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Adaptive Phase Adjustment Synchronization Method for Source Voltage Distortion in Electric Ship Application

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***Abstract* - In any distributed power system where the impedance of the generator is non-negligible compared to the impedance of its nonlinear loads, the source voltage typically contains some distortion. Specifically, US Navy ship power generators experience a significant amount of voltage distortion. Since Shunt Active Power Filters (SAPFs) normally use the waveform of the source voltage for their reference generator, a significant voltage distortion can create undesired harmonics in the current reference, thus inject undesired harmonics into the line. This paper proposes a phase adjusting algorithm that is robust to source voltage distortion. Low Pass Filter (LPF) is utilized to suppress the distortion; phase shift caused by LPF or other factors is adaptively adjusted to zero by closed loop control. This approach can be implemented in either Instantaneous Reactive Power Theory based control or Synchronous Reference Frame Theory based control and no predictive estimations are needed for precise synchronization.**

Index terms – Shunt Active Power Filter (SAPF), Adaptive

I. INTRODUCTION

Power electronics based distribution systems are becoming increasingly common, particularly for mobile applications such as aeroplanes, vehicles and electric ships. Due to the extensive use of devices with power electronics, there has been deterioration of power quality due to harmonic distortion observed in voltage and current. Shunt Active Power Filters (SAPF) are known to be effective in mitigating harmonics caused by nonlinear loads that produce current distortion [1,2,3].

Multiple SAPFs can be utilized in parallel, or they can be separated and placed close to various harmonic producing loads in the power system grid, thus making SAPFs effective at minimizing current harmonic disturbances at their initial source. These benefits of SAPFs have caused the U.S. Navy to begin to test their implementation for their future electric ships, as part of their $52 Million, 5 year, electric ship consortium research program [4].

The principle of the SAPF is shown in Fig. 1. The SAPF is considered to be a current source connected in parallel with the nonlinear load. It suppresses the harmonic currents by injecting an equal but opposite harmonic current to the point of connection with the nonlinear load.

The SAPF consists of a voltage source inverter, current reference generator, a control circuit and a DC link voltage regulator. In addition to the sophisticated PWM inverter technology, the Instantaneous Reactive Power (IRP) theory or "p-q theory" and Synchronous Reference Frame (SRF) transformation or "SRF transform" have made it possible to generate the accurate reference current in a SAPF.

However, a difficulty in implementing SAPFs on an electric ship is that it is not possible to use conventional methods to calculate the required current reference for the SAPF. Without an accurate current reference, SAPFs may actually inject more harmonics than they mitigate [5-12]. Specifically, U.S. Navy ship power generators experience a significant amount of voltage distortion. This is typical of any distributed power system (e.g. manufacturing plants) where the impedance of the generator is non-negligible when compared to the impedance of its nonlinear loads. For example, Fig. 2 shows a typical source voltage of a Navy ship, which was taken by the authors at sea on the US Coast Guard Healy in 2003. As Fig. 2 shows, there is significant harmonic distortion on the voltage, and it would be virtually impossible to directly use this signal to create a current reference for the SAPF.

SAPF current reference is generated in several ways. Conventional techniques [1-3] generate the current reference by measuring the source voltage and creating a reference signal in phase with the voltage. Thus, the generated current reference of SAPF follows the waveform of the source voltage. However, a disadvantage of the approach is that source voltage distortion creates undesired harmonics in the current reference. These harmonics in the current reference cause the SAPF to inject more distortions into the line current. In this instance, it is possible for the SAPF to create harmonics in addition to the load, thus making Total Harmonic Distortion (THD) worse than if there were no SAPF [5-12].

