Modified SRF theory based on active power filter with quasi-Z-source inverter single-stage PV system

Teoria SRF modificada baseada em filtro de energia ativo com sistema fotovoltaico de estágio único de inversor de fonte quase Z

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ABSTRACT  
The proliferation of non-linear loads employing semiconductor-based power converters has led to a widespread challenge within electrical grids. This challenge pertains to the degradation of power quality (PQ) due to the emergence of harmonic currents generated by these particular loads. Consequently, numerous researchers have advocated for the adoption of shunt active power filters (APF) to mitigate the impact of these harmonics. This article introduces an enhanced methodology aimed at identifying compensation currents for a shunt active power filter (SAPF). The SAPF operates within a single-stage photovoltaic (PV) system utilizing a quasi-Z-source inverter (qZSI). The primary goals of this technique are to achieve a reduction in total harmonic distortion (THD) by less than 3 percent and to decrease the peak value of the DC-link voltage. The proposed system's efficacy is validated through an extensive simulation conducted using the Matlab/Simulink environment.  

Keywords: SAPF. QZSI. PV System. PowerQuality. SBC. MPPT.  

RESUMO  
A proliferação de cargas não-lineares empregando conversores de potência baseados em semicondutores levou a um desafio generalizado nas redes elétricas. Esse desafio está relacionado à degradação da qualidade de potência (PQ) devido ao surgimento de correntes harmônicas geradas por essas cargas específicas. Consequentemente, numerosos pesquisadores têm defendido a adoção de filtros de potência ativa shunt (APF) para mitigar o impacto dessas harmonicas. Este artigo introduz uma metodologia melhorada destinada a identificar as correntes de compensação para um filtro de potência ativa de shunt (SAPF). A SAPF opera dentro de um sistema fotovoltaico (PV) de estágio único utilizando um inversor de fonte quase-Z (qZSI). Os objetivos principais desta técnica são alcançar uma redução na distorção harmônica total (THD) em menos de 3% e diminuir o valor de pico da tensão da ligação CC. A eficácia do sistema proposto é validada por meio de uma simulação extensiva realizada usando o ambiente Matlab/Simulink.  

Palavras-chave: SAPF. QZSI Sistema PV. Qualidade de Energia. SBC MPPT.  

RESUMEN  
La proliferación de cargas no lineales que emplean convertidores de potencia basados en semiconductores ha llevado a un desafío generalizado dentro de las redes eléctricas. Este desafío se refiere a la degradación de la calidad de energía (PQ) debido a la aparición de corrientes armónicas generadas por estas cargas particulares. En consecuencia, numerosos investigadores han abogado por la adopción de filtros de potencia activa de derivación (APF) para mitigar el impacto
de estos armónicos. Este artículo introduce una metodología mejorada destinada a identificar corrientes de compensación para un filtro de potencia activa de derivación (SAPF). El SAPF opera dentro de un sistema fotovoltaico de una sola etapa (PV) utilizando un inversor de fuente cuasi-Z (qZSI). Los objetivos principales de esta técnica son lograr una reducción de la distorsión armónica total (THD) en menos del 3 por ciento y disminuir el valor máximo del voltaje del enlace de CC. La eficacia del sistema propuesto se valida a través de una extensa simulación realizada utilizando el entorno de Matlab/Simulink.

**Palabras clave:** SAPF. QZSI. Sistema FV. Calidad de Energía. SBC. MPPT.

### 1 INTRODUCTION

The extensive utilization of semiconductor-based power converters within the electrical grid serves the purpose of transforming electrical energy into diverse formats, whether continuous or alternating. This transformation caters to the requirements of various devices such as elevators, computers, electric arc, different types of engines, classical and smart mobile phones, and electric vehicles (EV). Nonetheless, this prevalent adoption also brings about notable drawbacks, notably the proliferation of harmonic currents engendered by these loads. This proliferation subsequently results in the deterioration of power quality, as referenced by (Singh, H& al., 2018, Benzahia, A& al., 2019).

