Shunt Active Power Filter for Power Quality Improvement of Renewable Energy Systems: A Case Study

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Abstract: - This paper introduces an application of an active power filter (APF) in a real industrial zone smart grid for power quality (PQ) improvement issues. The random harmonics generated by on-grid PV inverters and non-linear loads that represent the topology of the industrial smart grid are mitigated, also the reactive power, voltage levels, and power factor were adjusted using a shunt active power filter (SAPF). Detailed design of APF and its hysterics control strategy were presented using the MATLAB/SIMULINK software package. The results prove that SAPF is an effective device to mitigate total harmonic distortion (THD), and has a fast dynamic response to regulate the grid's power factor (PF).

Key-Words: - **S**hunt active power filter, Harmonics mitigation, Power factor correction, Distributed generation, Hysteresis current controller, Power quality improvement

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1 Introduction

The connection of utility grids with new renewable energy resources such as photovoltaic and wind technologies raises challenges in front of power quality issues. The main research topics in the smart grid field focus on how to improve the quality of electrical services. Continued development in the field of power electronic devices such as nonlinear loads, variable frequency drives, and soft starters are the major cause of poor PQ problems like harmonics, poor power factor, sag, and swell distortions, [1], [2], [3]. Therefore, it's critical to evaluate new solutions to increase the quality of utility services.

Active and passive power filters are the main solutions to mitigate PQ problems, passive power filters (PPF) have many drawbacks, such as their inability to compensate for sub-harmonics, tuning the circuit's accuracy, and difficulty with its large size in comparison with active power filters (APF), [4].

There are many research topics in the field of renewable energy technology focused on delivering real power to the loads in addition to mitigating harmonics and increasing the power factor up to unity. Recently, APFs have become the most effective solution to eliminate the harmonics, inter-harmonics, and sub-harmonics due to their advantages; (i) fast response to grid variations, (ii) ability to compensate for random harmonics. (iii) high control accuracy. In practice, APFs inject a current into the point of common coupling (PCC) equal but opposite in its direction to the grid harmonics and generate – absorb reactive power into the grid to cancel a wide range of harmonics that affect on utility system in addition to increase the grid's power factor (PF), [5]. Furthermore, APFs keep the grid system balanced and stable with load variations and grid transients.

In this paper, shunt APF is further designed to solve practical PQ problems of renewable energy sources that integrate with utility grids in Hebron city in Palestine to mitigate grid harmonics and increase the PF of the system to unity. This paper is organized as follows: the methodology of shunt active power filter design is presented in section 2, the simulation of the selected case study and the results are provided in section 3, and finally, the conclusion is drawn in section 4.

2 Problem Formulation

Shunt active power filter is a three-phase inverter and there are two main types of SAPF regarding its connection, each one has its advantages and disadvantages depending on its effects and capacity, [6], [7]:

Series active power filter (series-APF): it is a filter used in series with the loads and designed to mitigate the voltage harmonics of the grid by generating negative voltage harmonics to cancel the effects of the load voltage harmonics and keep the grid's voltage in pure sine shape against transients, sag and swell events. Figure 1 shows the topology of the series APF.

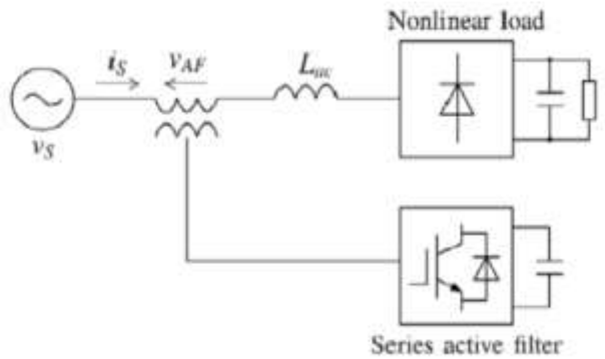

Fig. 1: Series active power filter configuration, [7].

Shunt active power filter (shunt-APF): it is a filter connected in parallel with nonlinear loads that are used to reduce the grid's current distortion and increase the utility power factor by injecting negative current harmonic into the grid. Figure 2 shows the topology of shunt APF.

