SRF-PLL synchronized and Lyapunov based controller for 3-phase shunt active power filter

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Abstract:
Shunt active power filter (SAPF) offers compensation to harmonics generated due to non-linear loads, reactive power and unbalance in the distribution power networks. Due to the broad utilization of non-linear loads have caused current harmonic contamination to the electrical power system. The performance of SAPF depends on the control technique that is used in detection of current components of load that are necessary to be mitigated. In this work a three phase SAPF based on Lyapunov function has been designed for compensation of harmonics generated due to non-linear loads. A control law is determined in the proposed method which makes the derivative of Lyapunov function consistently a negative value for the all stable states. Also to generate a corrective mitigation current, it is important that SAPF should operate in phase with the operating power system. Hence a proper synchronization technique needs to be integrated when designing the control algorithms of SAPF. Furthermore, the harmonic compensation efficacy of the proposed Lyapunov based SAPF is compared with the one based on the other two conventional approaches. Results are obtained by simulating the SAPF in MATLAB/Simulink, which shows that total harmonic distortion (THD) of source current with Lyapunov based controller is significantly improved than the other two conventional methods.

Keywords: Active power filter, Lyapunov, Synchronous Reference Frame, PLL

I. Introduction:
The electric power quality has become an important part of the distribution power system. Harmonics are the primary cause for poor power quality of the distribution system. Harmonics are qualitatively defined as sinusoidal waveforms having frequencies that are integral multiples of the power line frequency. In power system engineering, the term harmonic is widely used to describe the distortion for voltage or current waveforms [1]. In the present scenario, there is an increase in loads that are nonlinear and reactive in nature such as fans, electric pumps, TV, diode rectifier etc. [2]. The aforementioned loads increase reactive power burden and harmonic distortion in the distribution system. Furthermore, with the existence of widespread distributed generations (DGs), the situation from harmonic distortions viewpoint goes extra aggravated on account of harmonic current components injected by DG systems. Generally, the injected harmonic currents deteriorate power quality by increasing total harmonic distortion (THD) of a power system. To compensate reactive power burden and harmonic dis- tortion various custom devices are used such as Shunt active power filter [3], [4], Static Compensator (STATCOM) [5], [6], Distribution Static Shunt Compensator (DSTAT- COM) [7], Dynamic Voltage Restorer (DVR) [8], [9], Passive filter [10], Shunt Hybrid Active filter (SHAF) etc. The harmonic related problem is mitigated by using active power quality conditioner. The active power quality conditioner can be connected in series or parallel and combinations of both (unified power quality conditioners) as well as hybrid configurations [11-14]. The series APLC operates as a voltage regulator and harmonic isolator between the nonlinear load and distribution system. The series active filter injects voltage component in series with the supply voltage and therefore can be regarded as controlled voltage source, compensating voltage sags and swells on the load side. The injected harmonic voltages are added or subtracted, to / from the source voltage to maintain pure sinusoidal voltage across the load. Hybrid APLC is a combination of passive and active power line conditioner.
The hybrid series APLC is controlled to act as harmonic isolator between the source and non-linear load by injection of controlled harmonic voltage source. Unified power quality conditioner is the integration of the series and shunt APLC. The series active power filter has the capability of voltage regulation and harmonic compensation at the utility-consumer point of common coupling. The shunt active power filter absorbs current harmonics, compensate for reactive-power and negative-sequence current, and regulate the dc- link voltage between both active power line conditioners. Power system current harmonics are the major problems in the distribution system, due to widespread use of non-linear loads. From the literature, the shunt active power line conditioner is an attractive choice to solve the current harmonic as well as reactive-power problems. The shunt APLC is compensating harmonic currents drawn by the non-linear loads besides power factor correction. However, due to their inherent weaknesses of inflexibility, instability, and large size, they are soon replaced by active power filters (APFs) which offer versatile solution to harmonic problems [15-18].