Among the proposed solutions are the shunt active power filters, which have proven to be an effective solution in maintaining power quality compared to the passive filters. They rely on the voltage / current source inverter connected with non-linear loads in parallel at the common coupling point (PCC). The inverter generates the harmonic components drawn from non-linear loads. Therefore, the source current becomes sinusoidal and the power factor is improved owing to the injected reactive components that ensure the compensation of reactive power (Ali. T & al., 2018, Teta A & al., 2021, Ali T & al., 2017).

Due to the increasing prevalence of renewable energy exploitation, several improvements have been made to enhance the traditional shunt active filters by connecting the renewable energy source (RES) to the DC side of the SAPF to reduce the energy consumption from the main grid, eliminate harmonic currents, ensure reactive power compensation, and maintain active power injection (Rezk, H& al., 2015, Krama A & al., 2019)

Although all the advantages of PV energy sources, they are suffering from
Numerous drawbacks such as their non-linear properties and full dependence on the environmental conditions. Therefore, it is extremely required to accurately track the maximum power drawn from the PV sources (S. Senguttuvan & al., 2018). The Perturb and Observe (P&O) approach, which is based on the perturbation of PV voltage and the observation of the output power behavior, is one of numerous MPPT methods that have been proposed in the literature to address this issue. (De B & al., 2012, Chomsuwan, K & al., 2002). The incremental conductance (INC) method which uses the P-V slope to identify the maximum power point (Hua C & al., 1998), and artificial intelligence-based approaches (Lin W & al., 2011, Cherif K & al., 2022, Cherif K & al., 2022).

The ZSI offers a number of advantages over traditional two-stage PV systems that include voltage source inverters and DC-DC boost converters, including a reduced number of power switches and the integration of buck and boost capabilities within a single stage. The Shoot Through state, which is a new operational state introduced by the ZSI, is created by simultaneously engaging the upper and lower switches on the same leg. Through a single-stage arrangement, this unique condition permits effective regulation of PV voltage. (Teta A & al., 2021, Teta A & al., 2019).

The central focus of this study is enhancing the synchronous reference frame (SRF) theory for governing a three-phase SAPF linked with a PV system via a QZSI. Validation and testing of this Interactive PV-SAPF are conducted within the Matlab/Simulink framework. The remainder of this paper is structured as follows: Section II outlines the various components of the examined system, Section III elucidates the employed control methodologies, Section IV encompasses the outcomes and discourse, and Section V encapsulates the conclusion of the present study.

2 PROPOSED SYSTEM

The proposed topology of the SAPF studied in this paper is composed of a quasi-z-source inverter powered by a photovoltaic system in the main aim to ensure its improved operation mode such as the compensation of the harmonics in order to improve the source current and to benefit from the available solar source of energy. Indeed, in this study the identification of the harmonic components is
carried out using the SRF method. Whereas, the inverter is controlled using the backstepping controller taking and taking into account the extraction of the maximum possible power of the photovoltaic system using hill climbing MPPT algorithm. Figure 1 represents a comprehensive scheme of the proposed system.

![System configuration diagram](image)

**Figure 1.** System configuration.

**3 MODELING OF the Proposed SYSTEM**

**3.1 PV SYSTEM**

Figure 2 presents the equivalent circuit of one diode model of a PV cell. Is it is shown clearly, it is composed of a current source (indicating the current produced from photon interaction), a parallel reversed diode, a shunt resistance \( R_{sh} \) with high value, and a series resistance \( R_s \) with a low value (Kouzou A & al., 2022, Boulanouar, S& al., 2022).

![Equivalent circuit for a photovoltaic cell](image)

**Figure 2.** Equivalent circuit for a photovoltaic cell.

From this figure, the Kirchhoff’s current law can be applied to express the photo current produced by a PV source as follows:
\[ I_{ph} = I_d + I_{sh} + I \] (1)

(Here you should define the three components of the currents, even they are clear in the figures itself)

The current in the diode \( I_d \) is given by:

\[ I_d = I_0 \left( e^{\frac{V + R_{sl}}{V_t a}} - 1 \right) \] (2)

The current in the \( R_{sh} \) resistance is given by:

\[ I_{sh} = \left( \frac{V + R_{sl}}{R_{sh}} \right) \] (3)

From the equation (1), we obtain the expression of the load current or the PV cell output current \( I \) as follows:

\[ I = I_{ph} - I_d - I_{sh} \] (4)