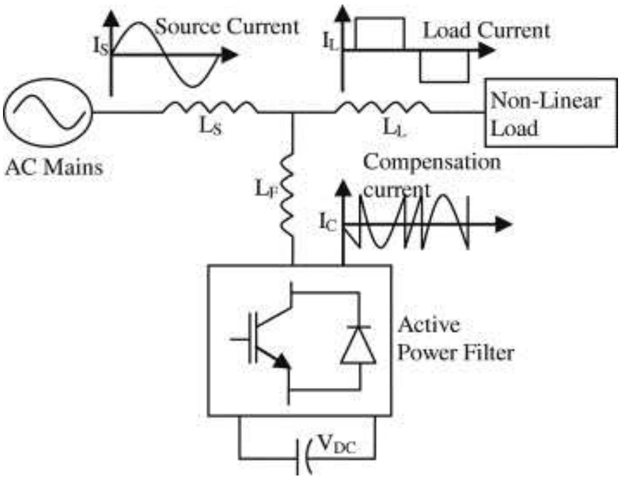

Fig. 2: Configuration of shunt-active power filter, [7].

Also, there are two types of inverter topologies; (i) voltage source inverter (VSI). (ii) Current source inverter (CSI). The literature review shows that using VSI is more efficient than CSI in high-power applications (in MV applications), while CSI is better than VSI in low-power applications. CSI needs additional overvoltage protection in the DC-link inductor in case of switch faults. Both types have significant losses, the main losses in VSI are in its AC-linking inductance filter while the losses in CSI are in its DC-link inductance, [8]. Since the total harmonic distortion of the current (THDi) in renewable energy sources and industrial zones is much greater than the total harmonic distortion of the voltage (THDv), current-controlled VSI is usually used for this purpose.

Shunt-APF can be two-level or multilevel inverters which is better in dealing with high power-high voltage applications, also it can be modeled two two-level inverters that are connected in series and parallel operation. Shunt-APF is a three-phase voltage source inverter that is used to stabilize the system's performance depending on generating specific reference current of the IGBT bridge to mitigate random harmonics and compensate the power factor up to unity, [9], [10], [11], [12].

There are different control techniques of reference current calculation, the most popular one is the instantaneous reactive power theory (P-Q theory) that depends on measuring the three-phase voltages and currents, then converting it into a two-phase model (a & B) by Clark transformation matrix. This two-phase signal can be regulated using different control techniques such as hysteresis, PI, and fuzzy controllers to evaluate the reference currents in two phases. Then, reference currents are used to gate the Inverter Bridge after evaluating three-phase reference currents by inverse Clark transformation, [13], [14], [15].

Figure 3 illustrates the control procedure of reference calculation. Figure 4 shows the overall transfer matrices.

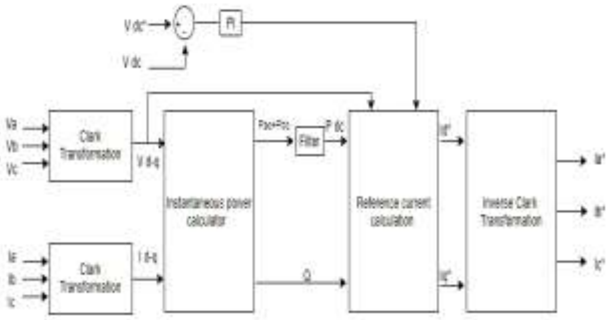

Fig. 3: Control procedure of reference current calculation.

Reference current calculation using (P-Q theory) has the following steps, [6]:

2.1 Two-phase Calculation

The two-phase calculation method was used to convert three-phase measurements into the two-phase model (a & b) using Clark transforms to simplify the calculations according to Equation (1).

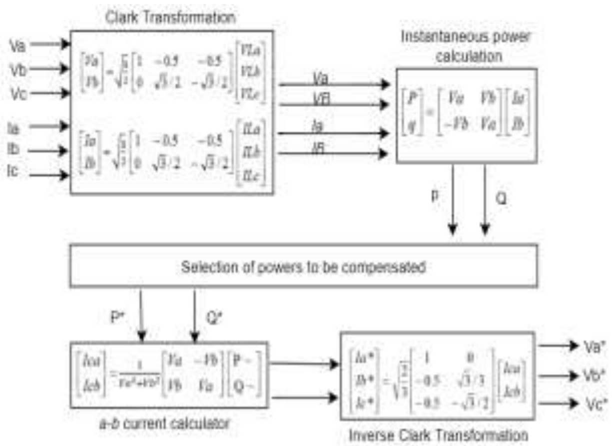

Fig. 4: Overall transfer matrices of generating reference currents.