A typical SAPF is able to measure degree of harmonic current contamination of a power system and based on that measured data, it generates and injects corrective mitigation currents back into the polluted power system to directly cancel out harmonic currents, thus minimizing severity of harmonic current contamination. This is attainable when all the control techniques applied in its control system are functioning as desired. Nonetheless, many technical issues and challenges remained to be addressed for effective installation of SAPF into the polluted power system. One of the most critical issues is synchronization of the SAPF, where its generated output voltage needs to be properly synchronized with the grid voltage to achieve stable and continuous mitigation operation. The problems will be increasingly difficult when the grid voltage is subjected to faults such as harmonic contamination and unbalanced faults. Failure to synchronize leads to incorrect mitigation and may eventually worsen the harmonic issues which are supposed to be reduced.

Phase synchronization in this aspect can be regarded as a process to minimize phase differences between the output voltage of SAPF and the connected grid voltage and at the same time matching their operating frequency. This process has to be achieved before connecting the SAPF to the designated power system, thereby allowing the power system and the synchronized SAPF to work together. The simulation model is also developed in MATLAB/ Simulink environment. Results of simulations are compared with the other two compensation techniques based SAPF under four different scenarios. Under the first three scenarios, THD is compared among p-q theory [19], SRF method [20] and Lyapunov function based control technique. In the fourth and last case, the enhanced penetration level of renewable energy by Lyapunov function based SAPF is compared with the one based on the other two compensation techniques. The switching pulses are produced by the hysteresis based controller to track the references current. Simulations are performed under various load condition such as a simple nonlinear load with and without utility side voltage distortion, a modified IEEE 13 bus test distribution system loaded with a 3-phase chopper fed direct current (DC) motor drive at a single bus and last especially for increasing the harmonic-constrained penetration level of renewable energy. The achieved results verify the usefulness of SAPF with the Lyapunov function inspired control technique in delivering harmonics compensation under different system scenarios.

II. Shunt Active Power Filter:

The basic principle of active power line conditioner was proposed during 1970s. However, the actual design of active power line conditioner was proposed by Gyugyi and Strycula in 1976 [21]. The shunt APLC often refers to the compensation in the current harmonics and reactive-power. Fig.1 (a) shows the schematic diagram of the shunt active power line conditioner and Fig.1(b) presents the corresponding waveforms of the system. The shunt active power line conditioner compensates current harmonics by injecting equal-but-opposite harmonic components. It operates as current source injecting the harmonic components generated by the load but phase shifted by 1800. As a result, components of harmonic currents in the load current are cancelled by the effect of the shunt APLC and the source current remains sinusoidal and in phase with the respective voltage [22]. This principle is applicable to any type of non-linear load that creates harmonics.
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Figure 1(a) Schematic diagram of shunt APLC system and (b) Schematic waveforms

Figure 2 Basic diagram of SAPF

III. LYAPUNOV THEORY BASED CONTROL ALGORITHM

According to the Lyapunov method, SAPF energy reduces along the trajectories of the system. Lyapunov stability theorem conditions that a nonlinear system is universally asymptotically stable in case Lyapunov function $V(x)$ fulfils these properties:

\[
\begin{align*}
V(0) & \\
V(x) & > 0 \quad \text{for all } x \neq 0 \\
\dot{V}(x) & < 0 \quad \text{for all } x \neq 0 \\
V(x) & \to \infty \quad \text{as } ||x|| \to \infty
\end{align*}
\]

The Lyapunov function for SAPF defined as stored energy in it and is a positive definite function. Now considering the SAPF model shown in figure 2.
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\[
V_{sa} = L \frac{di_{c1}}{dt} + R_i c_1 + V_{dp} + V_{PQ} \quad (1)
\]
\[
V_{sb} = L \frac{di_{c2}}{dt} + R_i c_2 + V_{bp} + V_{PQ} \quad (2)
\]
\[
V_{sc} = L \frac{di_{c3}}{dt} + R_i c_3 + V_{cp} + V_{PQ} \quad (3)
\]
\[
\frac{dV_{dc}}{dt} = \frac{1}{C_{dc}} i_{dc} \quad (4)
\]

We assume that the source is balanced hence

\[
V_{sa} + V_{sb} + V_{sc} = 0 \quad (5)
\]
\[
V_{PQ} = -\frac{1}{3} \sum_{n=1}^{3} V_{nP} \quad (6)
\]