Replacing (2) and (3) in equations (4), the PV cell output current becomes:

\[ I = I_{ph} - I_0 \left[ e^{\left( \frac{V + R_{sl}}{V_t a} \right)} - 1 \right] - \left( \frac{V + R_{sl}}{R_{sh}} \right) \] (5)

Where the junction thermal voltage \( V_t \) is defined by

\[ V_t = \frac{N_s K T}{q} \] (6)

Where:

- \( I_{ph} \): photo current [A];
- \( I_0 \): diode saturation current [A];
- \( K \): Boltzmann constant (1.38e-23 J/K).
- \( V \): cell voltage [V];
- \( a \): diode ideality factor;
- \( N_s \): number of cells connected in series;
- \( q \): electron's charge e = 1.6 e-19 C;
$T$: temperature of the cell [°K];

The characteristics of the PV array used in this paper is listed in Table I. Figure 3 shows the characteristic curves of the photovoltaic system: P-V and I-V for a maximum generated power of around 400W under the standard test conditions (T= 25°C, G = 1000 W/m²) (Kouzou A & al., 2022).

<table>
<thead>
<tr>
<th>PV ENN solar energy ES120 Characteristics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage in open circuit (Voc)</td>
<td>141 V</td>
</tr>
<tr>
<td>Optimal operation voltage (Vmp)</td>
<td>110 V</td>
</tr>
<tr>
<td>Short circuit current (Isc)</td>
<td>1.32 A</td>
</tr>
<tr>
<td>Optimal operating current (Imp)</td>
<td>1.1 A</td>
</tr>
<tr>
<td>Maximum power on STC (Pmax)</td>
<td>121 W</td>
</tr>
</tbody>
</table>

Source: Authors

Figure 3. I-V and P-V Characteristics of PV string under STC condition (T= 25°C, G = 1000 W/m²).

3.2 SAPF MODELLING

The SAPF system is depicted in Fig 4, where the energy storage element is represented by capacitor Cdc, and the coupling filter connecting to the filter at the point of common coupling (PCC) is denoted by $R_f - L_f$. 
3.2.1 Model of SAPF in Three-Phase System (a-b-c)

In balanced systems, the source voltage can be expressed as follows:

\[
\begin{align*}
v_{sa} &= V_m \cos(\omega t) \\
v_{sb} &= V_m \cos(\omega t - 2\pi) \\
v_{sc} &= V_m \cos(\omega t + 2\pi)
\end{align*}
\]  (7)

According to the depicted equivalent circuit in Figure (4), one can express the three-phase voltages as follows:

\[
\begin{align*}
v_a &= v_{fa} - v_{ifa} - v_{Rfa} = v_{fa} - L_f \frac{d i_{fa}}{dt} - R_f i_{fa} \\
v_b &= v_{fb} - v_{Lfb} - v_{Rfb} = v_{fb} - L_f \frac{d i_{fb}}{dt} - R_f i_{fb} \quad (8) \\
v_c &= v_{fc} - v_{Lfc} - v_{Rfc} = v_{fc} - L_f \frac{d i_{fc}}{dt} - R_f i_{fc}
\end{align*}
\]

The three-phase equations are then given by:

\[
L_f \frac{d}{dt} \begin{bmatrix} i_{fa} \\ i_{fb} \\ i_{fc} \end{bmatrix} = -R_f \begin{bmatrix} i_{fa} \\ i_{fb} \\ i_{fc} \end{bmatrix} + \begin{bmatrix} v_{fa} \\ v_{fb} \\ v_{fc} \end{bmatrix} - \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} \quad (9)
\]

For the DC bus:

\[
C_{dc} \frac{dv_{dc}}{dt} = S_a i_{fa} + S_b i_{fb} + S_c i_{fc} \quad (10)
\]