$$\begin{bmatrix} Va \\ Vb \end{bmatrix} = \sqrt{\frac{3}{2}} \begin{bmatrix} 1 & -0.5 & -0.5 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} VLa \\ VLb \\ VLc \end{bmatrix}$$

$$\begin{bmatrix} Ia \\ Ib \end{bmatrix} = \sqrt{\frac{3}{2}} \begin{bmatrix} 1 & -0.5 & -0.5 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} ILa \\ ILb \\ ILc \end{bmatrix} \quad (1)$$

2.2 Instantaneous Power Calculation

instantaneous real power (P) and instantaneous reactive power (Q), both include two components, DC components due to the fundamental of the load current (power dissipated in 50 Hz) and an AC component corresponding to the harmonic current of the load (power dissipated in frequencies other than 50 Hz). This instant power can be calculated depending on equation (2).

$$\begin{bmatrix} P \\ q \end{bmatrix} = \begin{bmatrix} Va & Vb \\ -Vb & Va \end{bmatrix} \begin{bmatrix} Ia \\ Ib \end{bmatrix} \quad (2)$$

$$P = P^{-} + P^{\sim`}$$
$$Q = Q^{-} + Q^{\sim`}$$

2.3 AC Real Power Calculation

AC real power reference $P^{\sim}$ can be extracted from total power P by a low pass filter to separate the two components from each other and select the AC component only to be compensated.

2.4 Reference Current Calculation in Two-Phase Mode

The compensating currents Ia-ref and IB-ref in two-phase mode can be calculated depending on equation (3).

$$\begin{bmatrix} Ia* \\ IB* \end{bmatrix} = \frac{1}{Va^2+Vb^2} \begin{bmatrix} Va & -Vb \\ Vb & Va \end{bmatrix} \begin{bmatrix} P\sim \\ Q\sim \end{bmatrix} \quad (3)$$

2.5 Three-Phase Reference Current Calculation

Compensating current in three-phase mode can be evaluated depending on two-phase results using inverse Clark transform according to equation (4).

$$\begin{bmatrix} Ia* \\ Ib* \\ Ic* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -0.5 & \sqrt{3}/3 \\ -0.5 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} Ica \\ Icb \end{bmatrix} \quad (4)$$

2.6 Hysteresis Band Current Controller (HCC)

It is a controller used to force the compensated grid current (Ig) to follow the calculated reference current (I-ref). The accuracy of the hysteresis controller depends on its hysteresis band (HB) which represents the current ripple. However, narrower HB in HCC leads to increased switching loss in shunt-APF. Figure 5 shows the block diagram of the hysteresis current controller, [9].

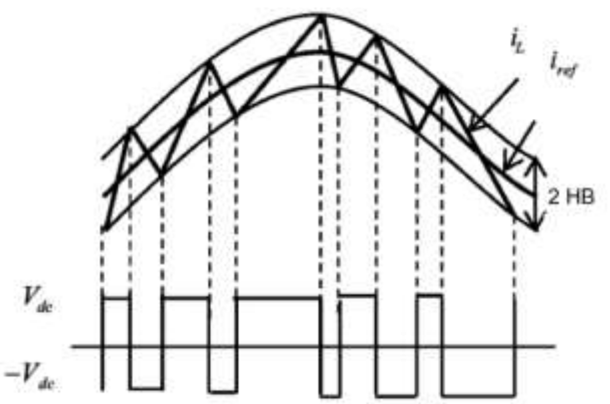

Fig. 5: Block diagram of hysteresis current controller.

3 Problem Solution

To study the performance of shunt-APF in the presence of local non-linear load in an industrial zone that represents the topology of a bad power quality smart grid. Simulation was done using the MATLAB/ SIMULINK software package with an overall simulation time of 100 ms, shunt APF became in service after the first two cycles (40 ms), and the results were carried out as follows.

3.1 The Selected Case Study

Shunt-APF is connected to an 11 kV, 50 Hz grid, to compensate and mitigate the effect of non-linear load that represents the topology of industrial zone loads. Figure 6 shows the overall system design.

