# Shunt active power filter control based on Z-source inverter fed by PV system

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**ABSTRACT**

In this paper, an integration of a Z-source inverter (ZSI)-based shunt active power filter (SAPF) fed by a photovoltaic (PV) system for the enhancement of power quality is proposed. The ZSI provides substantial advantages including improved boost functionality, reduced harmonics, and superior performance compared to traditional inverters. In this paper, the SAPF control is based on instantaneous reactive power theory. A proportional-integral (PI) controller is implemented for DC-link voltage control, with the primary aim of this study being the elimination of total harmonic distortion (THD) in the source current. To demonstrate the effectiveness of the proposed approach, simulations were conducted using MATLAB/Simulink across various operating conditions. The outcomes substantiate and validate the efficacy of the proposed method.



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## 1. INTRODUCTION

The widespread use of non-linear loads in industrial applications has caused undesirable effects related to the power quality [1], [2]. This increase within the use of non-linear masses encompasses a vital impact on consumers, because the main issues in power quality consist current, voltage and frequency distortions. However, the need for consistent power quality is growing due to the increasing use of sensitive devices that rely on smooth sine waveforms [3], [4]. To eliminate harmonic currents and address the power issues caused by these non-linear loads, numerous studies have been conducted. Historically, passive filters have been used to reduce current harmonics and alleviate energy pollution in the network over an extended period. However, this type of filter has several drawbacks, such as being large in size, heavy, and sensitive to dynamic parameters, leading to resonance issues.

These challenges were successfully addressed by implementing an active filter, a concept that gained recognition around the 1970s [5], [6]. The shunt active power filter (SAPF) offers a versatile solution for reducing harmonic currents and improving power factor. Moreover, it can effectively adjust to various load types. The SAPF system consists of a voltage/current source inverter that interacts with a linked capacitor connected in parallel with non-linear loads [7], [8]. The electrical converter produces the required harmonic elements to mitigate the harmonic currents caused by non-linear loads. As a result, it aligns the main current to be sinusoidal and in phase with the supply voltage [9], [10]. Consequently, filters have become significantly important [11],

[12]. The second option offers numerous benefits, such as the elimination of harmonic current, compensation of reactive power, and simultaneous injection of active power. However, it also has several drawbacks, including non-linear properties and a strong reliance on environmental conditions. There is an urgent need for accurate monitoring of the maximum energy harvested from photovoltaic sources [13]. Many approaches for maximum power point tracking (MPPT) have been suggested in the literature to address this issue. These include techniques like perturbation and observation (P&O), which involves perturbing the photovoltaic system and monitoring the changes in the output power. The conductance method utilizes the slope of the PV to determine the point of peak energy, and these approaches are reinforced by artificial intelligence [13], [14]. Additionally, Z-source inverter or ZSI features an additional state termed "shoot-through," which is created by concurrently operating the higher and lower switches of the same leg. attributable to this extra state, the electrical phenomenon periodic voltage will be simply controlled employing a single-phase configuration [15], [16].

The aim of this article is to introduce a cost-effective solution for current compensation by proposing a three-phase active power filter connected to a PV system via ZSI [11] managed by instantaneous reactive power theory [17]. The DC side voltage control of the SAPF was achieved using a standard PI controller [18]. The effectiveness and performance of the system under study were evaluated through simulation using sim power system in MATLAB/Simulink. The following sections of this paper is outlined. Section 2 details the SAPF topology based on the Z-source inverter, while section 3 covers the control of SAPF. Section 4 presents simulation results, and lastly, section 5 provides the conclusions of this work.

## 2. SAPF TOPOLOGY BASED ON Z-SOURCE INVERTER

### 2.1. PV power generating unit

Excess power generation from the PV power generation system can be routed through the DC-DC converter circuit. Also, it can be used in the energy storage unit and start providing the energy stored in the battery when a PV system is not powerful enough as shown in Figure 1 [19]. The subsequent are the essential equations of the PV module as shown in Figure 2. The modeling of the PV panel can be described as in (1) and (2).

$$I_{ph} = I_d + I_{pv} = I_{ph} - I_d \tag{1}$$

$$V_{pv} = \frac{AkT_c}{e} ln\left(\frac{I_{ph}+I_d-I_c}{I_d}\right) - R_s I_c \tag{2}$$

Where $I_{pv}$ donates output current in amps. Photovoltaic cell voltage is displayed as Figure 2. The output of boost converter (12 V) is supplied to the Z-source inverter to boost. The equivalent ZSI circuit in shoot through state is presented in Figure 3(a). The voltage of inductor is equal to capacitor voltage VL=VC while $T_{st}$ cycle.

The indicated ZSI circuits in the state of non-shoot through shown in Figure 3(b). The change pattern of ZSI is shown in Figure 4. During the non-shoot through state, the inductance voltage $V_L$ and also the input voltage $V_i$ may be described as (3)-(6).

$$V_L = V_{dc} - V_c \tag{3}$$

$$V_i = \frac{1}{1-\frac{T_{st}}{T}} V_{dc} \tag{4}$$

$$V_i = BV_{dc} \tag{5}$$

$$B_i = \frac{1}{1-\frac{T_{st}}{T}} \tag{6}$$

Where $B \geq 1$; the operation modes are: i) PV power generation mode, ii) battery backup mode, and iii) continuous supply mode as shown in Figures 5-7.

#### 2.1.1. PV power generation mode

During daylight hours or when there is ample sunlight, the photovoltaic power generation mode is activated to produce sufficient energy. The PV sustained SAPF functions as a harmonics and reactive power controller, and any surplus power is stored in a battery. Refer to Figure 5, it is the current flow chart detailing the photovoltaic power generation mode.

#### 2.1.2. Battery backup mode

Battery backup mode is supported overnight or in the absence of sunlight. In battery backup mode ZSI operates to hardly manage compensation continuity. Figure 6 indicates the output current flowchart for battery backup mode.