Hence, the three-phase frame definition of the SAPF can be described using
the following equations:

\[
\begin{align*}
L_f a \frac{d i_f a}{d t} &= -R_f a i_f a + v_f a - v_s a \\
L_f b \frac{d i_f b}{d t} &= -R_f b i_f b + v_f b - v_s b \\
L_f c \frac{d i_f c}{d t} &= -R_f c i_f c + v_f c - v_s c \\
C_{dc} \frac{d v_{dc}}{d t} &= S_a i_f a + S_b i_f b + S_c i_f c
\end{align*}
\] (11)

\[ \begin{align*}
L_f a \frac{d i_f a}{d t} &= -R_f a i_f a + v_f a - v_s a \\
L_f b \frac{d i_f b}{d t} &= -R_f b i_f b + v_f b - v_s b \\
C_{dc} \frac{d v_{dc}}{d t} &= S_a i_f a + S_b i_f b
\end{align*}\] (12)

3.2.2 Model Of Sapf In Stationary Reference Frame (α – β)

By employing the Concordia Transform on the three-phase model presented in equation (11), the model in the stationary reference frame can be formulated as follows:

\[
\begin{align*}
L_f a \frac{d i_f a}{d t} &= -R_f a i_f a + v_f a - v_s a \\
L_f b \frac{d i_f b}{d t} &= -R_f b i_f b + v_f b - v_s b \\
C_{dc} \frac{d v_{dc}}{d t} &= S_a i_f a + S_b i_f b
\end{align*}
\] (12)

Where:

\[
\begin{bmatrix}
  i_f a \\
  i_f b
\end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix}
  1 & -\frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} \\
  0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}
\end{bmatrix} \begin{bmatrix}
  i_f a \\
  i_f b
\end{bmatrix}
\] (13)

\[
\begin{bmatrix}
  v_s a \\
  v_s b
\end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix}
  1 & -\frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} \\
  0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}
\end{bmatrix} \begin{bmatrix}
  v_s a \\
  v_s b
\end{bmatrix}
\] (14)

\[
\begin{bmatrix}
  v_f a \\
  v_f b
\end{bmatrix} = \begin{bmatrix}
  S_a \\
  S_b
\end{bmatrix} v_{dc}
\] (15)

\[
S_a = \frac{1}{\sqrt{6}} (2S_a - S_b - S_c)
\]

\[
S_b = \frac{1}{\sqrt{2}} (S_b - S_c)
\] (16)
3.2.3 Model of SAPF in Synchronous Reference Frame (d – q)

To derive the SAPF equations in the synchronous frame, you can utilize the Park transform in the following manner:

\[
\begin{align*}
L_{fd} \frac{di_{fd}}{dt} &= -R_{fd}i_{fd} + v_{fd} - v_{sd} \\
L_{fq} \frac{di_{fq}}{dt} &= -R_{fq}i_{fq} + v_{fq} - v_{sq} \\
C_{dc} \frac{dv_{dc}}{dt} &= S_{d}i_{fd} + S_{q}i_{fq}
\end{align*}
\]  

(17)

Where:

\[
\begin{bmatrix}
i_{fd} \\
i_{fq}
\end{bmatrix} = \begin{bmatrix}
\cos wt & \sin wt \\
-\sin wt & \cos wt
\end{bmatrix} \begin{bmatrix}
i_{fa} \\
i_{fb}
\end{bmatrix}
\]  

(18)

\[
\begin{bmatrix}
v_{sd} \\
v_{sq}
\end{bmatrix} = \begin{bmatrix}
\cos wt & \sin wt \\
-\sin wt & \cos wt
\end{bmatrix} \begin{bmatrix}
v_{sa} \\
v_{sb}
\end{bmatrix}
\]  

(19)

\[
\begin{bmatrix}
v_{fd} \\
v_{fq}
\end{bmatrix} = \begin{bmatrix}
S_{d} \\
S_{q}
\end{bmatrix} v_{dc}
\]  

(20)

\[
S_{d} = S_{\alpha} \cos wt + S_{\beta} \sin wt \\
S_{q} = -S_{\alpha} \sin wt + S_{\beta} \cos wt
\]  

(21)