Alternatively, Synchronous Reference Frame (SRF) based control can be used to create the current reference for the

SAPF. SRF transform based methods work properly for the compensation of the load current harmonics in three-phase systems even with distorted line voltages but complicate the harmonic current cancellation in selective mode due to the necessary synchronization signal for each of the harmonics that must be cancelled [13]. This means in the Synchronous Reference Frame, the extra harmonics created by source voltage distortion may not affect the current reference. But, in this method, synchronization solutions are based on precise zero-cross-detection by using a phase locked loop (PLL). Proper synchronization will be affected by multiple zero crossing which may further cause false synchronization. So, this approach is also sensitive to voltage distortions.

Dealing with and suppressing the effects of source voltage distortion when generating current references for SAPFs has become an emerging area of research [5-12].

In [5,6,7], source voltage distortion is mitigated by sending the distorted source voltage through a Low-Pass-Filter (LPF). However, the LPF shifts the phase of the reference current and results in a sacrifice of power factor. When the source voltage distortion is significant, the phase shift caused by an effective LPF becomes large and power factor decreases significantly. Line voltage estimation method is introduced in [8] to create reference signals without distortion. The method is dependent on line and load current measurements. Similarly, predictive methods have been proposed in [9,10,11] to compensate for delays caused by filtering the source voltage.

In an alternative approach, internal sine and cosine signals have been created without net voltage zero crossing detection [12]. This method has a disadvantage that the internal frequency of the sine and cosine signal has to remain within obtainable boundaries (0.2% of net frequency f_0). For small distributed power systems, such as the electric ship, this requirement is overly restrictive. For example, the source voltage on the US Coast Guard Healy in Fig. 2 varies from 59Hz to 61Hz, which is over 3% of f_0.

This paper proposes a new phase adjusting methodology for SAPF that is robust to source voltage distortion and creates a precise current reference generator. Moreover, this proposed method can help to avoid false synchronization and thus gives more accuracy. The approach has the following features.

- *Low Pass Filter (LPF) is used to suppress the distortion of the source voltage. However, the delay due to the LPF is compensated during steady state operation. Thus, the cut off frequency of the LPF is able to remain low which helps to achieve good filtering result without sacrificing the power factor.*
- *The phase shift caused by LPF or other factors is adaptively adjusted to zero by closed loop control. No predictive estimations are needed for precise synchronization. So, the approach is not affected by the load current. Thus, the approach is robust to load uncertainties and to changes in nominal frequencies.*
- *This approach can be implemented in either Instantaneous Reactive Power Theory based control or Synchronous Reference Frame Theory based control.*

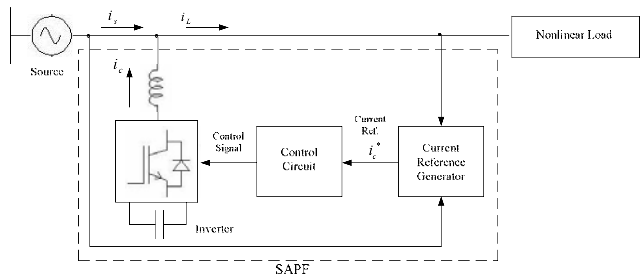


Fig. 1 Principle of a Shunt Active Power Filter

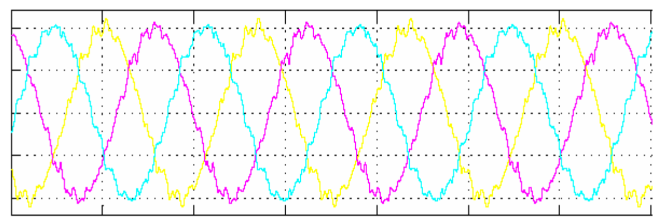


Fig. 2 Measured source voltage of U.S. Coast Guard Healy at sea

II. CONTROL STRATEGIES

A. Instantaneous Reactive Power (IRP) based control

Fig. 5 shows the conventional IRP based control for APF [2]. Transformation of the three-phase voltages v_a, v_b and v_c and the three- phase load currents i_{La}, i_{Lb} and i_{Lc} and into the $\alpha - \beta$ orthogonal coordinates give the following expressions:

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \quad (1)$$

Where x denotes line current or voltage.

