A Comprehensive Study on Shunt Active Power Filters for Grid – Tied wind systems

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Abstract. The term power quality (PQ) has got major attention at the distribution side and consumer side in the recent years. Continuous rise of power electronic devices in grid-tied applications, uninterruptable power supplies (UPS) and motor drive applications etc, simplifies the control technology, and makes the system robust and flexible. But, these devices inject the current harmonics into the line which pollutes the electrical system. In addition, it draws more reactive power and creates the unbalance in the system. Initially, passive filtering techniques (inductors and capacitors) were used to lessen the PQ problems. Because of the lacking of the quality performance, the passive filter methods have been replaced with advanced power electronic topologies. Researchers, constantly investigates for better and cost effective solutions to improve system PQ. Shunt active power filter (SAPF) is one of the better solutions for enhancing the power quality by compensating the harmonic currents and other reactive power problems in the grid-tied system. In this paper, the basic structure of SAPF is briefly discussed along with the detailed control system functionalities. This paper provides a concise assessment on SAPF classifications, topologies and comparisons of single-phase, three-phase three-wire (3P3W) and four-wire (3P4W) systems. The features of all the configurations are provided along with their complications, so as to identify the better topology for specific application. The merits and demerits of these configurations are also discussed briefly.

Keywords: APF’s, SAPF’s, power quality, harmonics mitigation, grid-tied.

1. Introduction
Increase of nonlinear loads ensuing harmonic currents in the line and cause several power quality issues in the electrical distribution systems. The unwanted harmonics, unbalanced currents and uncompensated reactive power affects the effectiveness of the distribution system by introducing unbalances and harmonics in the source voltages. The presence of current harmonics causes severe problems, such as failures/malfunctioning of sensitive equipment, errors in the measuring equipment, and overheating of devices/instruments etc [1, 2]. According to the newest revised report of IEEE 519-2014 standards [3] the total harmonic distortion (%THD) in the current must be less than 5%. Initially, passive filtering techniques (LC filters) were used to accomplish the IEEE 519 standards [4]. But, due to their massive sizes, limited compensation abilities, electromagnetic interference (EMI) issues, the researchers are developed active power filters (APFs) to substitute them [5], [6]. The APFs (custom power devices) are shown impressive performance to minimize the current harmonics and reactive power problems caused by nonlinear loads [7-9]. APFs are small in size, vigorous in control, accurate in compensation.

Commercial SAPFs were developing by the well-known companies (Schaffner [14], ASEA Brown Boveri (ABB) [15], and Schneider Electric [16]) to accomplish the consumer’s demands. These designs are majorly of three-phase three-wire (3P3W) and four-wire (3P4W)
systems with several current and voltage ratings to accomplish industrial and commercial applications. Though, every company uses different control techniques for SAPFs. For example, Schaffner designed SAPFs with a Fast Fourier Transform (FFT) integrated digital controller [14]; ABB uses a closed-loop based digital controller [15]; whereas Schneider Company uses two control methods [16]:

1. FFT analysis based digital control method
2. Analog control method (without FFT).

Nowadays for the installation of new distribution systems, it’s better to set up 3P4W SAPF based grid tied systems, instead of single-phase [17, 18] and/or 3P3W [19] SAPF systems. The main benefit of a 3P4W SAPF structure is that, it can handle both the three-phase and single-phase loads at the same time. Hence, the 3P4W systems can be analysed as a distinct arrangement of 3P3W and single-phase two-wire (1P2W) systems. Therefore, the 3P4W SAPF based grid tied systems has grab the attention of the researchers. On the other hand, the 3P4W systems are also treated as the most sensitive networks to power quality issues. Additionally, the 3P4W SAPF system also suffers with neutral line current problem. The existence of negative-sequence and zero-sequence current components produces the unbalanced currents. These sequence components are the reasons for heating of neutral wire, overheating and malfunctioning of electrical and electronic devices. However, these power quality issues can be easily compensated by the implementation of SAPFs. Based on the applications, circumstances and the nature of the supply available, a number of SAPF topologies are implemented and successfully installed to mitigate the various power quality issues in the 1P2W, 3P3W and 3P4W systems.