The switching function of the leg of the voltage source converter

\[
\begin{aligned}
c_i &= \begin{cases} 
1 & 
0 & 
\end{cases} 
V_{IP} &= c_i V_{dc} 
\end{aligned} \quad (7)
\]

**IV. PHASE SYNCHRONIZATION TECHNIQUES**

This section discusses about the phase synchronization techniques which have so far been integrated in the control system of SAPF. It includes the two common techniques in the literature namely zero-crossing detection (ZCD) and phase-locked loop (PLL), and the more recent techniques such as artificial neural network (ANN) or adaptive linear neuron (ADALINE) [fundamental component extraction], and unit vector generation. In this manuscript, the synchronization techniques are classified according to the intended application of SAPF, i.e., either for single-phase or three-phase power system, as illustrated in Figure 3. Over the years, work on SAPF for three-phase system have become popular compared to single-phase system, particularly due to wider applications of power electronics devices and nonlinear loads in a three-phase environment. However, to avoid redundancy, this manuscript will examine the synchronization technique itself and subsequently, suitability of each technique for single-phase and three-phase system applications will be highlighted.

![Synchronization Technique Diagram](image)

**Figure 3.** Overview of synchronization techniques applied to SAPF. ZCD: zero-crossing detection; PLL: phase-locked loop; ANN: artificial neural network; ADALINE: adaptive linear neuron.
Among the five techniques presented in this manuscript, phase-locked loop (PLL) technique is the most recognized and commonly applied approach due to its uncomplicated control structure and effectiveness in handling various grid conditions. PLL is actually an old technology which appeared in the literature in the 1930s, and it has successfully been applied over the past decades in various areas, such as in communication, control systems, and instrumentation. PLL structure contains three basic functional blocks known as phase detector (PD), loop filter (LF), and voltage-controlled oscillator (VCO), as illustrated in Figure 4. In a closed-loop control operation, PD will first compare the two input signals (a reference phase signal \( \theta_{\text{ref}} \) and a feedback signal \( \theta \)) and generate a phase error signal \( \Delta \theta \). The generated error is then filtered by LF (typically a low-pass filter (LPF)) which suppresses noise and other high-frequency elements from PD. The filtered signal is subsequently processed by VCO to generate an updated output phase \( \theta \) which is then feedback to the PD. As the looping process continues, the error generated will continuously be reduced and when it reaches zero value, the output phase will be locked and matches the desired reference phase signal \( \theta_{\text{ref}} \).

Subsequently, for the application of SAPF, the basic PLL has further been enhanced as synchronous reference frame (SRF)-based PLL (or simply SRF-PLL). SRF-PLL technique has successfully been applied in both single-phase and three-phase systems. As its name implies, SRF-PLL is a technique that utilizes SRF theory for the implementation of its PD block, in which three-phase voltage in \( abc \) natural reference frame is first transformed into two-phase \( \alpha\beta \) stationary frame (by means of Clarke-transformation) and then into \( dq \) rotating reference frame (by means of Park-transformation), as shown in Equations (4) and (5), respectively. Note that constant \( k \) refers to sampling rate. A proportional-integral (PI) is then applied to manipulate the resulting \( q \) variable and eventually the angular frequency \( \omega \) of the utility will be generated as the output. The utility phase angle \( \theta \) can be obtained by integrating the angular frequency, and the looping process continues by feeding the phase angle back to the \( \alpha\beta \) – \( dq \) transformation block until the phase angle is locked to a fixed value.