3.2 QUASI-Z-SOURCE INVERTER

The Quasi Z-source inverter (QZSI) (qZSI) is a modified topology of Z-source inverter (QZSI) (ZSI) topology which is used mainly since 2002 in power electronics for converting DC power to AC power. Both the ZSI and the qZSI are designed to provide certain advantages over traditional inverters, such as improved voltage boosting capabilities, reduced harmonic distortion and overcoming their main limitation of same leg commutation. The qZSI is a modification of the original topology of ZSI that offers some advantages in terms of component stresses and power handling (Abu-Rub, H& al., 2012). Indeed, the main distinction between ZSI and qZSI lies in their circuit topology.
3.2.1 Z-Source Inverter (ZSI)

The ZSI employs an impedance network (usually a single or multiple inductor/capacitor combinations) between the DC source and the inverter's power switches (Liu Y & al., 2014). Where, the impedance network enables voltage boosting and flexibility in controlling the inverter's output. Furthermore, the ZSI can provide shoot-through operation (both the upper and lower switches of a leg are turned on simultaneously) without damaging the switches while this feature allows offering more flexibility of this new topology (Anderson J & al., 2008). Figure 5 shows the equivalent circuit of the ZSI.

Figure 5. a- ZSI equivalent circuit, b- non-shoot through state, and c- shoot through state.

3.2.2 Quasi-Z-Source Inverter (QZSI)

The qZSI uses a slightly different impedance network, which is generally a capacitor connected in series with a small inductor. This configuration offers some advantages in comparison to the ZSI topology in terms of reduced voltage stress on the switches, lower total harmonic distortion, and potentially better power handling capabilities. In the same time the qZSI can also achieve shoot-through operation without damaging the switches in similar way as in ZSI. Additionally, it can manage a broad range of input voltages, as depicted in Figure 6-(a). Differently from the traditional Voltage source inverter (VSI), the Z-source inverter introduces an extra operational mode defined as the shoot-through zero state, in which both upper and lower switches are simultaneously closed. This circumstance is typically avoided and it is not allowed in traditional inverter configurations due to the
potential damage of semiconductor devices and the input DC source that may result from the high current circulation that appears when the switches of the same leg are activated causing a hard short-circuit of the input DC source [18-21]. Hence, the qZSI operates under two modes, the first is similar to the conventional inverter that is called non-shoot-through mode, and the second mode is resulting from the aforementioned case of activation of the switches of one or more leg at the same time that is call shoot-through mode. These two modes are illustrated in Figure 6-(b) and Figure 6-(c), respectively.

Figure 6. a- QZSI equivalent circuit, b- non-shoot through state, and c- shoot through state.

4 CONTROL SCHEMES

The primary goal of an active power filter (APF) is to reduce the propagation of harmonics and offset reactive power through the injection of compensatory current. Achieving a unity power factor hinges on implementing a suitable control system for the APF. The entire control unit must effectively fulfill three key functions: generating reference currents, ensuring that the DC-link voltage matches the reference DC-link voltage, and producing control signals to be conveyed to the VSI power switches. Assessing APFs involves evaluating their performance in both steady-state and dynamic conditions, considering factors like THD reduction, reactive power compensation, and how they respond to rapid load changes. Additionally, techniques for identifying harmonics can be categorized into direct methods, where the injected current is measured, and indirect methods,
where the source current is measured.

4.1 DC-LINK VOLTAGE

Indirect control of the DC-link voltage is achieved through regulation of the voltage across the qZSI capacitor C1 where its average value should be kept equal to the reference required value. This control approach takes into account the distinctive nature of the DC link voltage, characterized by its pulsating waveform. Therefore, to avoid any kind of overshooting in the integrator term an anti-windup proportional-integral (PI) controller is used to ensure the saturation of the integral term and hence to avoid the overall system control from overshooting the set point or the reference to be reached. The proposed controller is illustrated in Figure 7 [4].

![Figure 7. Anti-windup PI voltage controller.](source: Authors)

4.2 COMPENSATING CURRENTS IDENTIFICATION

There are several methods that have been used for the identification of the compensating reference current, some of which are within the frequency approach such as fast Fourier transform and adaptive neural network, and others within the time domain such as d-q-0 (SRF) theory, and PQ theory (Ali T & al., 2018).