This paper provides a brief concept on APFs and SAPFs for the power engineers and researchers. In the 2nd section the classification of APFs has been discussed based on the type of circuit connections with brief comparisons among them. Section 3, explains the basic structure of SAPF and the key blocks of control unit with their working importance. Classifications of SAPFs are given in section 4 and the comparisons have made in various aspects. The section 5 explains the control techniques applied under non-ideal voltage conditions.

2. Classification of APF’S based on circuit connections

The classifications based on power circuit connections are essential for choosing the applications. The APFs are divided into three groups based on the power circuit connections, specifically Shunt APFs (SAPFs), Series APFs and Other combinations of APFs. Figure 1 shows the classification of APFs based on the power circuit topologies and its connections [11]. The shunt APFs (SAPFs) are connected parallel to the line to compensate the current harmonics, whereas the series APFs are connected in series with the line to mitigate voltage harmonics. The SAPF systems are mostly used configurations in the industrial applications, to lessen the current harmonics and other power quality problems.

APFs are mainly classified into two types namely, series APF and shunt APF, which improves the power quality in single phase, 3P3W, 3P4W supply systems. The series APF mostly used compensate the voltage related issues to protect the sensitive loads from the voltage harmonic distortions in the AC line. The shunt APFs are most recognized system to perform three major functions like, current harmonics compensation (less %THD) [4, 10, 11], improving source power factor(PF) with reactive power compensation [10, 12, 13], load balance (neutral current compensation). table 1. They are (Figure 1):

1. Standard inverter (VSI or CSI),
2. Switched capacitor model,
3. Lattice structure topologies
4. Voltage regulator models.
3. Configuration of shunt active power filter (SAPF)

A. Basic structure of SAPF:
Shunt APFs (SAPFs) are the mostly used APF configurations for the current harmonics mitigation, reactive power compensation, and/or neutral current compensation in the distribution system. SAPFs with a voltage source inverter (VSI) supported by DC-link capacitor or current source inverter (CSI) supported by inductor are extensively adopted systems by industries, and distribution companies.

Normally, SAPFs are coupled at the point of common coupling (PCC), between the utility grid and the nonlinear load. The basic single line diagram of SAPF is shown in Figure 2. The function of VSI is to generate AC voltages depends on the compensation condition and the filter inductor placed in series with VSI, improves the source current shape by reducing the switching ripples. Proper tuning of amplitude and phase of three phase output voltages of VSI decides the performance of SAPFs. It develops better coordination between the SAPF and utility grid.

B. Control structure and their functions of SAPF:
Majorly SAPF topology consists of two parts, one is a standard VSI fed by a DC-link capacitor and the other one is its controller. Voltage source inverter (VSI) systematically controls and produces the filter current \( i_f \) as injection current, to compensate the unbalanced real power occurs in the dynamic operation. In addition, a filter inductor is used to lessen the ripple content in injected filter current \( i_f \). The nonlinear load injects the harmonics in the electrical
grid system current via PCC. Few examples for practical nonlinear loads are adjustable speed drives (ASD), arc furnaces, switch-mode power supplies (SMPS), and power electronic loads. Though, generally in the research environments (simulation and laboratory), uncontrolled rectifier bridge load is mostly used, due to its serious current harmonic distortions [1, 20].

Normally, the bridge rectifier is connected to three types of loads: (1) RL (resistor – inductor) series load, basically called as inductive load; (2) RC (resistor – capacitor) parallel load, basically called as capacitive load; and (3) simple resistive load. Figure 3 represents the typical control structure of SAPF. However, the controller performs four most important functions namely control algorithms given as (see Figure 3): (i) reference current generator or harmonic extraction method; (ii) phase detector or synchronizer (iii) DC voltage (DC-link capacitor) regulation algorithm; and (iv) switching algorithm or current controller.