\[
\begin{bmatrix}
v_a(k) \\
v_\beta(k)
\end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix}
1 & -\frac{1}{2} & -\frac{1}{2} \\
0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}
\end{bmatrix} \begin{bmatrix}
v_Sa(k) \\
v_Sb(k) \\
v_SC(k)
\end{bmatrix}
\]

\[
\begin{bmatrix}
v_\alpha(k) \\
v_q(k)
\end{bmatrix} = \begin{bmatrix}
\cos \Theta & \sin \Theta \\
-\sin \Theta & \cos \Theta
\end{bmatrix} \begin{bmatrix}
v_a(k) \\
v_\beta(k)
\end{bmatrix}
\]
SRF-PLL technique is initially developed for the application in a three-phase system. However, with a little modification on the initial signal processing approach, it can also be used in a single-phase system. For single-phase application, there is a need to transform single-phase signal to αβ stationary frame by means of other approach due to the facts that Clarke-transformation (the usual transformation approach) is not applicable in a single-phase system. One interesting approach is revealed, where the single-phase signal is directly treated as a frame signal and meanwhile the framesignal is created by introducing a phase delay of $\pi/2$ to the actual single-phase signal (as illustrated in Figure 5b). The subsequent phase locking process for single-phase SRF-PLL is basically similar to that of three-phase SRF-PLL.

The main advantage of SRF-PLL technique is that it allows accurate and quick tracking of utility frequency and phase angle for the case when the source voltage is free from any distortions and unbalances. Unfortunately, it fails to work appropriately when the source voltage is unbalanced and/or distorted due to presence of harmonics.

One good way to alleviate this inherent issue is by applying additional low-pass filter (LPF) in the control loop after the $\alpha\beta - dq$ transformation block. However, there is a need to carefully match the order and cutting frequency of the LPF via heuristic manner, to provide a satisfactory compromise between its distortion rejection performance and speed. The good news is that the traditional SRF-PLL has been improved as self-tuning filter (STF)-based PLL (or simply STF-PLL) and decoupled double (DD) SRF-PLL (or simply DDSRF-PLL) to ensure its effectiveness when it is required to work under unbalanced and/or distorted utility grid.

![Image](Image1.png)

**Figure 5.** Control structure of synchronous reference frame (SRF)-PLL technique for (a) three-phase and (b) single-phase applications.

V. Simulation Results and Discussion

The performance of the Lyapunov Function-based Controller of SAPF has been tested under four systems scenarios. All the simulations are carried out using MATLAB/Simulink software. To assess the performance of the Lyapunov Function-based Controller of SAPF, the system is analyzed before and after compensation under all four system scenarios. The specification parameters of the system employed for analysis under case-1 in the MATLAB simulation, are shown in Table 1. In case-1 the proposed SAPF is first tested on a two-bus system with a 3-phase rectifier load. Also, the utility side is also assumed to have fundamental positive sequence at 415 Volt RMS line-to-line and free from any nonlinearity or unbalance. Accordingly, reference DC link voltage is taken as 700 Volt. The value of the DC-link capacitor is taken as 2000µF. The associated constantsof the controller are selected by hit-and-trial and kept fixed at 15 and 0.7 respectively. However, the technical specification of the system in each of the scenarios is considered quite different.
TABLE I. Value of $\alpha$ versus THD and S.S. response.

<table>
<thead>
<tr>
<th>Value of $\alpha$</th>
<th>3</th>
<th>1</th>
<th>0.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>% THD</td>
<td>2.92</td>
<td>4.84</td>
<td>8.42</td>
</tr>
<tr>
<td>S.S. Response</td>
<td>1.07</td>
<td>0.07</td>
<td>0.5</td>
</tr>
<tr>
<td>Time (in sec)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6. Waveforms of p-q theory (a-b) before and (c-e) after compensation.
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The waveformsofthe p-q theory are shown in figure 6(a-e) before as well as after compensation. Waveforms 6(a-b) belong to the before compensation case. For an uncompensated system since load current is identical to the source current, hence load current waveform has not been displayed separately. The waveform of the source or load current clearly depicts the harmonics present in the same. With the connection of the p-q theory controlled SAPF, the quality of source current waveforms can be clearly distinguished from the load current. However, owing to the limitation of the p-q theory-based controllers, source current is not closer to the pure sinusoidal one. THD in each phase lies under the limits specified by IEEE Std. 519.

The transients can be witnessed in the source current from the period of 0.15 seconds with the p-q theory controlled SAPF also forming a significant base of comparison among the three simulated techniques. One probable cause of such transient in the source currents is the slow buildup of voltage across the DC link capacitor.

