A comparative analysis of DFPI correctors and different techniques to regulate a shunt active power filter

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Abstract: Power quality is a subject of intense study over recent years, given that it affects the economic impact and costs of utilities, supply and manufacturing. Modern powered electronic equipment is usually nonlinear in nature and causes propagation of harmonic current. This disruptive current can be countered by various solutions, but active power filtering is the most captivating solution. In this paper, a Shunt Active Power Filter (SAPF) system is considered with a new corrector design for both the DC and AC sides. The new design is based on an association between double fuzzy logic and single PI correctors resulting in two ‘DFPI’ correctors devoted to regulating the DC voltage and the AC current of the SAPF. The DFPI corrector is more advantageous than the classic PI or fuzzy controllers implemented alone for regulation purposes of the SAPF control variables (DC voltage and the AC current). This is demonstrated, in this paper, through the addressed theoretical analysis of the proposed DFPI corrector and the studies shown in the simulation section comparing the proposed DFPI, single fuzzy, double fuzzy and PI controllers. Performances in terms of the filtering quality of the AC feeder side and the SAPF DC-bus voltage regulation quality (THDi_s % / THDV_s %) are
noted. The obtained numerical results prove the effectiveness of the DFPI corrector which also described a faster response time, a reduced overshoot and a lessened static error.

**Keywords:** DFPI-based control; intersective PWM modulator; power quality improvement; PSF algorithm; SAPF.


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### 1 Introduction

The quality and purity of power distribution systems has been a topic of important focus over recent years. This is due to the increasing need of electrical energy, and the expanding growth in the field of renewable energies as an indispensable source of electricity in the future.

The prevalence of electronic equipment such as switching power supplies, three-phase diodes, thyristors rectifiers and asynchronous motors, are the main source of disturbance in electrical distribution networks (Chattopadhyay et al., 2010; Akagi, 2005; Sozański, 2013). Moreover, the quality of energy is degraded by the nonlinearity of these interfering charges commonly called ‘nonlinear loads’, or else when the sinusoidal waveform of the voltage or the current is deformed. Indeed, nonlinear loads generate harmonic currents and voltage that can cause an increase in these two variables; this affects the temperature of the equipment and thus reduces its lifespan. This can even
result in their complete deterioration (Wang et al., 2015; Tey et al., 2005; Salam et al., 2006).

To solve the problem of disturbances caused by harmonics, several solutions have been proposed, tested and implemented practically in different power-levels of the distribution systems. Active filters remain among the most popular ones which attract researchers specialised in powered electronics and automation who seek to reduce the effects of harmonics and consequently the depollution of electrical distribution networks (Pal et al., 2008; Singh et al., 2015; Routimo et al., 2007). These filters are one of the following types: serial, parallel and hybrid active filters. They are based essentially on very sophisticated semiconductor components which are fully controlled. However, shunt active power filters (SAPFs) can compensate for reactive power and thus ensure a near-unity power factor (Steela and Rajpurohit, 2014; Dey et al., 2013; Vardar and Akpinar, 2009). The principle of SAPFs is based fundamentally on the generation of currents in opposing phase with the harmonic currents generated by the nonlinear loads in order to ensure a fundamental sinusoidal current on the distribution network side (Demirdelen et al., 2013; Khadem et al., 2011; Moran et al., 1995).

The SAPF principally has two control variables to be regulated in order to result in improved filtering quality. These are DC-bus voltage ‘$V_{dc}$’ and output AC current ‘$i_{FA}$’. Regulation can be performed using classical PI correctors, intelligent or advanced correctors (Steela and Rajpurohit, 2014). Clearly, the better corrector is the one which ensures the fastest response time and the least overshoots and static errors. Fuzzy-PI correctors have especially proved to be very effective to reach the aforementioned targets (Karuppanan and Mahapatra, 2012). Fuzzy control does not require an accurate mathematical model and has better steady-state performance than the PI regulator, but the fuzzy controller is less beneficial during system dynamic process. Among fuzzy controllers found in the literature, single (Fuzzy) and double (DF) correctors are prevalent. The original idea of the DF model was introduced by Wang et al. 2010, wherein the authors demonstrated the effectiveness of their idea to regulate DC-bus voltage of a hybrid SAPF system when they compared its performance to that of a PID: Proportional-Integral-Derivative controller.