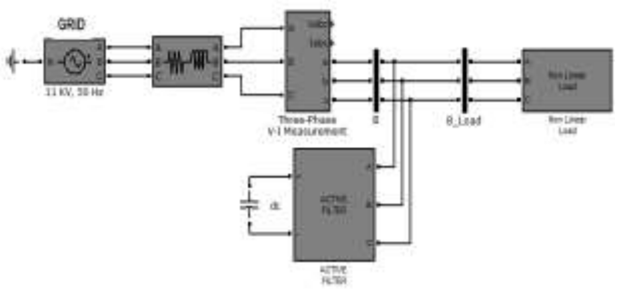

Fig. 6: Overall system design.

3.2 Non-linear Load

The topology of the industrial zone loads are non-linear loads that are full of random harmonics, practical harmonic measurements were used and simulated using current source generators to simulate each harmonic content. Table 1 shows the practical harmonic measurements for the first ten harmonic content. Figure 7 shows the load current wave shape.

Table 1. Practical harmonic measurements for the first ten harmonic content

Harmonic Order	Current (A)
1	165
2	4.1
3	14.3
4	0.21
5	4.73
6	0.25
7	2.65
8	0.171
9	2.16
10	0.03

3.3 Two-phase and Instantaneous Power Calculation

Two-phase calculation is done depending on the Clark transform matrix in equation (1), followed by instantaneous real and reactive power calculation according to equation (2). Figure 8 shows a two-phase calculation block diagram. Figure 9 shows the Instantaneous real and reactive power.

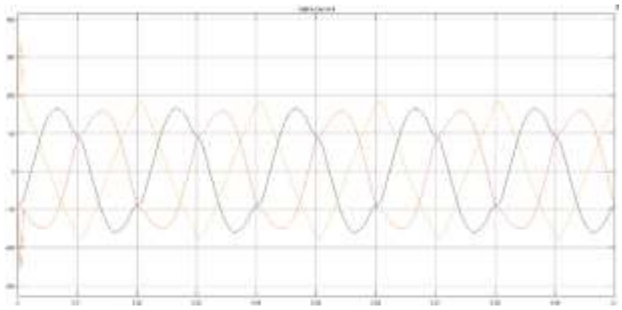

Fig. 7: Distorted current wave shape of the proposed load.

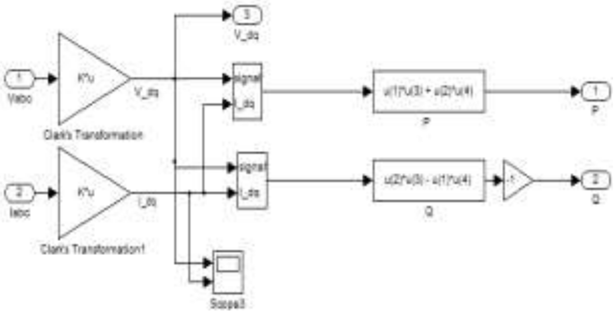

Fig. 8: Two-phase calculation block diagram followed by an instantaneous power calculation.

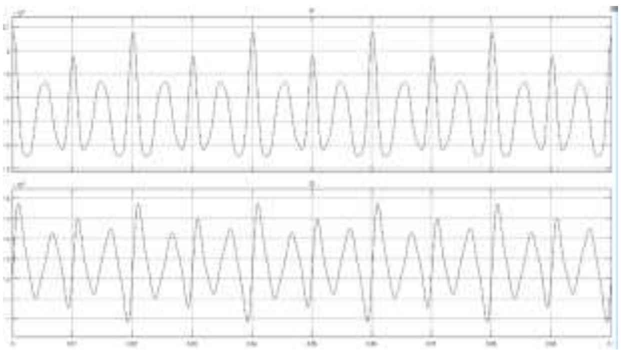

Fig. 9: Instantaneous real and reactive power.

3.4 AC Real Power Calculation

Real power (P) out of the previous step consists of two components, P-ac (that consumed by fundamental frequency, 50 Hz) and P-dc (that consumed in frequencies other than 50 Hz), applying LPF can separate P-ac and P-dc components from each other. P-ac also depends on the losses in the DC bus at the input of the inverter bridge, it is critical to keep the voltage level stable at a pre-determined value by applying a PI controller. Figure 10 shows the block diagram of evaluating P-ac. Figure 11 shows the power separation into its components (P-ac and P-dc).