According to the p-q theory, the instantaneous real power p_L and the instantaneous imaginary power q_L are defined as

$$p_L = v_\alpha i_{L\alpha} + v_\beta i_{L\beta} \text{ and } q_L = v_\alpha i_{L\beta} - v_\beta i_{L\alpha}$$

The commands of three-phase compensating currents injected by the SAPF i^*_{ac}, i^*_{bc} and i^*_{cc} are given by the following.

$$\begin{bmatrix} i^*_{ac} \\ i^*_{bc} \\ i^*_{cc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p^* \\ q^* \end{bmatrix} \quad (2)$$

p^* : instantaneous real power command
q^* : instantaneous imaginary power command

B. Synchronous Reference Frame based control

Fig. 3 shows the conventional SRF based control for APF. In the synchronous reference frame method, the load current is transformed into the d-q rotating frame. The transformation is defined by

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta - \frac{4\pi}{3}\right) \\ -\sin(\theta) & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{4\pi}{3}\right) \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \quad (3)$$

Here x denotes load voltages or currents.

III. PROPOSED ADAPTIVE PHASE ADJUSTING APPROACH FOR SHUNT ACTIVE POWER FILTER

A. General discussion for Synchronous Reference Frame based control

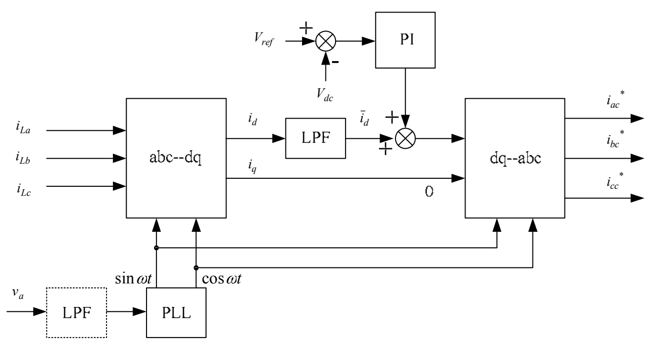


Fig. 3 Conventional SRF based control

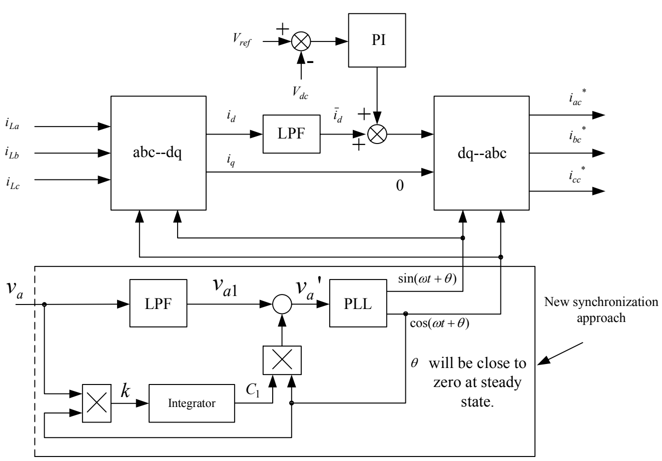


Fig. 4 Proposed adaptive phase adjusting approach for SRF

Fig. 3 shows the conventional synchronous reference frame control method for SAPF [1-3]. Phase Locked Loop (PLL) is used to create the sine and cosine signals in phase with the source voltage. Significant notching of source voltage can affect the precision of the phase since synchronization is done based on zero cross detection of the source voltage. As Fig. 3 shows, sometimes a LPF is used to suppress voltage distortion and to avoid multiple zero crossing. However, this introduces an undesirable phase shift.