In this contribution, a combined DF controller and PI regulator, thus dubbed a new doubled corrector ‘DFPI,’ is presented. Besides the goal of having more efficiency in regulating $V_{dc}$ (Elhaj et al., 2014), the purpose here is also to regulate $i_{FA}$ in order to diminish more and more the dragging error between it and its reference $i_{FA}^*$. The Bode diagram is used to design the PI regulator (Chaoui et al., 2006; Ladoux and Ollé, 2002). The Positive Sequence of the Fundamental Voltage Source Component Algorithm (PSF) was applied for current reference signal extraction (Chang and Shee, 2004) and the carrier-based PWM: Pulse Width Modulation modulator was used to generate the gating signals of the SAPF. The simulation section covers an analysis and comparative study between the proposed $DFPI_{Vdc}$ – $DFPI_{iFA}$ correctors, single fuzzy, DF and PI controllers. The simulation results confirmed the superiority of the proposed DFPI correctors in ensuring the compromise between good filtering quality, good DC voltage regulation and an improved power factor.
2 The studied system

Figure 1 depicts the system to be filtered using the proposed SAPF and the new DFPI correctors. The system is composed of a balanced three-phase power supply defined by its phase-to-neutral voltage $V_p$ and its internal impedance $(R_s, L_s)$. The system is also composed of a nonlinear load that generates harmonic currents through a diode bridge that feeds an inductive circuit $(R_L, L_L)$, a SAPF based on an IGBTs: Insolated gate bipolar transistors VSC, an inductive output filter $(R_f, L_f)$ and an upstream filter $(R_e, L_e)$. Roles and dimensioning of each component are available (Elhaj et al., 2014).

Figure 1 Schematic of the power system to be filtered using the proposed SAPF (see online version for colours)

3 Control circuit of SAPF

Figure 2 portrays the control circuit of the SAPF. The control circuit contains three blocks:

- One block for extracting reference currents.
- One block for regulating both the current of the shunt active filter $i_{sa}$ and the voltage $V_{dc}$.
- One block for generating pulses.
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Figure 2  Synoptic scheme of the control circuit (see online version for colours)

4 Currents reference extraction algorithm

The principle of the positive sequence of the fundamental (PSF) algorithm is illustrated in Figure 3. This algorithm requires a balanced source current, undistorted, and in phase with the positive sequence of the source voltage (Elhaj et al., 2014; Chang and Shee, 2004).

Figure 3  Block diagram of the algorithm

Furthermore, the desired three-phase currents of the source must be in phase with the positive sequence of the fundamental component of the source voltage. The reference currents can be expressed as follows:

\[
\begin{bmatrix}
    i_{L_a}^* \\
    i_{L_b}^* \\
    i_{L_c}^*
\end{bmatrix} =
\begin{bmatrix}
    1 & 0 & 0 \\
    1 & 1 & 0 \\
    1 & 1 & 1
\end{bmatrix}
\begin{bmatrix}
    \sin(\omega t + \phi_i^+) \\
    \sin(\omega t - 2\pi / 3 + \phi_i^+) \\
    \sin(\omega t + 2\pi / 3 + \phi_i^+)
\end{bmatrix}
\]

(1)
With $\phi_1^+$ being an argument of the positive sequence obtained from the Fortescue transformation of the fundamental component of the source voltage.

Finally, the fundamental positive sequence $I_{sm}$ can be expressed as follows:

$$I_{sm} = \frac{2}{3} \frac{P}{V_{sm}}$$

(2)

5 DFPI correctors conception

The double Fuzzy PI corrector is the result of the combination of two correctors, the first is based on fuzzy logic, whereas the second is a conventional PI regulator. This is done in order to benefit from the advantages of the two control techniques and consequently to enhance the compensation performance of SAPF (Elhaj et al., 2014; Elhaj et al., 2015; Saito et al., 2003; Angelico et al., 2014; Routimo et al., 2007).