### 2.1.3. Continuous supply mode

During a voltage interruption, the PV-SAPF model ensures a consistent supply of power to critical and sensitive loads. In such instances, the solar PV power supply unit or battery backup unit serves as the power source for the connected load. Semiconductor switches are used to disconnect the power supply from the distribution network.

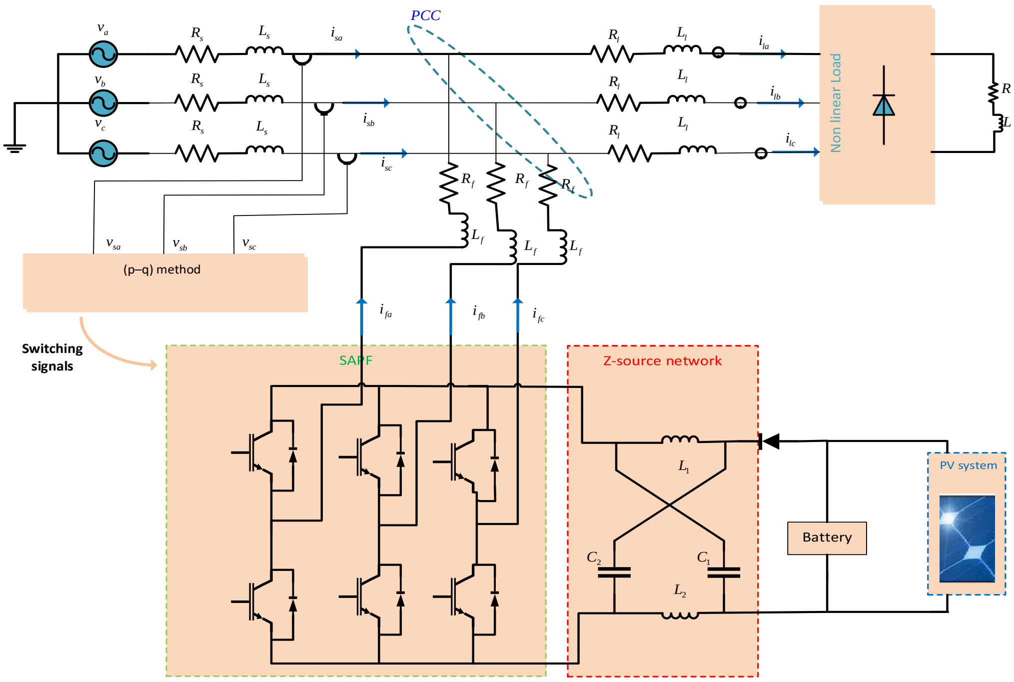



Figure 1. General scheme of SAPF based on two-level ZSI

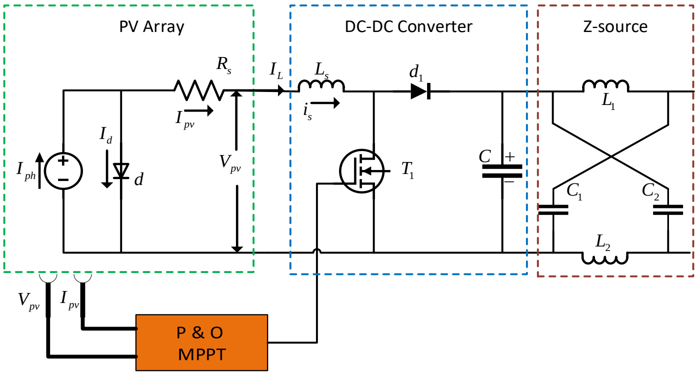
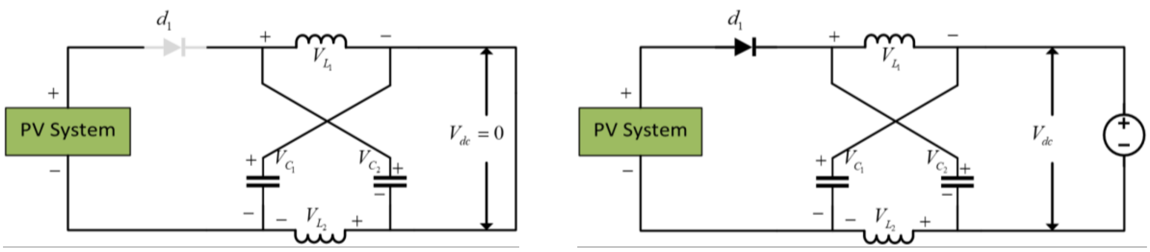



Figure 2. The proposed scheme of SPV array and DC-DC converter with MPPT control circuitry




(a) (b)

Figure 3. Equivalent scheme of ZSI (a) shoot through state and (b) non-shoot through state

