}(i) = &\frac{Z_{\mathrm{NIL}}(i) + Y_{\mathrm{G}}(d)}{1 - Y_{\mathrm{G}}(d) Z_{\mathrm{NIF}}(d)} \cdot \\ &\cdot \frac{\left[Z_{\mathrm{NIF}}(i) Z_{\mathrm{NIL}}(d) - Z_{\mathrm{NIF}}(d) Z_{\mathrm{NIL}}(i)\right]}{1 - Y_{\mathrm{G}}(d) Z_{\mathrm{NIF}}(d)} I_{\mathrm{IL}} \end{aligned} \tag{10}$$

$$I_{\mathrm{IF}} = \frac{Y_{\mathrm{G}}(d) Z_{\mathrm{NIL}}(d)}{1 - Y_{\mathrm{G}}(d) Z_{\mathrm{NIF}}(d)} I_{\mathrm{IL}} \tag{11}$$

where $\boldsymbol{Z}_{\mathrm{NIL}}$, $\boldsymbol{Z}_{\mathrm{NIF}}$ are only vectors for one load current I_{IL} and one APF current I_{IF}. The elements $Z_{\mathrm{NIF}}(i)$, $Z_{\mathrm{NIF}}(d)$ of $\boldsymbol{Z}_{\mathrm{NIF}}$ depend on where the current I_{IF} is applied (node f).

If the aim is the full compensation for the voltage $V_{\mathrm{N}}(i)$, we obtain from (9) the current I_{IF}

$$I_{\mathrm{IF}} = -\frac{Z_{\mathrm{NIL}}(i)}{Z_{\mathrm{NIF}}(i)} I_{\mathrm{IL}} \tag{12}$$

The demanded value of $Y_{\mathrm{G}}(d)$ may be calculated by comparing (11) and (12). For higher values of $Y_{\mathrm{G}}(d)$ than this demanded value the value of $V_{\mathrm{N}}(i)$ is again increasing towards the value defined by (10) for $Y_{\mathrm{G}}(d) \to \infty$. This is a difference from the case of the usage of the parallel APF in the simplest power system where the harmonic current and voltage are fully compensated for if $Y_{\mathrm{G}}(d) \to \infty$. This rule is valid here only if the APF current I_{IF} is generated by the feedback from $V_{\mathrm{N}}(i)$ $(d = i)$, regardless the node where the current I_{IF} is applied. In such a case it holds

$$\lim_{Y_{\mathrm{G}}(i)\to\infty} V_{\mathrm{N}}(i) = \lim_{Y_{\mathrm{G}}(i)\to\infty} \frac{Z_{\mathrm{NIL}}(i)}{1 - Y_{\mathrm{G}}(i) Z_{\mathrm{NIF}}(i)} = 0 \tag{13}$$

For the <u>branch current detection control strategy</u> the current I_{IF} is generated by amplifying the current detected at the branch d that connects the nodes d_1 and d_2.

By comparing (6) and (8) (for $\boldsymbol{V}_{\mathrm{I}} = 0$) we see that both the strategies yield the same results if

$$\boldsymbol{Y}_{\mathrm{G}} = \boldsymbol{G}\boldsymbol{Y}\boldsymbol{A} \tag{14}$$