| Features                 | VSI         | CSI          | Switched Capacitor | Lattice Structure | Voltage Regulator |
|--------------------------|-------------|--------------|--------------------|-------------------|-------------------|
| No of Phases             | 1P & 3P     | Usually 3P   | 1P                 | 1P                | 1P                |
| No of Switches           | 1P – 4      | 6 controlled | 1P – 2              | 1P – 4            | 1P – 4            |
|                          | 3P – 6 to 8 | and 6 diodes | bidirectional       |                   |                   |
| AC Elements              | N/A         | N/A          | 1 or 2 small AC    | 1 or 2 small AC   | 1 small AC        |
|                          |             |              | capacitors         | capacitors        | capacitor         |
|                          |             |              | 1 or 2 small AC    | 1 or 2 small AC   | 1 small inductor  |
|                          |             |              | capacitors         | capacitors        |                   |
|                          |             |              | 1 or 2 small AC    | 1 or 2 small AC   |                   |
|                          |             |              | capacitors         | capacitors        |                   |
| AC Elements Rating       | N/A         | N/A          | 1.5 * V_{rated}    | 1.5 * V_{rated}   | 1.5 * V_{rated}   |
| DC-link Elements         | 1 Large     | 1 Large      | N/A                | N/A               | Same as rated     |
| DC-link Rating           | 1.5 * V_{rated} | 1.5 * I_{rated} | N/A    | N/A               | rated voltage     |
| Power Rating             | Low & Medium| Medium       | Low & Medium       | Low               | Low & Medium      |
| Control Function         | Keeping     | Keeping      | Keeping             | Voltage            | Tracking DC-link  |
|                          | Capacitor   | Inductor     | Capacitor voltage  | Inductor current   | reference voltage |
|                          | voltage     | current      | constant            | constant           | (PAM)             |
|                          | constant    | constant     | (PWM)               | (PWM)              |                   |
| Control Complexity       | Simple       | Complex      | Complex             | Complex            | Simple            |
| Response Speed           | Fast         | Medium       | Slow                | Slow              | Fast              |
| Purpose                  | Eliminate   | Eliminate    | Indirectly          | Directly           | Indirectly        |
|                          | harmonics   | harmonics,   | controls the       | controls the      | controls the      |
|                          | in load     | improve       | current             | filter voltage /  | current           |
|                          | current      | power quality |                   | current            |                   |

Table 1. Types of SAPFs and their comparison
(i) **Reference current generation:** This control block major function is to generate the reference current signal $i_{ref}$ by taking the instantaneous load currents $i_L$ from the nonlinear load, along with fundamental current components and harmonic current components. The reference current $i_{ref}$ is given to the current control algorithm to regulate the operation of SAPF for effective elimination of harmonic distortion. Therefore, this algorithm is also acknowledged as harmonic extraction algorithm.
generated by SAPF for a proper synchronization with the input source/grid voltage signal $v_s$. It can be seen in Fig. 3. Hence, this algorithm is also called as synchronizer algorithm. It is important that some distinctive SAPF controllers do not need explicit PLL or synchronization methods.

(iii) **DC-link voltage regulator:** This control block regulates the DC-link capacitor voltage constantly, by comparing the instantaneous DC-link voltage $V_{dc}$ and with a chosen reference value. The required current magnitude ($I_{dc}$) to charge the DC-link capacitor, of the DC-link charging current $i_{dc}$ can be estimated using resultant error. The essential current magnitude $I_{dc}$ is the quantity of $i_{dc}$ required by the SAPF to normalize its switching losses so as to maintain the DC-link voltage of the capacitor $V_{dc}$ at the constant reference value.

(iv) **Switching or current control algorithm:** This control algorithm consists of an internal current control loop and a PWM generator to control the switching actions of SAPF. The current control loop inspects the generated filter current with the reference current signal $i_{ref}$. So, to produce the switching pulses and to control the SAPF, this algorithm consider the reference current $i_{ref}$, source/grid current $i_s$ and the DC-link charging current $i_{dc}$.

### 4. Classification of SHUNT ACTIVE POWER FILTERS (SAPFs)

In general the SAPFs are majorly classified into three types i) based on circuit topology, ii) based on power source, and iii) based on advanced inverter structures which is illustrated in Fig. 4. However, VSIs are the most commonly used SAPFs because of their unique quality of implementation to multilevel configurations which significantly improve harmonics compensation [21, 22]. Additionally, VSI based SAPFs have merits like size compatibility and less implementation costs [4] etc.