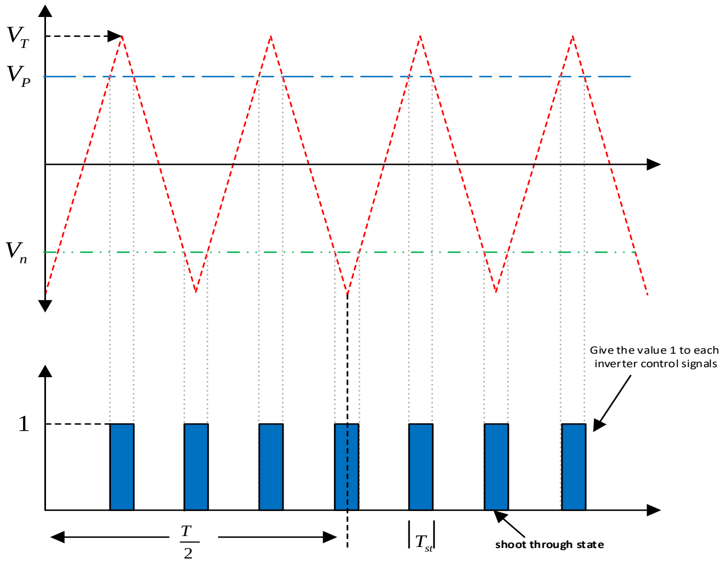



Figure 4. Switching cases for ZSI

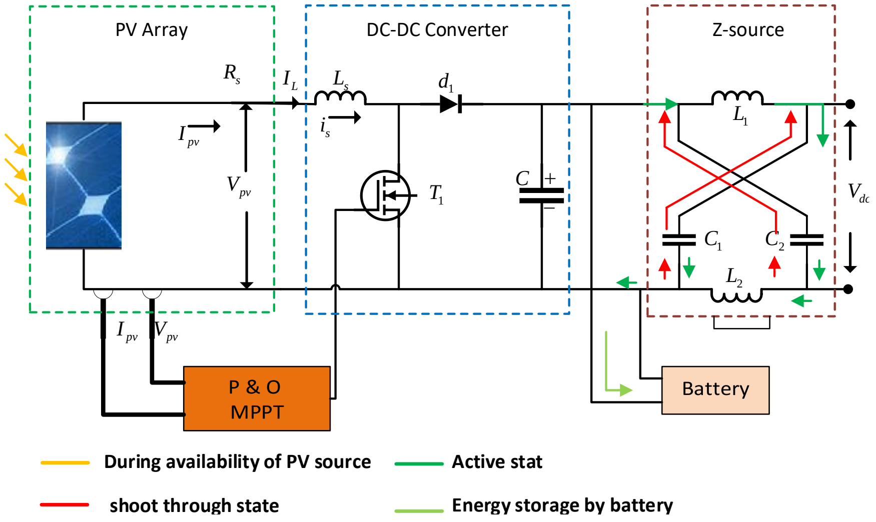



Figure 5. Current flowchart for photovoltaic power generation mode

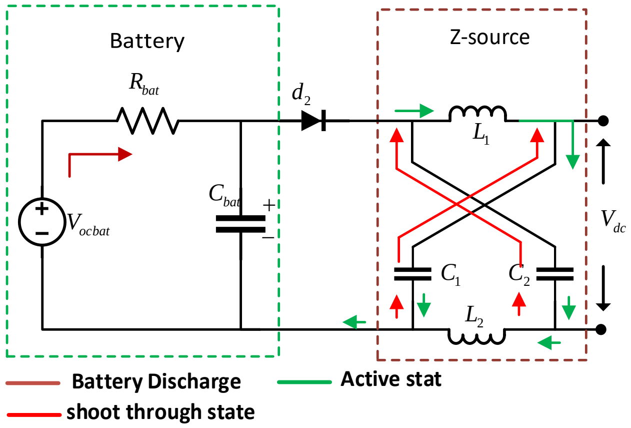



Figure 6. Current flowchart for battery backup mode

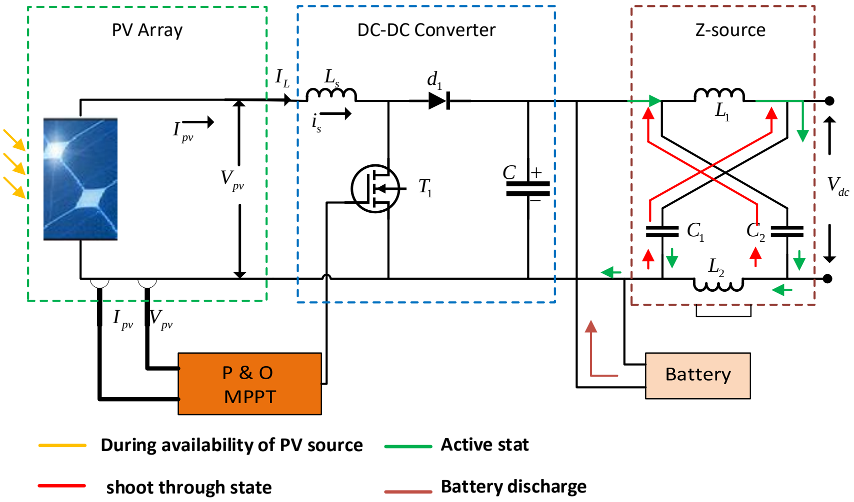



Figure 7. Current flow chart for continuous supply mode

## 3. PV-SAPF CONTROL SCHEME

The current compensation is implemented in the control scheme based on currently reactive power theory for 3-phase PV-SAPF. This is one of the most popular theories that has been used. Not only in theory but also in practice can be considered as the first successfully implemented method based on the use of static converters [20].

### 3.1. Hysteresis control

The principle of hysteresis output control is to keep each of the generated currents within a band surrounding the reference currents. Any violation of this band gives a commutation command to stay within the band. The main function of the proposed model is to keep the output current within the standard limits.

### 3.2. Fixed band hysteresis regulation

With this kind of current control, the frequency essentially depends on the derivation of the target current as displayed in Figure 8. The latter depends on the size of the decoupling inductance and the voltage drop across it. The filter affects the switching frequency and the dynamic behavior of the active filter. Figure 9 displays the main promotion of this method is the simplicity of implementation, while the variable switching frequency, which cannot be properly controlled, can become its main disadvantage [21].