Figure 4 shows the principle of DFPI corrector schematic.

**Figure 4** The schematic diagram of the DFPI corrector

The characteristics of each fuzzy corrector used to regulate both the voltage $V_{dc}$ and the current of the SAPF are summarised, respectively, in Tables 1 and 2. The two DFPI correctors ($DFPI_{Vdc}$ and $DFPI_{i_{pa}}$) are based on the Mamdani concept (Borne et al., 1998; Jain et al., 2002; Wang, et al., 2010).

**Table 1** Characteristics of the $DFPI_{Vdc}$ corrector

<table>
<thead>
<tr>
<th>Type of membership function</th>
<th>Number of membership function</th>
</tr>
</thead>
<tbody>
<tr>
<td>The error ‘e’</td>
<td>Gaussian</td>
</tr>
<tr>
<td>The error derivative ‘de’</td>
<td>Gaussian</td>
</tr>
<tr>
<td>The output ‘Ocd’</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Method of defuzzification</td>
<td>Bisector</td>
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</table>

**Table 2** Specifications of the $DFPI_{i_{pa}}$ corrector

<table>
<thead>
<tr>
<th>Type of membership function</th>
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</thead>
<tbody>
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<td>Gaussian</td>
</tr>
<tr>
<td>Method of defuzzification</td>
<td>Bisector</td>
</tr>
</tbody>
</table>
Figures 5 and 6 portray the membership functions used by each fuzzy logic corrector in order to regulate, respectively, the voltage $V_{dc}$ and the current $i_{fs}$ of the SAPF.

**Figure 5** DFPI $\_V_{dc}$ corrector membership functions of (a) input variables $e$ & $de$, (b) output variable $Ocd$

![Graph showing membership functions for $V_{dc}$ corrector](image)

**Figure 6** DFPI $\_i_{fs}$ corrector membership functions of (a) input variables $e$ and $de$ and (b) output variable $Ocd$

![Graph showing membership functions for $i_{fs}$ corrector](image)

Tables 3 and 4 represent the fuzzy rules used in the design of the two correctors DFPI $\_V_{dc}$ and DFPI $\_i_{fs}$, respectively (Elhaj et al., 2014; Elhaj et al., 2015). Moreover, the two correctors use 25 fuzzy rules as the output. The number of fuzzy rules is fixed by the product of the number of membership functions of the two inputs (Lee, 1990; Tsengenes, and Adamidis, 2011).

**Table 3** Rules of the DFPI $\_V_{dc}$ corrector

<table>
<thead>
<tr>
<th>Ocd/e</th>
<th>NB</th>
<th>NS</th>
<th>Z</th>
<th>PS</th>
<th>PB</th>
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<tbody>
<tr>
<td>NB</td>
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<td>Z</td>
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<td>PB</td>
</tr>
<tr>
<td>PB</td>
<td>Z</td>
<td>PS</td>
<td>PS</td>
<td>PB</td>
<td>PB</td>
</tr>
</tbody>
</table>

**Table 4** Rules of the DFPI $\_i_{fs}$ corrector

<table>
<thead>
<tr>
<th>Ocd/e</th>
<th>NB</th>
<th>NS</th>
<th>Z</th>
<th>PS</th>
<th>PB</th>
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<tbody>
<tr>
<td>NB</td>
<td>PB</td>
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<td>PS</td>
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<tr>
<td>NS</td>
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<td>Z</td>
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<td>PS</td>
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<td>PB</td>
<td>Z</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
</tr>
</tbody>
</table>
6 Dimensioning of the PI regulators

When a PI regulator is introduced in a system, its coefficients must be well dimensioned to avoid system discrepancy. This section concerns the dimensioning of both PI regulators coefficients. For that the method of the Bode diagram is adopted (Ladoux and Ollé, 2002; Chaouiet al., 2006).