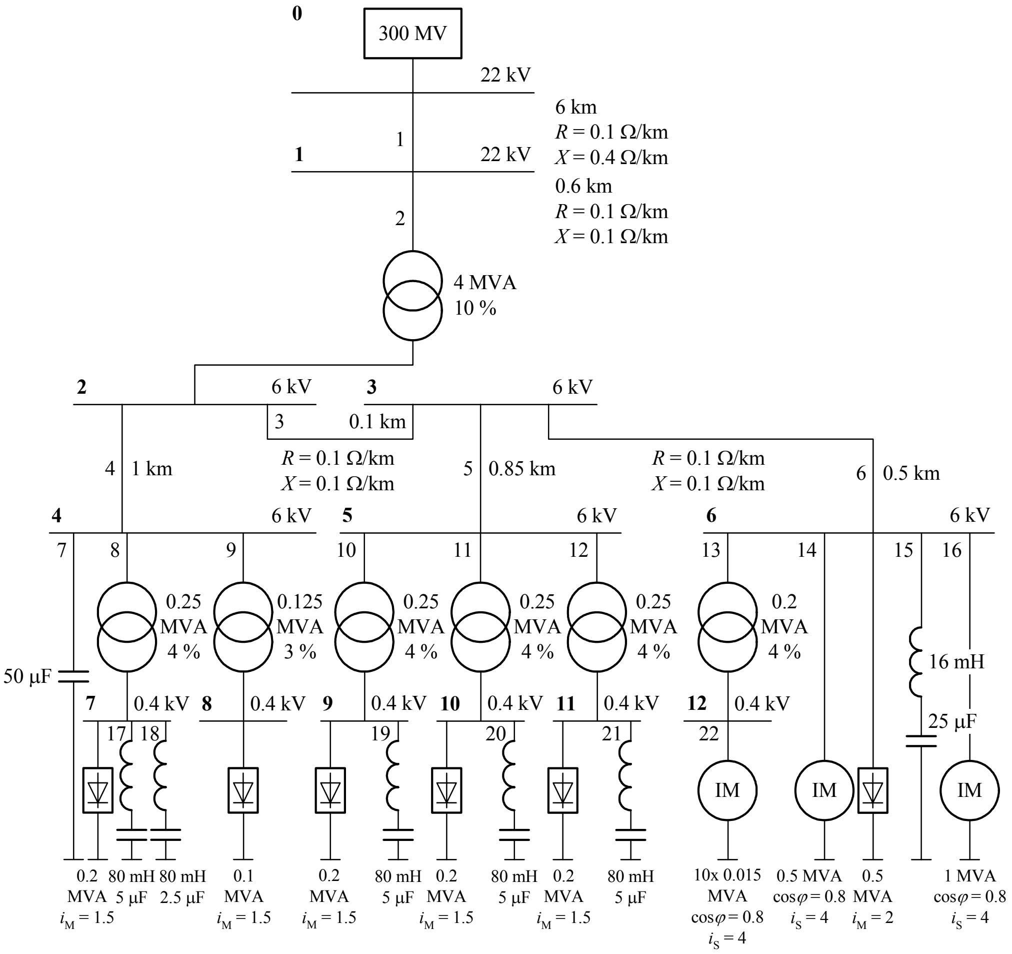

Fig. 1. Multibus industrial power system

For only one current I_{IF} the gain vector has a form

$$\boldsymbol{G} = \left[0,...,0,G(d),0,...,0\right] \tag{15}$$

and therefore

$$\begin{aligned} \boldsymbol{Y}_G &= \boldsymbol{G}\,\boldsymbol{Y}\,\boldsymbol{A} = \\ &= \begin{bmatrix} 0,...,0,G(d)Y(d,d),0,..., \\ 0,-G(d)Y(d,d),...,0 \end{bmatrix} = \\ &= \left[0,...,0,Y_G(d_1),0,...,0,-Y_G(d_2),...,0\right] \end{aligned} \tag{16}$$

It is evident that the current detection control strategy gives as the same results as those obtained by using the voltage detection control method with two voltage feedbacks from the nodes d_1, d_2 that determine the branch d, whose current is used as a feedback signal in the current detection strategy. These two voltage feedbacks have opposite signs and the gains are multiplied by the admittance matrix element $Y(d, d)$ of the branch d.

Therefore, the similar rules of the influence of the gain on the voltage $V_N(i)$ compensation as those stated for the voltage detection strategy before may be applied.