In this work, a modified SRF technique is used for the identification of the compensating currents to be injected into the grid as shown in Figure 8, where the photovoltaic source current is added along with the loss current so that the compensation current can be obtained as follows (Kamel K & al., 2018, Dehdouh A & al., 2023):

\[
\begin{bmatrix}
    i_{ca} \\
    i_{cb}
\end{bmatrix} =
\begin{bmatrix}
    \sin(\theta) & \cos(\theta) \\
    -\cos(\theta) & \sin(\theta)
\end{bmatrix}
\begin{bmatrix}
    \bar{i}_d - \bar{i}_c \\
    \bar{i}_q
\end{bmatrix}
\]  

(22)
Where:

\[ idc = ipv - iloss \]

**4.3 BAKSTEPPING CONTROL**

Backstepping control (BSC) is a nonlinear control technique used to design controllers for complex and nonlinear systems. It's particularly can be useful for systems that challenges when the conventional linear control methods are used. The BSC approach was developed to address the control of nonlinear systems while ensuring its stability and improving its performance. It involves a systematic process of designing a series of control laws for a dynamic system. Whereas, each control law is designed for a virtual subsystem of the overall system, and the control design process "backs up" through the subsystems, hence the term "backstepping."(Badra M S & al., 2017, Teta A, 2021). The control diagram of the backstepping controller is shown in figure 9.

The errors resulting from the difference between the compensating currents, which present the reference currents, and the output current of the inverter (injected currents into the grid) can be defined as follows:

\[ e_1 = if_a - ic_a \] (23)

\[ e_2 = if_b - ic_b \] (24)

\[ e_2 = if_c - ic_c \] (25)
The candidate functions of Lyapunov are chosen as follows:

\[ V = V_1 + V_2 + V_3 \]  \hspace{1cm} (26)

Where:

\[ V_1 = \frac{1}{2} e_1^2 \]  \hspace{1cm} (27)

\[ V_2 = \frac{1}{2} e_2^2 \]  \hspace{1cm} (28)

\[ V_3 = \frac{1}{2} e_3^2 \]  \hspace{1cm} (29)

Based on equation (11), the derivatives of the Lyapunov functions can be expressed through:

\[ \dot{V} = \dot{V}_1 + \dot{V}_2 + \dot{V}_3 \]  \hspace{1cm} (30)

Where:

\[ \dot{V}_1 = e_1 \dot{e}_1 = e_1 \left( \frac{1}{L_f} \left( v_{fa} - v_a - R_{fa} i_{fa} \right) - i_{ca} \right) \]  \hspace{1cm} (31)

\[ \dot{V}_2 = e_2 \dot{e}_2 = e_2 \left( \frac{1}{L_f} \left( v_{fb} - v_b - R_{fb} i_{fb} \right) - i_{cb} \right) \]  \hspace{1cm} (32)

\[ \dot{V}_3 = e_3 \dot{e}_3 = e_3 \left( \frac{1}{L_f} \left( v_{fc} - v_c - R_{fc} i_{fc} \right) - i_{cc} \right) \]  \hspace{1cm} (33)

In order to satisfy the Lyapunov stability conditions, it is necessary to reformulate equations (29), (30) and (31) as follows:

\[ \dot{V}_1 = -k_1 e_1^2 + e_1 \Delta_1 \]  \hspace{1cm} (34)

\[ \dot{V}_2 = -k_2 e_2^2 + e_2 \Delta_2 \]  \hspace{1cm} (35)
\[ \dot{V}_3 = -k_3 e_3^2 + e_3 \Delta_3 \quad (36) \]

Where:

\[ \Delta_1 = \left( k_1 e_1 + \frac{1}{L_f} (v_{fa} - v_a - R_f i_{fa}) - ic_a \right) \quad (37) \]

\[ \Delta_2 = \left( k_1 e_1 + \frac{1}{L_f} (v_{fb} - v_b - R_f i_{fb}) - ic_b \right) \quad (38) \]

\[ \Delta_3 = \left( k_1 e_1 + \frac{1}{L_f} (v_{fc} - v_c - R_f i_{fc}) - ic_c \right) \quad (39) \]