6.1 PI\(_{i_a}\) regulator

According to the curves displayed in Figure 7 (Ladoux and Ollé, 2002) portraying an enhanced view of a small part of the modulating signal and the carrier signal above and the output voltage and its mean value below. The following algorithm helps us to extract the transfer function of the regulating current loop:

\[
V_f = V_{dc}(2\alpha - 1), \text{ and } \alpha = \frac{A_v + A_m}{2A_p}.
\]

where \(<V_f>\) is the mean value of the SAPF output voltage, \(\alpha\) is the duty cycle, \(A_p\) and \(A_m\) are, respectively, the carrier and the modulating signal amplitudes, and \(T_c\) is the carrier signal period.

Figure 7 Extracting of the SAPF output voltage mean value (see online version for colours)

Then, the transfer function of the system will be expressed by:

\[
\text{OLT}_{sys}(p) = \frac{i_f}{V_f} = \frac{<V_f>}{A_m} = \frac{V_{dc}}{A_p} \frac{20\%}{L_c p}.
\]

From (3) one can deduce that:

\[
\frac{<V_f>}{A_m} = \frac{V_{dc}}{A_p}.
\]

Assuming a voltage drop in the output filter inductance of 20% of the SAPF output voltage mean value, then:

\[
\frac{i_f}{<V_f>} = \frac{20\%}{L_c p}.
\]
Consequently,

$$\text{OLTF}_{\text{sys}}(p) = \frac{1}{a \cdot p}$$  \hspace{1cm} (7)

where

$$a = \frac{L_p \cdot A_p}{20\% \cdot V_{dc}}$$  \hspace{1cm} (8)

The transfer function of the corrected system using a PI regulator is given by:

$$\text{OLTF}_{\text{cor}}(p) = \frac{1 + \frac{K_p}{K_i} p}{\frac{a}{K_i} p^2} = \frac{1 + \tau_1 p}{\tau_2 p^2}$$  \hspace{1cm} (9)

with

$$\tau_1 = \frac{K_p}{K_i} \text{ and } \tau_2 = \frac{a}{K_i}$$  \hspace{1cm} (10)

In the harmonic state ($p = j \omega$), the $\text{OLTF}_{\text{cor}}(j \omega)$ will be expressed by:

$$\text{OLTF}_{\text{cor}}(j \omega) = \frac{1 + j \frac{\omega}{\omega_0}}{\omega^2 \left( \frac{\omega}{\omega_0} \right)^2}$$  \hspace{1cm} (11)

with

$$\omega_1 = \frac{1}{\tau_1} \text{ and } \omega_0 = \frac{1}{\sqrt{\tau_2}}$$  \hspace{1cm} (12)

The CLTF$_{\text{cor}}$ is given by $\text{CLTF}_{\text{cor}} = \frac{\text{OLTF}_{\text{cor}}}{1 + \text{OLTF}_{\text{cor}}}$. Thus,

$$\text{CLTF}_{\text{cor}}(p) = \frac{1 + \tau_1 p}{1 + \tau_1 p + \tau_2 p^2}$$

$$\text{CLTF}_{\text{cor}}(j \omega) = \frac{1 + j \frac{\omega}{\omega_1}}{1 + j \frac{\omega}{\omega_1} + j \left( \frac{\omega}{\omega_0} \right)^2 p^2}$$  \hspace{1cm} (13)
By studying the Gain\(_{\text{dB}}\) \((\omega)\) and the Phase \((\omega)\) of the CLTF\(_{\text{in}}\) \((j\omega)\) in the Bode diagram one can extract the gain asymptotes and the phase margin at the specific angular frequencies \(0, \omega_0, \omega_1, +\infty\).

Then \(\omega_0, \omega_1\) can be easily obtained by resolving the following equations:

\[
\text{Gain}_{\text{dB}}(\omega_0) = 0 \quad (14)
\]

\[
\text{Phase}(\omega_1) = \angle \epsilon \text{ phase margin} \quad (15)
\]

where \(\omega_0\) is the cutting frequency. It should be chosen so that the passing band of the PI is inferior to the cutting frequency in order to keep a lessened trailing error between \(i_p\) to its reference. Practically the passing band is limited to a quarter of the cutting frequency (Ladoux and Ollé, 2002) so that:

\[
\omega_0 = \frac{1}{4} \cdot 2\pi f_c \quad (16)
\]

### 6.2 PI\(_{\text{dc}}\)\_V\(_{\text{dc}}\) regulator

The transfer function of the system is expressed by (Ladoux and Ollé, 2002),

\[
\text{OLTF}_{\text{sysVdc}}(p) = \frac{V_{\text{dc}}}{i_{\text{Fam}}} \quad (17)
\]

with \(i_{\text{Fam}}\) as the maximum value of the APF active current.