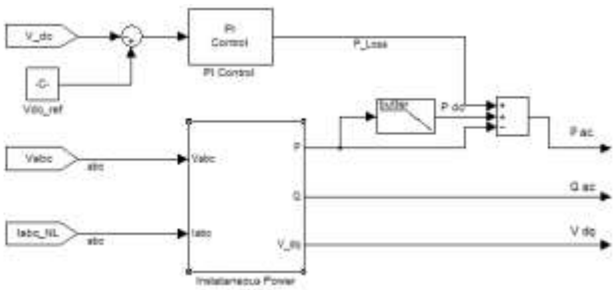

Fig. 10: The block diagram of evaluating P-ac.

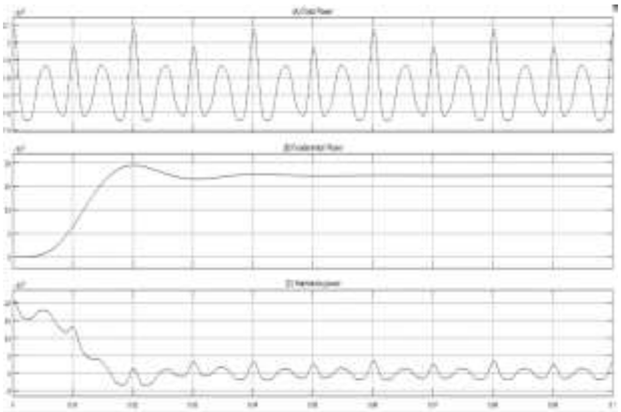

Fig. 11: Real power separation, (a) total power, (b) P-dc component, and (c) P-ac component.

3.5 Three-phase Reference Current Calculation

Compensating currents are reference currents of an inverter's bridge (it is a control signal in a PWM generator) used to mitigate random harmonics and increase the grid's PF up to unity.

Generating reference current process depends on evaluating reference currents in a two-phase model according to equation (3) followed by inverse Clark transform according to equation (4) to get the references in the three-phase model. Figure 12 shows reference current curves in two-phase and three-phase models respectively.

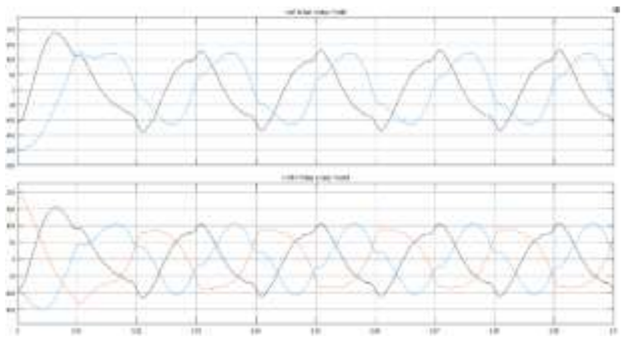

Fig. 12: Reference current in two-phase and three-phase models, respectively.

The summation of references at any instant of time equals zero to make the system stable and balanced.

3.6 Hysteresis Current Controller Design

The compensating current in Figure 12 is an analog signal with high error and is not able to be used as firing signals of the inverter bridge. A hysteresis controller is used to control on error value and force the compensated current to follow the reference current. Figure 13 shows the block diagram of Hysteresis Current Controllers.

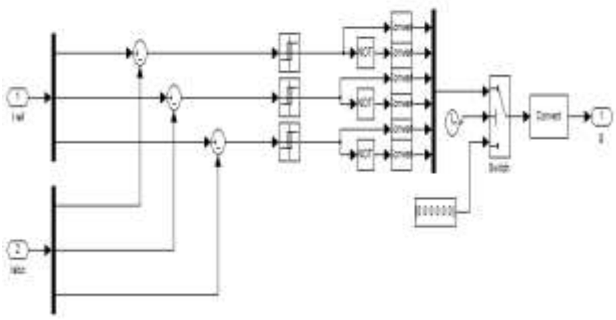

Fig. 13: Hysteresis current controller block diagram.

Hysteresis Controllers make the grid current follow reference currents with small hysteresis bands (HB) to minimize the error value and increase the accuracy of the output current. Figure 14 shows the input and output signal of the Hysteresis Controller with HB = 10 (a ripple of 10 A is allowable).