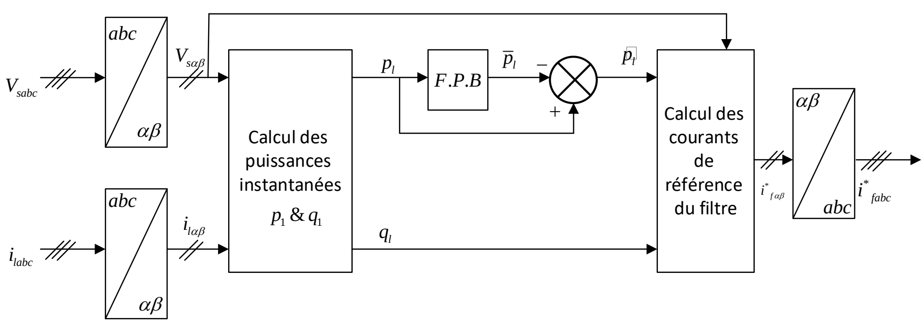



Figure 8. Schematic diagram of the instantaneous power method

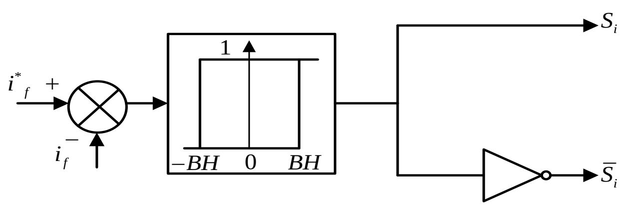


Figure 9. Hysteresis band current controller

## 4. SIMULATION RESULTS

The elements of the PV-SAPF system are presented in Table 1. Modelling is carried out using MATLAB/Simulink. The results of the simulation study are presented before and after connecting the PV-SAPF system. It is noted that the initial state of the capacitors voltage in the system is zero as revealed in Figure 10.

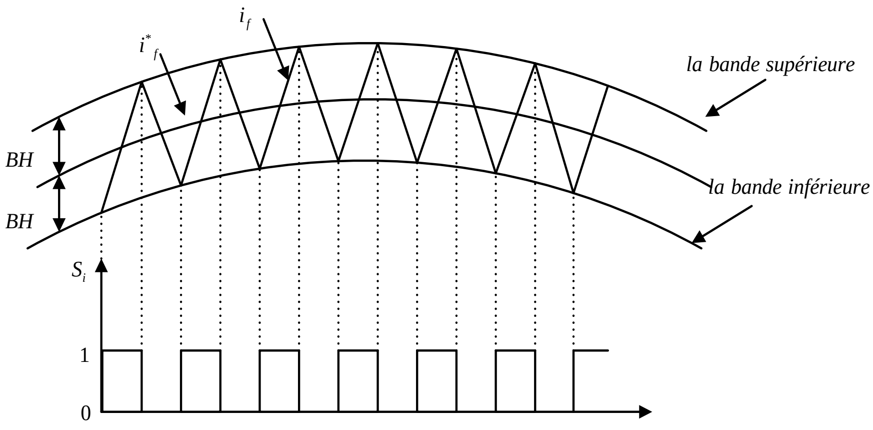



Figure 10. Control of switches by fixed band hysteresis

### 4.1. DC voltage variation

First, the gain of proportional integral controller and its response to a stepwise disturbance in the DC bus voltage from 160 to 140 V is verified in Figure 11. Obviously, the traditional PI controller gives very satisfactory results. It can help in detecting the output current under control.

### 4.2. Continuous operation

The results of the state of the system before and after connecting of the filter are depicted as shown in Figures 12 to 14 [22]–[25]. Figure 15(a)-(c) shows the source current, filter current and DC bus voltage, respectively, which are the results obtained with the filter connected. Before the filter is connected, the load current is fully supplied from the network. The capacitors in the Z-source network are charged from the battery bank, which in turn is charged by the SPV, until the capacitors reach the line voltage level $V\ dc\ =\ 80\ volts$. Where we notice the elimination of ripple in the active and reactive powers after connecting the filter, and thus the reactive power was successfully compensated.

### 4.3. Load variation

In this case, the burden is suddenly reduced from $R_1 = 24\,\Omega$ to $R_2 = 16\,\Omega$ (with a change of 33%). A raise When the source current is increased, there is a minor reduction in voltage across the two terminals of the Z-source inverter (approximately 1 V). Figure 11 demonstrates the highly satisfactory outcomes. Table 2 presents a comparison showing the superiority of the proposed system over other methods.

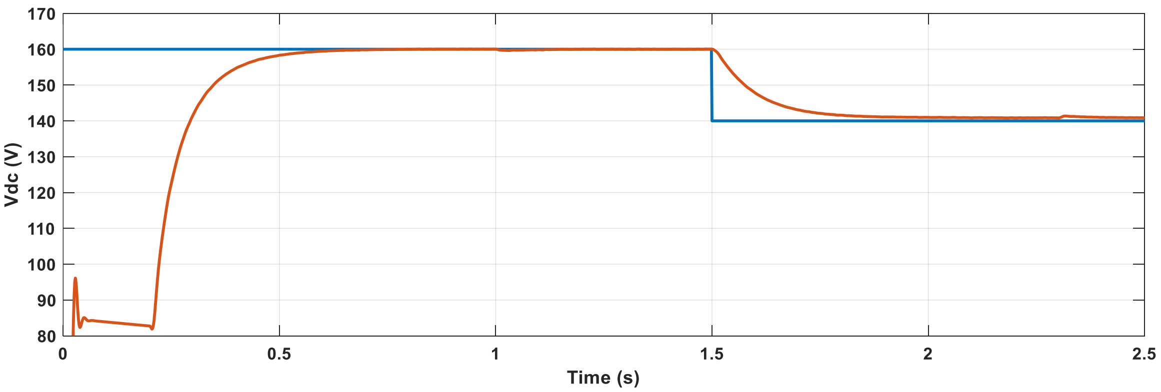



Figure 11. DC bus voltage response with conventional PI-based reference DC voltage variation