By ignoring the switching losses in the active filter and in the output filter, the energy is the same in both DC and AC sides. Thus, the variation in the stored energy in the capacitor \(C_{\text{dc}}\) for small changes in \(V_{\text{dc}}\) around its reference voltage \(V'_{\text{dc}}\) is deduced from:

\[
dE_{\text{dc}} = C_{\text{dc}} V_{\text{dc}}^\prime \cdot \frac{d}{dt} V_{\text{dc}} \cdot dt = P_{\text{dc}} \cdot dt \quad (18)
\]

where \(P_{\text{dc}}\) is the active power in the APF AC side and which is given by:

\[
P_{\text{dc}} = 3V_{\text{Farms}} i_{\text{Farms}} = \frac{3}{\sqrt{2}} V_{\text{Farms}} i_{\text{Farms}} \quad (19)
\]

where \(V_{\text{Farms}}, i_{\text{Farms}}\) are the RMS values of the active components of \(V_p\) and \(i_p\), respectively.

Thus:

\[
\text{OLTF}_{\text{sysVdc}}(p) = \frac{3V_{\text{Farms}}}{\sqrt{2} C_{\text{dc}} V_{\text{dc}}^\prime p} = \frac{1}{b \cdot p} \quad (20)
\]

with

\[
b = \frac{\sqrt{2} C_{\text{dc}} V_{\text{dc}}^\prime}{3 V_{\text{Farms}}} \quad (21)
\]
It is obvious from (20) that the extracted Open Loop Transfer Function (OLTF) is based on an integrator, as it is currently expressed in (7). Consequently, the dimensioning of the PI coefficients can be done similar to the steps done with the current regulator as presented in Section 6.1.

7 Results and analysis

7.1 Presentation of the simulation conditions

The system in Figure 1 was simulated in Simulink/MATLAB environment using the Fuzzy logic toolbox. The simulation parameters are displayed in Table 5. Note that a load variation is programmed at 0.25 s and the simulation time is set at 0.5 s which will explain the presence of a transient time in \( V_{dc} \) at 0.25 s.

<table>
<thead>
<tr>
<th>Table 5</th>
<th>Simulation parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>AC supply line-to-line voltage and frequency</td>
<td>380 V, 50 Hz</td>
</tr>
<tr>
<td>Supply impedance</td>
<td>( R_s = 0.07 \Omega, L_s = 0.25 \text{mH} )</td>
</tr>
<tr>
<td>Rectifier load 1</td>
<td>( R_L = 10 \Omega, L_L = 50 \text{mH} )</td>
</tr>
<tr>
<td>Rectifier load 2</td>
<td>( R_L = 5 \Omega, L_L = 25 \text{mH} )</td>
</tr>
<tr>
<td>Time of variation</td>
<td>0.25 s</td>
</tr>
<tr>
<td>Output-filter impedance</td>
<td>( R_f = 10 \text{m\Omega}, L_f = 0.7 \text{mH} )</td>
</tr>
<tr>
<td>Upstream-filter impedance</td>
<td>( R_s = 0.387 \Omega, L_s = 0.3 \text{mH} )</td>
</tr>
<tr>
<td>DC link capacitor and resistance</td>
<td>( C_{dc} = 3.1 \text{mF}, R_{dc} = 97 )</td>
</tr>
<tr>
<td>DC link reference voltage</td>
<td>( V_{dc} = 550 \text{V} )</td>
</tr>
<tr>
<td>The carrier based PWM properties: ( A_{pr}f_p )</td>
<td>6.25 A, 5kHz</td>
</tr>
<tr>
<td>Current PI Coefficients: ( a, f_c, ) phase</td>
<td>25.88 ( \mu \text{s}, 5 \text{kHz}, \pi/3 \text{rad} )</td>
</tr>
<tr>
<td>DC voltage PI Coefficients: ( b, f_c, ) phase</td>
<td>3.7 ms, 5kHz, ( \pi/3 \text{rad} )</td>
</tr>
</tbody>
</table>