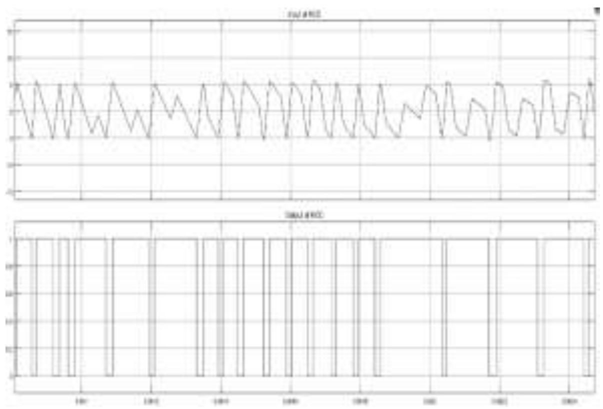

Fig. 14: Input and output signal of hysteresis controller with HB = 10.

3.7 Shunt APF Performance

The purpose of using Shunt-APF was achieved. The level of THD reduced significantly and PF increased up to unity. Figure 15 shows the current wave shapes before and after installing shunt-APF.

Figure 16 shows the PF correction response up to unity value, which means that shunt-APF works as

STATCOM. Table 2 summarizes a comparison of THD and PF before and after installing APF. Lastly, the current wave shapes before and after installing APF. (a) load current, (b) SAPF current and (c) grid current are presented in Figure 15.

Table 2. Comparison of APF performance before and after installing APF

Parameter	Before adding APF	After adding APF
THD of voltage	8.3%	1.3%
THD of current	23.4%	2.8%
PF	0.80	0.97

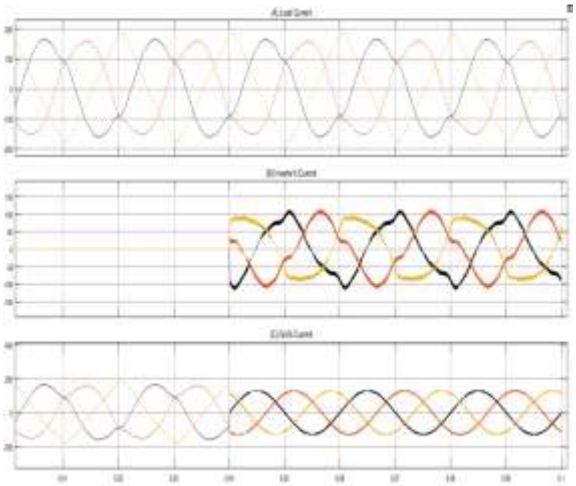

Fig. 15: Current wave shapes before and after installing APF. (a) load current, (b) SAPF current, (c) grid current.

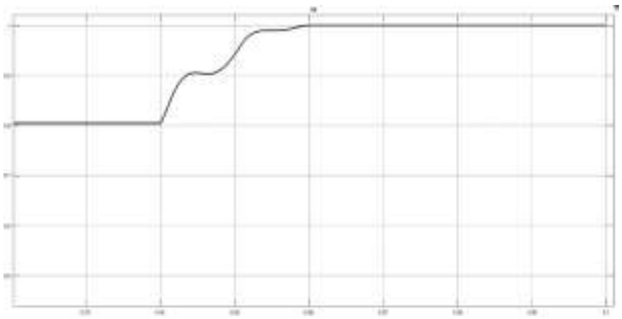

Fig. 16: PF regulation response.

4 Conclusion

The performance of shunt-APF in a practical industrial zone with a non-linear load that is full of harmonics for PQ improvement was studied using hysteresis current controllers that were implemented by the MATLAB/SIMULINK package and studied under different conditions. The proposed Shunt-APF designed using instantaneous reactive power theory (p-q theory) and the results show that inserting SAPF can significantly improve the smart grid performance by mitigating random harmonics and limiting it within the standards, it is also can increase PF up to unity which means that SAPF works as STATCOM.

References:

[1] Mishra, Debani Prasad, Kshirod Kumar Rout, Sivkumar Mishra, Mandakurit Nivas, Rambilli Krishna Prasad Rao Naidu, and Surender Reddy Salkuti. "Power quality enhancement of grid-connected PV system." *International Journal of Power Electronics and Drive Systems* 14, no. 1 (2023): 369.