The major pros of the CSI based SAPF is boost type nature, long life for energy device, high fault protection and main cons are high conduction losses, bulky and costly [23-25]. However VSI topology is less in size, lower weight and cheaper than CSI configuration. Hence, this document is mainly concentrates on the VSI based SAPFs [26].

![SAPFs classification based on the power circuit](image)
To compensate these problems various 3P4W SAPFs has developed namely four-leg (4L), two capacitors (2C) or split capacitor type and three full H-bridges (3HB) topology. Figures 5, 6 & 7 represents the 2C, 4L and 3HB based SAPF topologies respectively. In the split capacitor topology, the neutral wire is connected in between the two capacitors. However, this topology need extra control loop to balance the DC voltages of the two capacitors [27, 28]. For the 4L configuration, extra two active switches are added in the fourth leg (neutral wire) to balance neutral current. This configuration gives superior performance than that of the 2C topology [29-31]. In contrast, the three H-bridge inverter topology three full H-bridges (3HB) are used with a common DC-link capacitor. This configuration uses three single phase isolated transformers to connect with 3P4W system. Additionally, this topology needs extra switches compared with other configurations.

In this configuration, each H-bridge produces single-phase voltage, which differs with the other topologies (three-phase voltage in 4L and 2C topologies) which reduces the DC-link voltage by 1.732 times. However, because of independent control operation, the controllability of this structure can be enhanced [30].

There are lots of advanced configurations such as multilevel; interleaved-buck full-bridge (IB-FB) inverters etc have been developed by the researchers based on inverter system topology. There are various classifications of multilevel topologies mentioned in the literature [31-32] such as H-bridge, flying capacitor, diode clamped, and modular multilevel.

![Diagram of 2C SAPF configuration](image-url)

**Figure 5. Two capacitor or split capacitor (2C) based SAPF configuration**

These are the mostly used SAPF configurations to balance power quality problems in the grid/distribution medium to higher power applications. Additionally, these topologies are also capable of minimizing the $dv/dt$ issues of the active switches. However, the major disadvantages of these topologies are high number of switching devices, complexity in the control technique, large size and high cost.
Figure 6. Four pole or four-leg (4L) based SAPF configuration

Figure 7. Three H-bridges (3HB) based SAPF configuration
Table 2: Comparison of SAPF’s based on applications and circuit configurations

| Topology | VSI | CSI | 2C | 4L | 3HB | Multi-level | IB – FB |
|----------|-----|-----|----|----|-----|-------------|--------|
| Phases   | 1P & 3P | 1P & 3P | 3P | 3P | 3P | 1P & 3P | 1P & 3P |
| Power Rating | Low-Medium | Medium | Low-Medium | Low-Medium | High | High | Low-Medium |
| Circuit complexity | Less | Less | Medium | Medium | High | High | High |
| Control complexity | Less | Medium | Medium | Less | High | High | Less |
| Control Parameter | Voltage & Current | Voltage & Current | Voltage & Current | Voltage & Current | Voltage & Current | Voltage & Current |
| Control of Neutral Current | No | No | Yes | Yes | Yes | Yes | No |
| Shoot-through issue | Yes | Yes | Yes | Yes | Yes | Yes | No |
| Application | Diode bridge rectifier | Motor drives | ACs, Industry loads | TV, PC, commercial loads | Distributed systems, industrial drives, Arc furnaces | Industry loads, Motor drives | High rating drives, Traction | Arc furnaces, industries |