Figure 8 shows the Bode diagrams for both gains and phase margins of the AC current and DC voltage regulators of the SAPF. According to these diagrams one can confirm that the first regulator cuts at \( \frac{2 \pi \cdot 10^4}{4} \) rad/s while the second one cuts at \( 2\pi \cdot 20 \text{rad/s} \). Therefore, it is obvious that the phase margin for both regulators is \( \pi / 2 \) rad.
Figure 8  Bode diagrams the closed loop transfer functions of (a) PI\_i\_f regulator, (b) PI\_V\_dc regulator (see online version for colours)

The PI coefficient values that were gotten from using the method of the Bode diagram are reported in Table 6.

Table 6  PI regulators coefficients

<table>
<thead>
<tr>
<th></th>
<th>$\tau_1$ (ms)</th>
<th>$\tau_2$ ($\mu$s)</th>
<th>$K_i$</th>
<th>$K_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI_i_f</td>
<td>1.8</td>
<td>0.031</td>
<td>834.65</td>
<td>1.47</td>
</tr>
<tr>
<td>PI_V_dc</td>
<td>6.9</td>
<td>127</td>
<td>28.93</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Figures 9–16 summarise the simulation results of the considered SAPF system. In order to demonstrate the effectiveness of the proposed (DFPI\_V\_dc, DFPI\_i\_f) correctors, the results are organised in the following sections.

7.2  Without connection to the SAPF

Figure 9 illustrates the source current $i_{sa}$ (Figure 9a), its harmonic spectrum (Figure 9b) and its simultaneous plot with the voltage source $V_{sa}$ (Figure 9c) before connecting the SAPF. The wave form of $i_{sa}$ is non-sinusoidal and the harmonic analysis of the first 25 orders carried out a harmonic spectrum containing, along with the fundamental, the harmonic currents of order $(6 \pm 1 h)$, where $h$ designates the harmonic order, the percentage of the total harmonic distortion THDis is 22.16%. This rate does not comply with international standards. Moreover the current $i_{sa}$ is not totally in phase with the voltage $V_{sa}$, thus the power factor is also affected by the presence of harmonic currents.
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7.3 Application of the DFPI\_V\_dc corrector

After connecting the SAPF to the studied system and apply the corrector DFPI\_V\_dc for regulating the voltage $V_{dc}$, the results presented in Figure 10 show the effectiveness of the DFPI\_V\_dc especially in obliging $V_{dc}$ to follow its reference $V_{dc}^*$ after a transient state of about 0.05 s (Figure 10a). Furthermore, the current $i_{sa}$ recovered its sinusoidal waveform (Figure 10b) as for $V_{sa}$ although the latter is still in need of improvement (Figure 10d). However, the sTHDi and sTHDV\_s (Figure 10c and e) are respecting the standardisation (both THDs are inferior to 5%).
7.4 Application of the $V_{dc}$ and $F_{fa}$ correctors

Now, two different DFPI correctors are applied. The first one regulates $V_{dc}$ and the second one corrects $i_{abc}$ SAPF currents. The results are depicted in Figure 11. Figure 11a shows $V_{dc}$ and its reference, the regulation is satisfactory but the transient time is longer if compared to Figure 10a. Figure 11b–e reveal a small improvement in the waveform quality of both $i_{sa}$ and $V_{sa}$ with respective THDs of 1.30 and 2.90%, which present better results if compared to Figure 10b–e.