To solve this problem, we propose a new approach to adjust the phase shift of the signal entering the PLL to zero. The method has been described in Fig. 4. The output of the PLL is fed back to compensate for the phase shift caused by the LPF used in this approach. Specifically, in steady state, the output of the integrator (C_1) will approach to a constant value. However, as we show below, C_1 is constant if and only if the averaged value of $v_a \cdot \cos(\omega t + \theta)$ is equal to 0. This condition occurs if and only if θ is adjusted to zero. Thus, the integrator in Fig. 4 has the effect of adaptively adjusting the phase shift of the PLL to become zero in steady state. The speed of the integrator is designed to be slow to assure system stability. Thus, in the proposed control method, the current reference of the SAPF remains in phase with source voltage. Voltage distortion has minimal influence on APF performance and LPF has been utilized without sacrificing power factor.

B. Technical analysis for Synchronous Reference Frame based control

The following analysis provides detailed explanation of the approach described in Fig. 4.

Assume $$v_a = A_1 \sin \omega t + \sum_{n=2}^{\infty} A_n \sin(n\omega t + \theta_n) \quad (4)$$

$$v_{a1} = B_1 \sin(\omega t + \theta_1) + \sum_{n=2}^{\infty} B_n \sin(\omega t + \theta_n{}')$$

$$(0 < \theta_1 < \frac{\pi}{2}) \quad (5)$$

v_{a1} is the output of LPF. It has no multiple zero crossing. So, the remaining higher order harmonics will not affect the PLL. $\sin(\omega t + \theta)$ and $\cos(\omega t + \theta)$ are the output of PLL. The input to the integrator obtained by feeding back a PLL output and multiplying it by the source voltage, is

$$k = v_a \cdot \cos(\omega t + \theta) = A_1 \sin \omega t \cos(\omega t + \theta) + \sum_{n=2}^{\infty} \sin(n\omega t + \theta_n) \cos(\omega t + \theta) \quad (6)$$

Assume $\bar{k}$ is the averaged value of k. From equation (6), we get

$$\bar{k} = \frac{1}{T} \int \frac{1}{2} A_1 [\sin(2\omega t + \theta) - \sin\theta] dt + \frac{1}{T} \int [\sum_{n=2}^{\infty} \sin(n\omega t + \theta_n) \cos(\omega t + \theta)] dt$$
$$= -\frac{1}{2} A_1 \sin\theta \quad (7)$$

From equation (7), we get

$$\bar{k} = 0 \Leftrightarrow \theta = 0 . \qquad (-\pi < \theta < \pi) \tag{8}$$

The value of the shifted phase θ can be adjusted to zero by controlling the value of $\bar{k}$. To avoid transient distortion, the integrator is designed to work slowly. Thus, the output of the integrator can approximately represent the integration of the averaged k. Both the average calculation and PI control is shown.

From (4) to (8) and Fig. 4,

$$v_a' = B_1 \sin(\omega t + \theta_1) + \sum_{n=2}^{\infty} B_n \sin(n\omega t + \theta_n') + C_1 \cos(\omega t + \theta)$$

$$= (B_1 \cos\theta_1 - C_1 \sin\theta) \sin\omega t + (B_1 \sin\theta_1 + C_1 \cos\theta) \cos\omega t + \sum_{n=2}^{\infty} B_n \sin(n\omega t + \theta_n') \tag{9}$$

Since the output of the PLL is $\sin(\omega t + \theta)$ and $\cos(\omega t + \theta)$, v_a' can also be represented as

$$v_a' = V \cdot \sin(\omega t + \theta) + \sum_{n=2}^{\infty} B_n \sin(n\omega t + \theta_n') \tag{10}$$

The higher order harmonics can be ignored since they will not affect the PLL.
From (9) and (10), we get

$$\frac{B_1 \sin\theta_1 + C_1 \cos\theta}{B_1 \cos\theta_1 - C_1 \sin\theta} = \frac{\sin\theta}{\cos\theta} \tag{11}$$

$$\Rightarrow \theta = \theta_1 + \arcsin\frac{C_1}{B_1} \quad (\text{If } |C_1| \le B_1) \tag{12}$$

According to (12), the output of the integrator should be limited when $|C_1| \le B_1$. So θ can be within the range of $-\frac{\pi}{2} < \theta - \theta_1 < \frac{\pi}{2}$. Since θ_1 and B_1 are constants, the value of θ can finally be determined by the value of C_1.
At steady state,

$$C_1 = -B_1 \sin\theta_1 \tag{13}$$

Thus, θ has been adjusted to zero, and the output of the PLL is in phase with the fundamental component of the source voltage as desired.