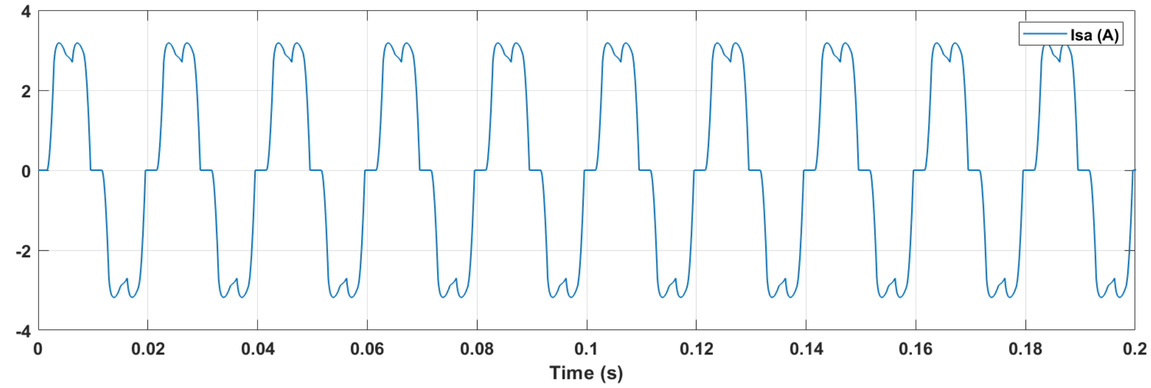



Figure 12. Simulation results of source current before connecting the filter

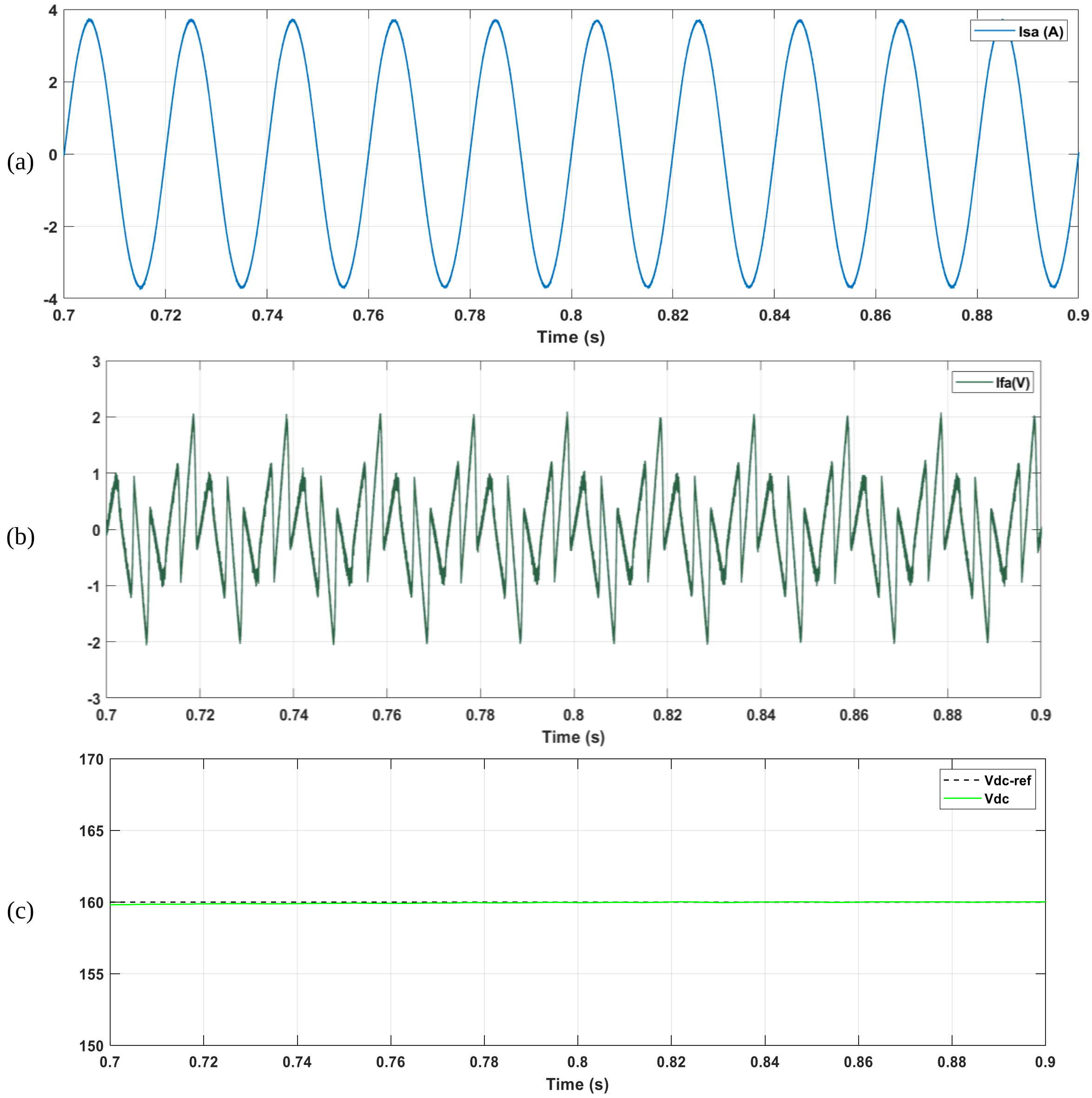



Figure 13. Simulation results of (a) source current $I_{sa}$, (b) filter $I_{fa}$, and (c) DC bus voltage $V_{dc}$, after the modelling of ZSI-SAPF

Table 1. Parameters of system

| Parameters | | Value | Parameters | | Value |
|---|---|---|---|---|---|
| System voltages (line to line) Vrms | | $57\ V$ | Capacitance | $C_{z-source}$ | $1100\ \mu F$ |
| Frequency | $f$ | $50\ Hz$ | Switching frequency | $f_{z-source}$ | $1\ KH$ |
| Filter (series SAPF) | $L_s, R_s$ | $0.45\ \Omega, 2.5\ mH$ | $K_p$ | $K_p$ | 6.8 |
| Battery voltage | | $30\ V$ | $K_i$ | $K_i$ | 1.1 |
| Battery capacity | | $33\ Ah$ | Sample time | | $1e^{-4}$ |
| Filter (shunt SAPF) | $L_f, R_f$ | $0.9\ \Omega, 4\ mH$ | Charge non-linéaire | $R_C$ | $17\ \Omega$ |
| Inductance | $L_{z-source}$ | $5\ mH$ | | | |