**Figure 11** Simulation results after applying the DFPI $V_{dc}$ and DFPI $F_{fa}$ correctors (a) $V_{dc}$ and $V_{dc}^*$, (b) $i_{sa}$, (c) harmonic spectrum of $i_{sa}$, (d) $V_{sa}$ and (e) harmonic spectrum of $V_{sa}$ (see online version for colours)

Figure 12 illustrates the following:

- $i_{sa}$ and $V_{sa}$ in a concurrent plot (Figure 12a), one can see them in phase which proves the compensation not only of harmonic currents but also of the power factor.
- $i_{fa}$ and $i_{fa}^*$ (Figure 12b) shows the synchronisation between the two currents is satisfactory and proves the effectiveness of the DFPI $i_{fa}$ corrector.

The three-phase source current $i_{abc}$ (Figure 12c) and source voltages $V_{abc}$ (Figure 12d). It is obvious that the signals are balanced, so the introduced SAPF system has not disturbed the original system.
A comparative analysis of DFPI correctors and different techniques

Figure 12 Other results after applying the DFPI \( V_{dc} \) and DFPI \( i_{Fa} \) correctors (a) \( i_{sa} \) and \( V_{sa} \), (b) \( i_{Fa} \) and \( i_{Fa}^* \), (c) \( i_{sabc} \) and (d) \( V_{sabc} \) (see online version for colours)

7.5 Application of the DF \( V_{dc} \) and DF \( i_{Fa} \) correctors

At this time, double fuzzy (DF) correctors will be applied without PI correctors. The results reported in Figure 13 show a regulation quality of \( V_{dc} \) (Figure 13a) resembling that seen in Figure 10a. However, the THD of \( i_{sa} \) (Figure 13c) increased by comparison to Figure 11c. The contrary can be observed in the THD of \( V_{sa} \) (Figure 13d) where it decreased in comparison with Figure 11d.

Figure 13 Simulation results after applying the DF \( V_{dc} \) and DF \( i_{Fa} \) correctors (a) \( V_{dc} \) and \( V_{dc}^* \), (b) \( i_{sa} \), (c) harmonic spectrum of \( i_{sa} \), (d) \( V_{sa} \) and (e) harmonic spectrum of \( V_{sa} \) (see online version for colours)
7.6 Application of the Fuzzy $V_{dc}$ and Fuzzy $i_{ra}$ controllers

Now when the fuzzy controllers are not doubled, as mentioned in Figure 14, the regulation of $V_{dc}$ (Figure 14a) too resembles to that of Figure 10a. The THD of $i_{sa}$ (Figure 14c) increased as well if compared to Figures 11c and 13c; nevertheless, the THD of $V_{sa}$ (Figure 14d) decreased considerably if compared to Figures 11d and 13d.

Figure 14 Simulation results after applying the Fuzzy $V_{dc}$ and Fuzzy $i_{ra}$ correctors (a) $V_{dc}$ and $V_{dc}^*$, (b) $i_{sa}$, (c) harmonic spectrum of $i_{sa}$, (d) $V_{sa}$ and (e) harmonic spectrum of $V_{sa}$ (see online version for colours)

7.7 Application of the PI $V_{dc}$ and PI $i_{ra}$ regulators

Finally, we will close the simulation section by presenting the results of the PI regulators applied alone without associating them with the fuzzy controllers. Figure 15 portrays the results showing a regulation of $V_{dc}$ (Figure 15a) which resembles that of Figure 11a, but both the THDs of $i_{sa}$ (Figure 15c) and $V_{sa}$ (Figure 15d) increased compared to all previous results.
A comparative analysis of DFPI correctors and different techniques

Figure 15 Simulation results after applying the PI \( V_{dc} \) and PI \( I_{dc} \) regulators (a) \( V_{dc} \) and \( V_{dc}^{*} \), (b) \( I_{dc} \), (c) harmonic spectrum of \( I_{dc} \), (d) \( V_{dc} \) and (e) harmonic spectrum of \( V_{dc} \) (see online version for colours)