[2] Salah Alqam, Fouad Zaro, Power Quality Detection and Classification Using S-Transform and Rule-Based Decision Tree, *International Journal of Electrical and Electronic Engineering & Telecommunications*, Vol. 8, No. 1, 2019, pp. 45-50.

[3] Fouad Zaro, Power Quality Disturbances Detection and Classification Rule-Based Decision Tree, *WSEAS Transactions on Signal Processing, ISSN / E-ISSN: 1790-5052 / 2224-3488*, Volume 17, 2021, Art. #3, https://doi.org/10.37394/232014.2021.17.3.

[4] Mishra, Debani Prasad, Kshirod Kumar Rout, Sivkumar Mishra, Mandakurit Nivas, Rambilli Krishna Prasad Rao Naidu, and Surender Reddy Salkuti. "Power quality enhancement of grid-connected PV system." *International Journal of Power Electronics and Drive Systems*, vol. 14, no. 1 (2023): 369.

[5] Yi, Jun, Yazhou Gao, Mengmeng Wang, Jian Zhu, Jin Ma, Wenchao Shi, and Haoliang Wang. "Research on APF Based on Adaptive Analysis Instantaneous Reactive Power Harmonic Detection Method." In *2023 IEEE 6th Information Technology, Networking, Electronic and Automation Control Conference (ITNEC)*, vol. 6, pp. 578-582. IEEE, 2023.

[6] Naamane, Debdouche, Zarour Laid, and Mehazzem Fateh. "Power Quality Improvement Based on Third-Order Sliding Mode Direct Power Control of Microgrid-Connected Photovoltaic System with Battery Storage and Nonlinear Load." *Iranian Journal of Science and Technology, Transactions of Electrical Engineering* (2023), pp.1-18.

[7] DD. Sureshkumar Sahu, and I. Ramesh. "Simulation of UPQC using Cascaded Multilevel Inverter & Comparing it with Shunt & Series Active Power Filters.", *International journal of scientific & Engineering Research,* Vol. 4, 2013, pp. 303-307.

[8] M. Routimo, M. Salo, H. Tuusa, "Comparison of voltage-source and current-source shunt active power filters", *IEEE Trans. Power Electron.*, vol. 22, no. 2, 2007, pp. 636-643.

[9] Sundaram, Elango, and M. Venugopal. "On Design and Implementation of Three Phase Three Level Shunt Active Power Filter for Harmonic Reduction Using Synchronous Reference Frame Theory." *International Journal of Electrical Power & Energy Systems* Vl. 81, 2016, pp. 40-47.

[10] Balal Afshin, Saleh Dinkhah, Farzad Shahabi, Miguel Herrera, and Yao Lung Chuang. "A review on multilevel inverter topologies." *Emerging Science Journal,* vol. 6, no. 1 (2022): 185-200.

[11] Beres, Remus Narcis, et al. "A review of passive power filters for three-phase grid-connected voltage-source converters." *IEEE Journal of Emerging and Selected Topics in Power Electronics*, Vol.4, No.1, 2016, pp. 54-69.

[12] Salmeron, P., and S. P. Litran. "Improvement of the electric power quality using series active and shunt passive filters." *IEEE Transactions on power delivery,* Vol. 25, No.2, 2010, pp. 1058-1067.

[13] E. Pouresmaeil, D. Montesinos-Miracle, O. Gomis-Bellmunt and A. Sudria-Andreu, "Instantaneous active and reactive current control technique of shunt active power filter based on the three-level NPC inverter", *Eur. Trans. Elect. Power*, vol. 21, no. 7, 2011, pp. 2007-2022.

[14] Buła Dawid, Dariusz Grabowski, and Marcin Maciążek. "A review on optimization of active power filter placement and sizing methods." *Energies,* Vol.15, No. 3, 2022, 1175.

[15] Priyanka, Kodada Durga, and Abitha Memala Wilson Duraisamy. "A Review on Advanced Control Techniques for Multi-Input Power Converters for Various Applications." *Smart Grids for Smart Cities,* Vol.1, No. 1, 2023, pp. 41-100.

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The authors have no conflicts of interest to declare that are relevant to the content of this article.

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