To guarantee the asymptotic stability of the proposed control approach, it is imperative to satisfy the Lyapunov condition such as \( \dot{V}_1 < 0 \), \( \dot{V}_2 < 0 \), and \( \dot{V}_3 < 0 \), hence \( V < 0 \). This entails meeting the following specified criteria:

\[
\begin{cases}
\Delta_1 = \left( k_1 e_1 + \frac{1}{L_f} (v_{fa} - v_a - R_f i_{fa}) - ic_a \right) = 0 \\
\Delta_2 = \left( k_2 e_2 + \frac{1}{L_f} (v_{fb} - v_b - R_f i_{fb}) - ic_b \right) = 0 \\
\Delta_3 = \left( k_3 e_3 + \frac{1}{L_f} (v_{fc} - v_c - R_f i_{fc}) - ic_c \right) = 0
\end{cases}
\]

(40)

This results in the ultimate expression for the derivative of the Lyapunov function:

\[ \dot{V} = -k_1 e_1^2 - k_2 e_2^2 - k_3 e_3^2 < 0 \quad (41) \]

Based on equation (12), the output voltage references for each phase of the Active Power Filter (APF) can be obtained. These references are crucial, as they must facilitate the injection of currents into the Point of Common Coupling (PCC) of the grid to effectively compensate for harmonic currents. Additionally, these references must align with the Lyapunov theory’s stability condition, ensuring the
generation of a stabilizing function. The output voltage references can be obtained using the following expressions:

\[ v^*_f = L_f(-k_1 e_1 + i c_a) + v_s + R_f i_f \]  

\[ v^*_b = L_f(-k_2 e_2 + i c_b) + v_s + R_f i_f \]  

\[ v^*_c = L_f(-k_3 e_3 + i c_c) + v_s + R_f i_f \]

4.4 INVERTER CONTROL TECHNIQUE

The simple boost control technique (SBC) is the simplest control that have been used in this paper for the control of the Z-source inverter to ensure the regulation of its boost factor or voltage gain.

In a Z-source inverter, the boost factor is a key parameter that determines the output AC voltage level. It can be controlled by adjusting the modulation index of the inverter's switches. A simplified control approach such as SBC can be used to achieve this regulation with a less complexity compared to more advanced control methods (Teta A & al., 2021). The main idea of SBC is illustrated in Figure 10.
The duty cycle is defined based on the intersection between the two reference lines and the triangular carrier signal. The inverter operates into the shoot-through mode whenever the triangle carrier signal exceeds the positive reference line or drops below the negative line. While the inverter operates under the conventional PWM approach whenever the triangular signal is within the interval of the two reference lines. Moreover, the shoot-through duty ratio undergoes changes inversely proportional to the modulation index, which can be mathematically expressed as explained and proved by (Singh H & al., 2018, Benzahia, A& al., 2019).

\[ D_0 = 1 - M \]  

(45)

Where M is the modulation index.

The voltage gain and boost factor of the Z-source inverter are, respectively:

\[ G = \frac{M}{2M-1} \]  

(46)

\[ B = \frac{1}{2M-1} \]  

(47)

Finally, the peak voltage stress at the input side of the inverter can be expressed as:
\[ \overline{v_{dc}} = \frac{1}{2M-1} V_{in} \]  

(48)

### 4.5 MAXIMUM POWER POINT CONTROL

The Hill Climbing Maximum Power Point Tracking (HC-MPPT) is used in this work which is a widely used in photovoltaic (PV) solar systems to maximize the energy extraction from the solar panels. The primary goal of the (MPPT) algorithm is to ensure that the PV system is operating at its maximum power point (MPP) independently of the location and the climate conditions.

The HC-MPPT algorithm is based on a simple approach but it has proved its effectiveness as a control technique to ensure the maximum power extraction from the PV system. It is based on the continuous adjusting of the operating point of the solar panels in small increments and observing whether the power output increases or decreases. The algorithm "climbs" the power curve to reach the maximum power point. The operation principle of this approach is shown in details in the flowchart of Figure 11.

It's important to note that while the Hill Climbing MPPT algorithm is simple and can work well under certain conditions, it may suffer from oscillations around the MPP, especially when the solar irradiance changes rapidly. To address this, some implementations use additional techniques such as Gray Wolf Optimization (GWO) or Practical Swarm Optimization (PSO), which offer better dynamic performance and faster tracking under changing conditions (De Brito, M & al, 2012, Boutota F & al 2023).
Figure 11. Hill climbing flowchart.