8 Comparative study

In order to recapitulate that which has been provided as commentary in the previous sections and extract conclusion, further curves (Figure 16) are added in this section to compare between the discussed controllers and demonstrate the effectiveness of the proposed (DFPI \( V_{dc} \), DFPI \( I_{dc} \)) corrector. Figure 16a shows the regulation of \( V_{dc} \). One can conclude that the DFPI \( V_{dc} \) corrector gave the best results. Figure 16b depicts \( I_{dc}(t) \) having a sinusoidal form but it is difficult to conclude which is the better corrector based on this figure. The same conclusion can be reached regarding the SAPF output current \( I_{dc}(t) \) as illustrated in Figure 16c. For that, Table 7 is adjoined with the goal of allowing the establishment of a comparative study using numerical data. It is obvious from this table that the proposed (DFPI \( V_{dc} \), DFPI \( I_{dc} \)) corrector brought about the best results concerning the THD of both the source current and the voltage where we recorded 1.3% for the current and 2.9% for the voltage. These are the lowest THDs recorded in the table, although the regulation of \( V_{dc} \) is not the best but it remains acceptable given that the \( V_{dc} \) follows its reference \( V_{dc}^{*} \).
Figure 16 Comparison results after applying all correctors of (a) \( V_{dc} \) and \( V'_{dc} \), (b) \( i_{sa} \) currents and (c) \( i_{fa} \) and \( i'_{fa} \) (see online version for colours)

Table 7 Comparative study between the controllers discussed in Section 7

<table>
<thead>
<tr>
<th>Controllers</th>
<th>THDIs (%)</th>
<th>THDVs (%)</th>
<th>( V_{dc} ) regulation quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>No connection of the SAPF</td>
<td>22.16</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Application of the DFPI _ ( V_{dc} )</td>
<td>1.83</td>
<td>4.93</td>
<td>Good</td>
</tr>
<tr>
<td>Application of the DFPI _ ( V_{dc} ) and DFPI _ ( i_{fa} )</td>
<td>1.30</td>
<td>2.90</td>
<td>Average</td>
</tr>
<tr>
<td>Application of the DF _ ( V_{dc} ) and DF _ ( i_{fa} )</td>
<td>1.49</td>
<td>3.40</td>
<td>Good</td>
</tr>
<tr>
<td>Application of the Fuzzy _ ( V_{dc} ) and Fuzzy _ ( i_{fa} )</td>
<td>1.54</td>
<td>2.92</td>
<td>Good</td>
</tr>
<tr>
<td>Application of the PI _ ( V_{dc} ) and PI _ ( i_{fa} )</td>
<td>2.39</td>
<td>4.21</td>
<td>Average</td>
</tr>
</tbody>
</table>

9 Conclusion

The study portrayed in this paper purposes to improve the power quality of a balanced three-phase electric network that feeds a diode rectifier connected to a passive circuit \((R_1, L_1)\) load in its terminals. This rectifier absorbs a non-sinusoidal current which harmonic spectrum contains, besides the fundamental component, harmonic currents within the orders \(6 \pm 1\) h. As a result, the THD is \((-30\%)\) of the source current exceeds the limits fixed by international standardisations such as IEEE 519 and IEC61000-3-2.
A comparative analysis of DFPI correctors and different techniques

To solve this problem, an SAPF was adopted introducing a new corrector design for regulating both the SAPF DC bus voltage and the AC output current as well. The proposed design of both correctors are based on an association between double fuzzy controllers and PI regulators which resulted in two DFPI correctors (DFPI\(_V\) to regulate \(V_d\), and DFPI\(_I\) to correct \(i_f\)).

A theoretical study of the DFPI approach was conducted and verified through computer simulations performed with Simulink/MATLAB software. The simulations were organised in sections dedicated to different controllers. The objective was to prove the effectiveness of the (DFPI\(_V\), DFPI\(_I\)) correctors when compared to other classes of controllers, specifically Fuzzy, DF, and PI. The comparative study and analysis demonstrated the superiority of the DFPI corrector in terms of power quality, specifically filtering quality. This study resulted in a lower THD of the source current and voltage with a near-unity power factor, a good regulation of the \(V_d\), a faster response time, a reduced overshoot, and a lower static error.

Prospective future studies will focus on the extension of the DFPI corrector to other systems involving other topologies of power converters such as DC choppers constituting a key bloc in PV systems.

References