The waveformsof the SRF theory are depicted in figure 7(a-e) before and after compensation. Because of the stiffness of the feeder according to Table 2, the voltage at PCC is indistinguishable from that of the source itself. Such scenarios exacerbate the PQ condition in the distribution feeders leading to their de-rating under the presence of harmonics. Waveforms 7(a-b) belong to the before compensation case. Again for an uncompensated system since load current is identical to the source current therefore...
load current waveform has not been presented individually. Wave-forms 7 (c-e) belongs to the after compensation case. Under the presence of SAPF, the source current waveforms can be clearly differentiated from the load current. Yet due to the imperfection of SRF based controller source current is not closer to the pure sinusoidal one though its THD exists under the limits specified by IEEE Std. 519.

Figure 8. Matlab/Simulink based model of Lyapunov function based control technique [23].

Figure 9. Waveforms of Lyapunov function based control technique (a-b) before and (c-e) after compensation.
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Figure 10. FFT analysis
(a) Before compensation, (b) After compensation.

Figure 8 depicts the MATLAB/Simulink based model of Lyapunov function inspired control technique for load compensation using SAPF. The waveforms of the Lyapunov function based control technique are shown in figure 9 (a-e) before and after compensation. Waveforms 9 (a-b) belong to the before compensation case. Again for an uncompensated system since load current is identical to the source current, therefore load current waveform has not been presented individually. Waveforms 9 (c-e) belong to the after compensation case. With the connection of the Lyapunov function controlled SAPF, the quality of source current waveforms can be clearly distinguished from the load current. However, again owing to the limitation of reference current racking of hysteresis loop controller, source current is not closer to the pure sinusoidal one yet its THD in each phase lies under the limits specified by IEEE Std. 519 and better than p-q and SRF theory.

THD of phase A of source current, before and after compensation, is depicted in figure 10. The THD of source current by the Lyapunov function based control technique is reduced from 30.04% to 1.61% in phase A. While the same is reduced from 29.18% to 3.19% with the well-known p-q theory and from 28.89% to 4.88% with the SRF theory. It becomes evident that the source current with the Lyapunov function based SAPF installed at the PCC is rather closer to the desired purely sinusoidal one.

Comparing the waveforms of source current i.e. 6(c), 7(c) and 9(c), it can be inferred that the Lyapunov function based control technique offers a better steady-state response. Rise time offered by the Lyapunov function based control technique is also somewhat lesser than the two conventional ones. Figure 6(c) shows the occurrence of high overshoot in the source current in the case of p-q theory. While the same is nearly absent in the response of the other two theories. The little transients can be again witnessed in the source current from the period of 0 sec to approximately 0.01 sec with the Lyapunov function based control theory but relatively lesser than both p-q theory and SRF theory based controller. Under the second scenario of the system or Case-2, the performance of the proposed Lyapunov function controlled SAPF is tested under utility or source-side disturbances.

VI. CONCLUSION:
A control algorithm, based on the Lyapunov function, is proposed for SAPF to mitigate harmonics and reactive power compensation of nonlinear loads. The performance of SAPF has been found satisfactory under all four cases of the study. The control algorithm is established on the...
Lyapunov function for achieving global stability in the system. The simulation results validate the control approach for SAPF. Hysteresis controller has been used to generate a switching signal for the voltage source inverter. Based on simulation results it is clear that all the control algorithm’s (p-q theory, SRF theory, Lyapunov function based control theory) performance found satisfactory i.e. THD is less than 5% according to IEEE 519 standards. Also underthefully fundamental plus balanced source volt-age and purely nonlinear loading condition Lyapunov function-based control algorithm gives the best performance over other control algorithms which are commonly used. The need of a synchronization algorithm is dependent on the characteristics of the applied harmonic extraction algorithm. Generally, an explicit synchronization algorithm can be omitted when operation of the applied harmonic extraction algorithm involves voltage processing stage such as the algorithm developed based on pq theory. However, SRF-PLL technique is still well accepted due to its uncomplicated control structure. Hence, further enhancements have been performed to improve capability of SRF-PLL which enables it to cope with distorted and unbalanced grid conditions.

REFERENCES