C. General discussion for instantaneous Reactive Power (IRP) based control

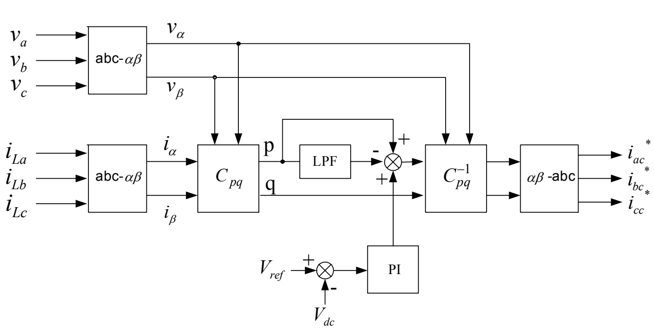


Fig. 5 Conventional IRP based control method

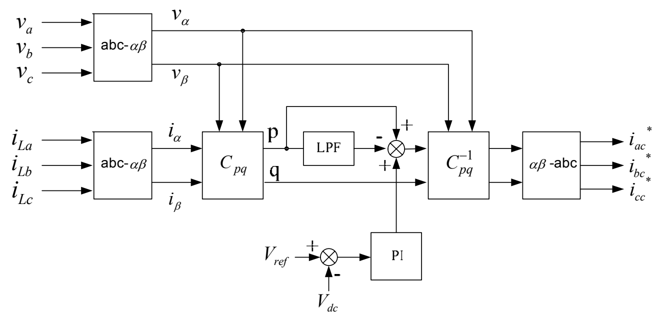


Fig. 6 Revised phase adjusting method in IRP based control

The above proposed phase adjusting method can also be revised and applied to IRP based control without utilizing the traditional PLL. Fig. 5 shows the conventional IRP based control for APF [2]. The generated current reference i_{ac}^*, i_{bc}^* and i_{cc}^* of SAPF follow the waveform of the source voltage. If the source voltage itself is distorted, the current reference can create undesired extra harmonics (see example in Section IV). Utilization of LPF still affects the power factor, especially when the distortion is significant.

Fig. 6 shows the revised phase adjusting method. Similar as Fig. 4, LPF is used to suppress the voltage signal distortion. The final voltage signal is fed back to compensate for the phase shift caused by the LPF. The integrator has the same function as in Fig. 4. The steady state condition of the added closed loop makes the averaged value of $v_\alpha \cdot v_\beta'$ equal to 0. In the mean time, the shifted phase φ is adjusted to 0.

D. Technical analysis for IRP based control

As in section II, we can also make a detailed analysis. Ideally, v_α and v_β have a phase difference of 90 degrees. Assume,

$$v_\alpha = E_1 \sin\omega t + \sum_{n=2}^{\infty} E_n \sin(n\omega t + \varphi_n) \tag{14}$$

$$v_\beta = -E_1 \cos\omega t - \sum_{n=2}^{\infty} E_n \cos(n\omega t + \varphi_n) \tag{15}$$

$$v_{\alpha 1} = V_1 \sin(\omega t + \varphi_1) \tag{16}$$

$$v_{\beta 1} = -V_1 \cos(\omega t + \varphi_1) \tag{17}$$

$$v_\alpha' = V_2 \sin(\omega t + \varphi) \tag{18}$$

$$v_\beta' = -V_2 \cos(\omega t + \varphi) \tag{19}$$

Since the distortion is suppressed by the LPF, we can consider the ideal condition with fundamental components only. (Although a few harmonics remain, they do not have any significant effect on the analysis of the fundamental component.) v_α' and v_β' are the final virtual voltage signals.