4. Multibus industrial power system

A simplified single line diagram of a multibus industrial power system is shown in Fig. 1. Some simplifications in the analysis have been considered: the transformers and induction motors have been represented by inductances only, and passive filters have been considered as ideal ones, without resistances, too; ground capacitances of the lines and cables have been neglected as well.

The rectifiers have been represented by ideal harmonic current sources ($\boldsymbol{I}_{IL}$ in (4)) with harmonic magnitudes determined by respective apparent powers, overload capacities, and by the so called magnitude law. Let us suppose for simplification that there is no phase shift among harmonics of all rectifiers. The harmonic spectrum of the voltage at the bus 0 ($\boldsymbol{V}_I$ in (4)) has been considered as that having the 50 % level of the respective standard for the high voltage system.

In the following analysis all quantities will be recalculated to the 6 kV level and expressed in the p.u. system with S_B = 1 MVA (the maximum power of the major rectifier, which is connected to the bus 6), V_B = 6 kV, 50 Hz.

A. Harmonic voltage reduction

The analysis will be focused mainly on the effectiveness of the harmonic voltage reduction at the bus 1 (the point of common coupling (PCC)) by using one APF, the harmonic voltages at other buses with the voltage 6 kV being checked too.

By using the same procedure as that in [5] we can find for the node voltage detection strategy that the expected most effective connection of the APF is at the bus 4. The procedure lies in finding the greatest element (in magnitude) in the first line of the matrix $\boldsymbol{Z}_{\mathrm{NIF}}$, because we consider the voltage distortion at the bus 1.

B. Bus voltage detection control strategy

The APF is connected at the bus 4 with the voltage feedback from the same bus.

The constant magnitude (= 50 p.u.) of the gain for all harmonics was chosen. The results are shown in Fig. 2. The THD factors of the bus voltages are in the range from 1.9 % (V_{N} (4)) at the bus 4 where the APF is connected) to 3.3 % (V_{N} (5)). The total RMS value of the current I_{IFRMS} = 0.93 p.u.

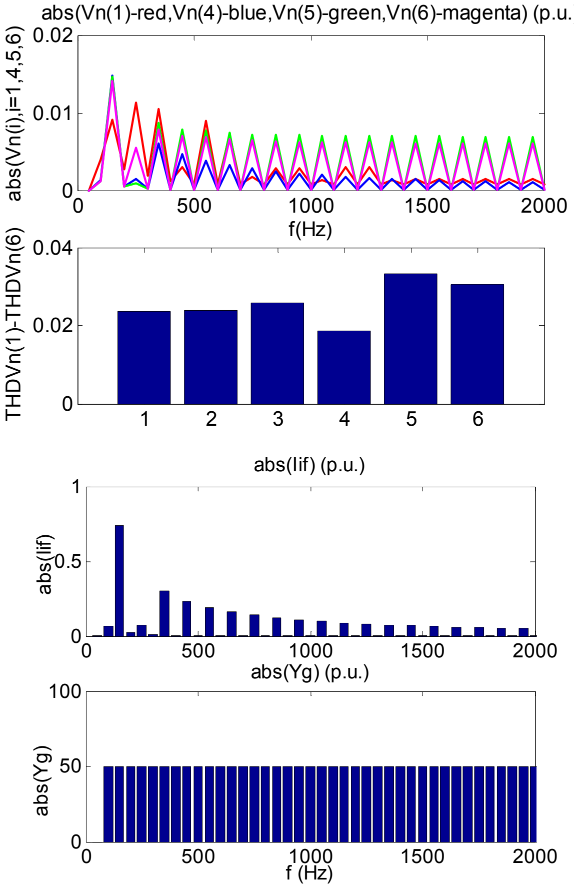

Fig. 2. APF is connected at the bus 4 with the voltage feedback from the same bus

Fig. 2 presents the harmonic spectra of the voltages at the buses 1, 4, 5, 6, the THDs of the voltages at the buses 1 – 6 and shows also absolute values of the demanded currents I_{IF} and of the gains Y_{G} for individual harmonics.