5 SIMULATION RESULTS

In this study, the proposed system is validating by MATLAB/Simulink environment. The parameters of this system at shown in figure 01 are listed in the following table:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid</td>
<td></td>
</tr>
<tr>
<td>Supply Vs</td>
<td>50 V, 50Hz</td>
</tr>
<tr>
<td>Source Resistance RS</td>
<td>0.1 Ω</td>
</tr>
<tr>
<td>Source Inductance Ls</td>
<td>50 μH</td>
</tr>
<tr>
<td>Non-linear load</td>
<td></td>
</tr>
<tr>
<td>Load resistance RL</td>
<td>10 Ω</td>
</tr>
<tr>
<td>Load inductance LL</td>
<td>1 mH</td>
</tr>
<tr>
<td>SAPF</td>
<td></td>
</tr>
<tr>
<td>Filter inductance Lf</td>
<td>2 mH</td>
</tr>
<tr>
<td>Filter resistance RF</td>
<td>10 m Ω</td>
</tr>
<tr>
<td>Switching frequency sf</td>
<td>5000 Hz</td>
</tr>
<tr>
<td>QZSI</td>
<td></td>
</tr>
<tr>
<td>QZSI inductances (L1), (L2)</td>
<td>560 μH</td>
</tr>
<tr>
<td>QZSI capacitors (C1), (C2)</td>
<td>1100 μF</td>
</tr>
<tr>
<td>Input capacitor (Cln)</td>
<td>1 mF</td>
</tr>
<tr>
<td>HIL: (L1), (L2), (Lb)</td>
<td>50 μH</td>
</tr>
</tbody>
</table>

Source: Authors
5.1 UNSTEADY IRRADIANCE

In this scenario, the irradiance profile is shown in figure 12. So it takes three values. Figure 13 illustrates respectively the power, voltage, and current of the PV system.

The source voltage is shown in figure 14, it remains fixed despite the change in radiation, unlike the current value, which decreases as the radiation increases and increases as the radiation decreases as illustrated in figure 16. Figure 15 presents the non-linear load current which is highly contaminated by harmonic components, and figure 17 shows the compensation current. This current depends on the irradiance value, when the irradiance increases the compensation current increases.
The active power generated by the primary source diminishes, dropping from 1.1 kW to approximately 0.85 kW, attributable to the power contribution from the PV source that bolsters the primary power network. Meanwhile, reactive power exhibits oscillations around zero, as depicted in figure 18. Across all phases, the total harmonic distortion (THD) decreases to less than 3 percent as shown in figure 19, and their magnitudes remain equitably distributed under conditions of fluctuating irradiance.

The DC-link voltage is controlled indirectly by the control of the QZSI capacitor. The voltage across the QZSI capacitor tracking voltage reference after
small deviations at 0.3s, and 0.6s because of unsteady radiation.

Figure 20. QZSI capacitor voltage.

Source: Authors

The main contribution of this paper appears clearly in the following figures. The improved SRF theory allows reducing of the peak value of the voltage across DC-link from 220V to less then 205V as shown in figure 21, and 22 respectivly.

Figure 21. DC-link voltage with classic SRF.

Source: Authors

Figure 22. DC-link voltage with improved SRF.

Source: Authors
The last figures 23, and 24 show the current loss by the SAPF without and with improved SRF theory respectively, this current loss is compensated by adding the PV current in the SRF theory to become fixed around zero.

Figure. 23. Current loss with classic SRF.

Source: Authors

Figure. 24. Current loss with improved SRF.

Source: Authors

6 CONCLUSION

In this study, it was confirmed that nonlinear loads cause the propagation of harmful harmonics which in turn influences the source currents. To solve such a problem, an overall evaluation was performed of the current control approach (backstepping) for the shunt active power filter (SAPF). The SAPF is based on a photovoltaic source through a single-stage QZSI which uses the improved SRF theory to reduce the DC-link voltage overshoot by compensation current loss. The elaborated filter equipped with the mentioned controller is tested under unsteady irradiation. Finally, through the presented simulation results, the control method introduced good results in terms of THD diminution and reactive power compensation.
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