Table 2. Comparison results between the proposed and different control strategies

| Topology | Control strategy | The output results of THD of proposed model | |
|---|---|---|---|
| | | Before connecting SAPF | After connecting SAPF |
| SAPF | (p–q) method proposed in [3] | 20.03% | 1.78% |
| SAPF | DPC strategy proposed in [3] | / | 1.16% |
| SAPF | Predictive-DPC-SVM strategy proposed in [3] | / | 0.90% |
| SAPF | Predictive control strategy proposed in [23] | 22.60% | 0.81% |
| ZSI-SAPF | (p–q) method proposed in this paper | 23.18% | 0.72% |

(a)

(b)

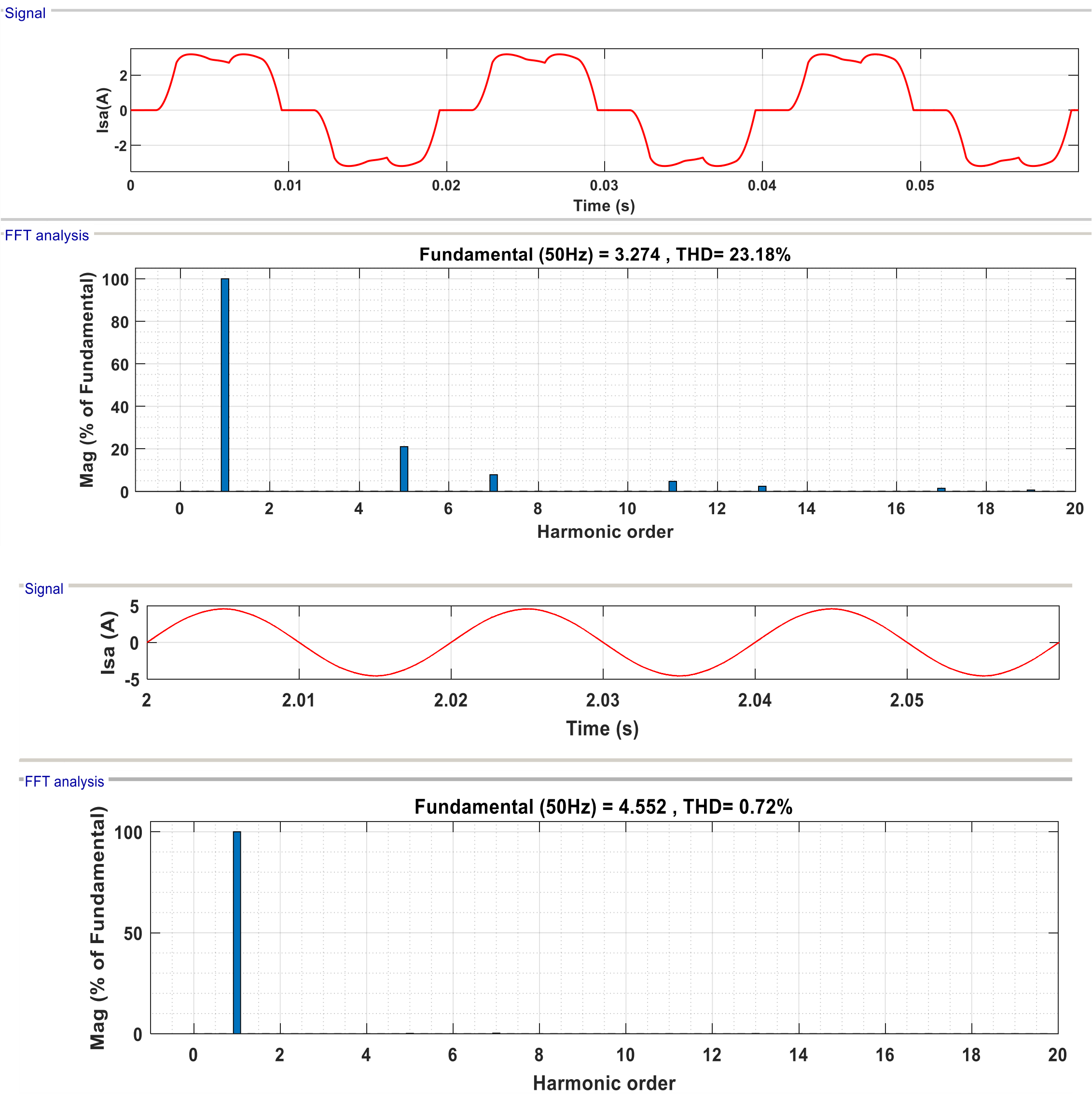



Figure 14. The results of the ZSI-SAPF: (a) before and (b) after

(a) (b) (c) (d) (e)