Table 3: Brief comparisons on 2C, 4L and 3HB based SAPF configurations

| Key Feature | Split (2C) | Capacitor | Four Leg (4L) | 3 (3HB) | H-bridge |
|-------------|------------|-----------|--------------|---------|---------|
| No. of Active Switches | 6 | 8 | 12 | |
| No. of DC-link Capacitors | 2 | 1 | 1 | |
| No. of control sensors | 2 (for DC voltage Regulation) | 0 or 1 (for hysteresis control) | 0 | |
| Minimum required DC-link Voltage | $\sqrt{3} \sqrt{2} \frac{V_s}{0.87}$ | $\sqrt{3} \sqrt{2} V_s$ | $\sqrt{2} V_s$ | |
| No. of series T/F | 0 | 0 | 3 | |
| Neutral current Compensation | Moderate | Excellent | Good | |
| Neutral current Control type | Indirect | Direct | Indirect | |
| Current harmonics and unbalance compensation | Good | Excellent | Better | |
| Cost | Low | Moderate | High | |
The IB-FB inverter topology is developed to compensate the shoot-through problem of the power switches. This will cause ringing and high EMI issues. In general, this configuration is used for low to medium power electrical systems [33-34]. The various characteristics on different issues with various topologies of SAPF are compared in Table 2. In [35], detailed design and analysis of 3P4W (2C and 4L) based SAPFs topologies have given along with the process to choose the minimum value and size of DC-link capacitor. In [36] a detailed analysis of 3HB based SAPF for unbalanced loads has specified with independent control technique. So, a concise assessment has shown in Table 3 on 2C, 4L and 3HB based SAPF topologies.

5. Discussion on working of SAPF's with non-sinusoidal grid voltage
A SAPF is subjected to a non-sinusoidal grid voltages operating with the abovementioned control techniques, then it fails to accomplish the sinusoidal source current. This is because the SAPF considers the source voltage angular position to generate and inject the filter current. The major cause for this is that the synchronization phase. So the traditional synchronization methods PLLs [37], ANN-based synchronizers [38], and ZCDs [39] may not respond to these errors properly and the performance will get worse [40]. The abovementioned control methods are mainly developed to operate SAPFs for the balanced sinusoidal voltage (or ideal voltage) based grid systems. Hence, the effective solution is to track the angular position accurately of the non-sinusoidal grid voltage. However, a few important modifications and development's have to be made to accomplish the practical requirements. These changes in the control methods will improve the performance of the SAPF fed to a non-sinusoidal (non-ideal) and/or unbalanced grid voltage conditions.

There are three control techniques which improves the SAPF performance with non-sinusoidal grid voltage situations. They are given as, adaptive notch filter (ANF) [41], optimization technique [42] and self-tuning filter (STF) [43]. The ANF technique is not suitable because it involves in gain adjustment and fine-tuning of the damping ratio in order to work properly. The optimization technique uses the complex iterative procedure to resolve the optimization issue. It takes more time for calculations which is a major difficulty, so less preferred over other techniques. Moreover, both the techniques namely optimization method and ANF techniques are limited to simulation environments only.

Having the advantages of performing efficiently with non-sinusoidal grid voltages and adaptability with reference current methods, the STF method is the better choice. With STF method the traditional SRF [44], PQ [43] and ANN techniques [40] acquired the facility to work under non-sinusoidal conditions. In the SRF technique, the STF algorithm is used in the PLL to improve its performance which is called as STF-PLL [44,45]. However, in the PQ theory model, the STF algorithm is directly incorporated with the main technique which is acknowledged as STF-PQ [43]. Lastly for the ANN based control technique, the STF algorithm is used as synchronizer in fundamental voltage extraction block which is called as STF-synchronizer[40].
6. Conclusion
A comprehensive investigation on the APFs, in particular SAPFs are presented in this paper for compensating the PQ issues at both the load and grid side. This paper gives a brief idea on APFs, SAPF classifications, topologies and comparisons of single-phase, three-phase three-wire (3P3W) and three-phase four-wire (3P4W) systems. The major intention of this paper is to present a complete summary on the working of SAPFs, so that the power engineers can get the knowledge and motivation for advance research on SAPFs. Various aspects of SAPF are being discussed and pointed out on the various issues with different topologies and control techniques. Comparisons are made for different classifications in various aspects which are shown in tables 1, 2 & 3. For non-ideal sources a few techniques have implemented by making small modifications to the regular methods. From the review it is very clear that, there is still need of more research to be done for the problems related with the typical power system Fast raise of renewable energy sources (RES) in the application of grid technologies play significant role. Having the advantages of harmonic currents elimination, reactive power compensation and active power generation with solar systems, RES based SAPFs are the major scope for the future research in the grid tied power systems.

7. References
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