C. Branch current detection control strategy

The APF is connected at the bus 2 with the current feedback from the branch 2.

The constant magnitude (= 5 p.u.) of the gain for all harmonics was chosen. The results are shown in Fig. 3. In Fig. 3 the magnitude of the equivalent gain $Y_{\mathrm{G}} = G \cdot Y(d,d)$ is also presented. The THD factors of the bus voltages are in the range from 2.2 % (V_{N} (3)) to 3.3 % (V_{N} (4)). The total RMS value of the current I_{IFRMS} = 1.05 p.u.

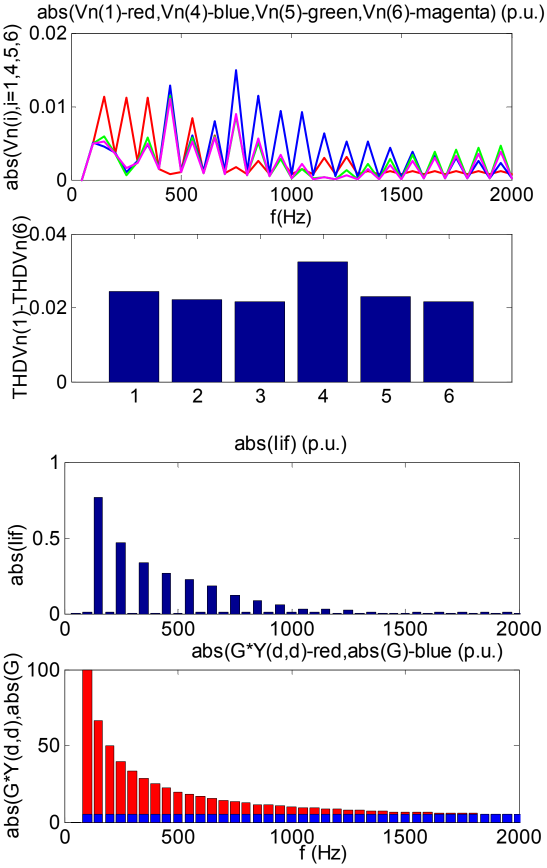

Fig. 3. APF is connected at the bus 2 with the current feedback from the branch 2

Comparing Figs. 2, 3 we see that both the control methods can yield similar results in terms of harmonic spectra and THDs of bus voltages, the demanded APF current I_{IF} being at the same level. Actually, the condition for that is a possibility to find proper places for connecting the APFs with these two control strategies in a real industrial power system.

Although the results of using both the methods are here comparable, we may recognize some partial differences. The harmonic spectrum and THD of $V_{\mathrm{N}}(4)$ with the bus voltage control strategy are better than those with the branch current control strategy, the harmonic spectrum being significantly lower especially above 500 Hz. The thing is that the APF with the first strategy is connected at this bus 4 and controlled by the feedback of $V_{\mathrm{N}}(4)$. On the other hand, the harmonic spectra in the whole frequency range and THDs of $V_{\mathrm{N}}(1)$ with both the methods are practically the same, while with the branch current control strategy the APF current I_{IF} for frequencies above 500 Hz is significantly lower than that with the bus voltage control method.

5. Conclusion

The bus voltage and branch current detection control strategies of the APFs used in multibus power systems for harmonic voltage mitigation have been analysed and compared. Contrary to searching only for conditions (the best APF location and the demanded current spectrum injected by the APF) that lead to the total harmonic voltage elimination at a specific bus of the system [5], the effectiveness of both the control methods with real gains has been assessed. Analysis of these control strategies of the APFs used in the multibus power systems is more complicated then in case of using them in the parallel APFs for simple singlebus systems.

The case study of the harmonic bus voltage mitigation in a multibus industrial power system has shown that both the control strategies applied by the APFs located at properly selected buses can yield similar results with some particular features originated from differences in the principles of these two methods.

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