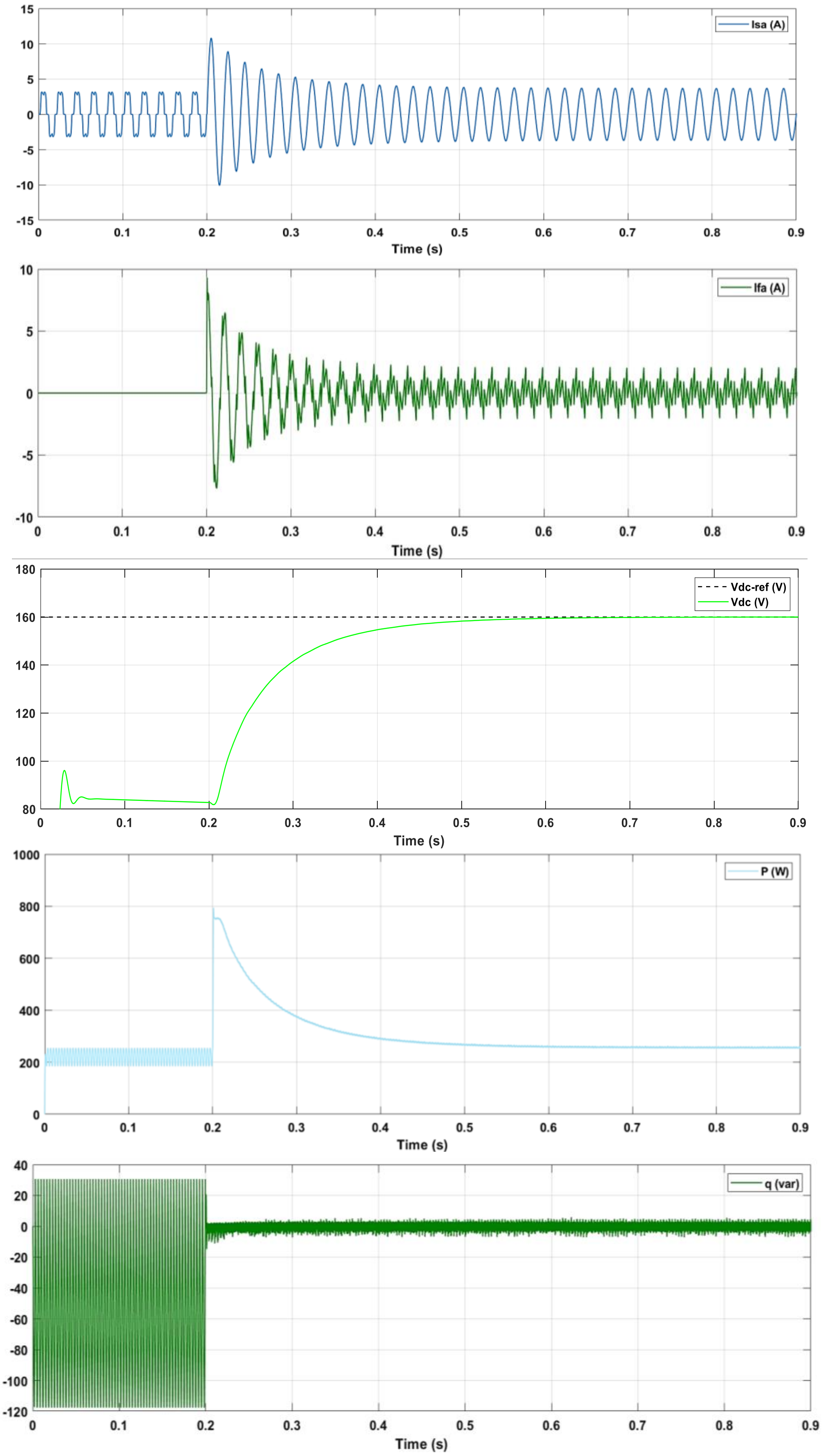



Figure 15. Simulation results of (a) source current I_sa, (b) filter I_fa, and (c) DC bus voltage V_dc, after the modelling of ZSI-SAPF

## 5. CONCLUSION

In this paper, a three-phase shunt active filter design utilizing a Z-source inverter controlled by instantaneous reactive power theory and a PI hysteresis control algorithm is presented. Performance of the proposed structure was evaluated under different operating with a non-specific load. Simulation results using MATLAB/Simulink show satisfactory performance. Besides, to underscore the performance of the proposed structure, an improvement in efficiency was obtained as compared to the conventional structure. On the other hand, it is evident that the proposed structure achieves the best THDi in the simulation test by 0.72%. Furthermore, the system performance can be improved by extending the control algorithm to optimize the parameters of the PI controller. In addition, the power factor operation is improved since the reactive power is equal zero.

## REFERENCES


[1] B. Mansour, B. Abdelkader, and B. Said, "Application of backstepping to the virtual flux direct power control of five-level three-phase shunt active power filter," *International Journal of Power Electronics and Drive Systems*, vol. 4, no. 2, p. 173, 2014.

[2] H. Akagi, "Modern active filters and traditional passive filters," *Bulletin of the Polish Academy of Sciences: Technical Sciences*, vol. 54, no. 3, pp. 255–269, 2006.

[3] A. Krama, L. Zellouma, A. Benaissa, B. Rabhi, M. Bouzidi, and M. F. Benkhoris, "Design and Experimental Investigation of Predictive Direct Power Control of Three-Phase Shunt Active Filter with Space Vector Modulation using Anti-windup PI Controller Optimized by PSO," *Arabian Journal for Science and Engineering*, vol. 44, no. 8, pp. 6741–6755, 2019, doi: 10.1007/s13369-018-3611-6.

[4] V. Mahajan, P. Agarwal, and H. O. Gupta, "Implementation of High-Voltage Multilevel Harmonic Filter Based on Rotated Carrier Modulation and Artificial Intelligence-Based Controllers," *Arabian Journal for Science and Engineering*, vol. 39, no. 10, pp. 7127–7143, 2014, doi: 10.1007/s13369-014-1280-7.

[5] F. Z. Peng, H. Akagi, and A. Nabae, "A Study of Active Power Filters Using Quad-Series Voltage-Source PWM Converters for Harmonic Compensation," *IEEE Transactions on Power Electronics*, vol. 5, no. 1, pp. 9–15, 1990, doi: 10.1109/63.45994.

[6] H. Sasaki and T. Machida, "A new method to eliminate AC harmonic currents by magnetic flux compensation — Considerations on basic design," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-90, no. 5, pp. 2009–2019, 1971, doi: 10.1109/TPAS.1971.292996.

[7] L. Zellouma *et al.*, "Etude de l'auto-adaptivité du filtre actif parallèle aux variations de la charge (in English: Study of the self-adaptivity of the parallel active filter to load variations)," *Revue Synthèse N° 17*, Janvier, pp. 64–72, 2008.

[8] A. Chebabhi, M. K. Fellah, A. Kessal, and M. F. Benkhoris, "Comparative study of reference currents and DC bus voltage control for Three-Phase Four-Wire Four-Leg SAPF to compensate harmonics and reactive power with 3D SVM," *ISA Transactions*, vol. 57, pp. 360–372, 2015, doi: 10.1016/j.isatra.2015.01.011.

[9] S. Saidi, R. Abbassi, and S. Chebbi, "Quality improvement of shunt active power filter with direct instantaneous power estimator based on Virtual Flux," *International Journal of Control, Automation and Systems*, vol. 14, no. 5, pp. 1309–1321, 2016, doi: 10.1007/s12555-014-0264-4.

[10] V. K. A. Shankar and N. S. Kumar, "Implementation of Shunt Active Filter for Harmonic Compensation in a 3 Phase 3 Wire Distribution Network," *Energy Procedia*, vol. 117, pp. 172–179, 2017, doi: 10.1016/j.egypro.2017.05.120.

[11] S. Parthiban and M. Vijayakumar, "Experimental validation of solar PV sustained ZSI based Unified Active Power Filter for enrichment of power quality," *Automatika*, vol. 62, no. 1, pp. 154–171, 2021, doi: 10.1080/00051144.2021.1913817.

[12] V. Madhaiyan and V. Subramaniam, "Extended reference signal generation scheme for integration of unified power quality conditioner in grid-connected photovoltaic system," *Electric Power Components and Systems*, vol. 43, no. 8–10, pp. 914–927, 2015, doi: 10.1080/15325008.2015.1008708.

[13] M. A. Mansor, K. Hasan, M. M. Othman, S. Z. B. M. Noor, and I. Musirin, "Construction and performance investigation of three-phase solar PV and battery energy storage system integrated UPQC," *IEEE Access*, vol. 8, pp. 103511–103538, 2020.

[14] J. M. Kwon, K. H. Nam, and B. H. Kwon, "Photovoltaic power conditioning system with line connection," *IEEE Transactions on Industrial Electronics*, vol. 53, no. 4, pp. 1048–1054, 2006, doi: 10.1109/TIE.2006.878329.

[15] J. Abbasi Bolaghi, A. Taheri, and M. H. Babaei, "Switched-capacitor inductor Z-source inverter with an impedance network," *International Transactions on Electrical Energy Systems*, vol. 31, no. 5, 2021, doi: 10.1002/2050-7038.12529.

[16] F. Z. Peng, M. Shen, and Z. Qian, "Maximum boost control of the Z-source inverter," *IEEE Transactions on Power Electronics*, vol. 20, no. 4, pp. 833–838, 2005, doi: 10.1109/TPEL.2005.850927.

[17] Y. L. Cui, H. Liu, J. Q. Wang, and S. G. Sun, "Simulation and reliability analysis of shunt active power filter based on instantaneous reactive power theory," *Journal of Zhejiang University: Science A*, vol. 8, no. 3, pp. 416–421, 2007, doi: 10.1631/jzus.2007.A0416.

[18] J. H. van der Lee, W. Y. Svrcek, and B. R. Young, "A tuning algorithm for model predictive controllers based on genetic algorithms and fuzzy decision making," *ISA Transactions*, vol. 47, no. 1, pp. 53–59, 2008, doi: 10.1016/j.isatra.2007.06.003.

[19] A. Abdelkarim, B. Youcef, L. Zellouma, D. Toumi, A. Ibrahim, and R. Aboelsaud, "Improved space vector modulation algorithm of 5-level three-phase z-source based cascaded inverter," *International Journal of Power Electronics and Drive Systems*, vol. 13, no. 4, pp. 2286–2295, 2022, doi: 10.11591/ijpeds.v13.i4.pp2286-2295.

[20] R. S. Herrera, P. Salmerón, and H. Kim, "Instantaneous reactive power theory applied to active power filter compensation: Different approaches, assessment, and experimental results," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 1, pp. 184–196, 2008, doi: 10.1109/TIE.2007.905959.

[21] A. Tripathi and P. C. Sen, "Comparative Analysis of Fixed and Sinusoidal Band Hysteresis Current Controllers for Voltage Source Inverters," *IEEE Transactions on Industrial Electronics*, vol. 39, no. 1, pp. 63–73, 1992, doi: 10.1109/41.121913.

[22] I. of E. and E. Engineers, *IEEE recommended practice and requirements for harmonic control in electric power systems*. IEEE, 2014.

[23] A. Pigazo, V. M. Moreno, and E. J. Estebanez, "A recursive park transformation to improve the performance of synchronous reference frame controllers in shunt active power filters," *IEEE Transactions on Power Electronics*, vol. 24, no. 9, pp. 2065–2075, 2009.

[24] A. Ibrahim, R. Aboelsaud, and S. Obukhov, "Improved particle swarm optimization for global maximum power point tracking of partially shaded PV array," *Electrical Engineering*, vol. 101, no. 2, pp. 443–455, Jun. 2019, doi: 10.1007/s00202-019-00794-w.

[25] S. Obukhov, A. Ibrahim, A. A. Zaki Diab, A. S. Al-Sumaiti, and R. Aboelsaud, "Optimal Performance of Dynamic Particle Swarm Optimization Based Maximum Power Trackers for Stand-Alone PV System under Partial Shading Conditions," *IEEE Access*, vol. 8, pp. 20770–20785, 2020, doi: 10.1109/ACCESS.2020.2966430.

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