Feeding back the output $v_\beta^/$ and multiplying it by v_α, the input to the integrator is obtained as,

$$h = v_\alpha \cdot v_\beta^/ \tag{20}$$

Assume $\bar{h}$ is the averaged value of h. From (20), we get

$$\bar{h} = 0 \text{ when } \varphi = 0 . \quad (-\pi < \varphi < \pi) \tag{21}$$

We can also adjust the value of the shifted phase φ to zero by controlling the value of $\bar{h}$ in the same manner as adjusting $\bar{k}$ and θ described in Section III.B..

From Fig. 5 and equations (14) to (21), we get

$$v_\alpha^/ = v_{\alpha 1} + G \cdot v_{\beta 1} \tag{22}$$

and $$v_\beta^/ = v_{\beta 1} - G \cdot v_{\alpha 1} \tag{23}$$

The condition of equation (21) is approximately satisfied at steady state. At that time, the output of the integrator is close to a constant. From equations (22) and (23), the constant is

$$G = -\tan(\varphi_1) \tag{24}$$

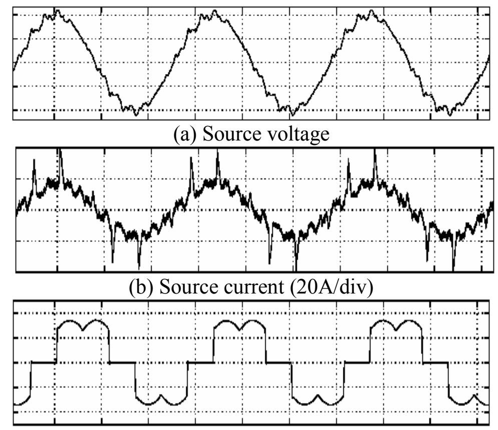
Then, the phase shift, φ of $v_\alpha^/$ and $v_\beta^/$ is 0, and once again the current reference signal created is both filtered and in-phase with the voltage source.

IV. EXAMPLE APPLICATIONS

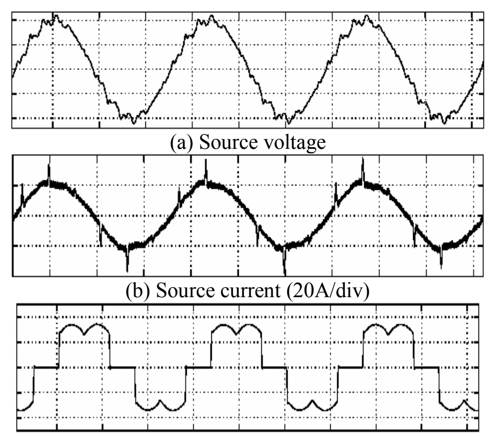
Application to source voltage taken from U.S. Coast Guard Healy

To examine the proposed approach, Fig. 7 and Fig. 8 apply the proposed approach for IRP based control using the experimental source voltage taken from the U.S. Coast Guard Healy at sea. The utilized voltage can cause significant distortion in reference current and thus affect the source current too. The example is set up similar to hardware-in-the-loop, where the experimental data is input into a simulation of the APF and nonlinear load. Fig. 7 shows the results of conventional IRP based control. It shows that the source voltage distortion creates undesired extra harmonics in source current after compensation. Fig. 7(b) shows that, some low order harmonics exist. Thus, the utilization of an effective LPF will cause noticeable phase shift and decrease the power factor. Fig. 8 shows the results when the revised phase adjusting approach is utilized. The harmonics in source current is suppressed greatly. The phase shift in source current is also adjusted to zero. Thus, the sacrifice of power factor is avoided.

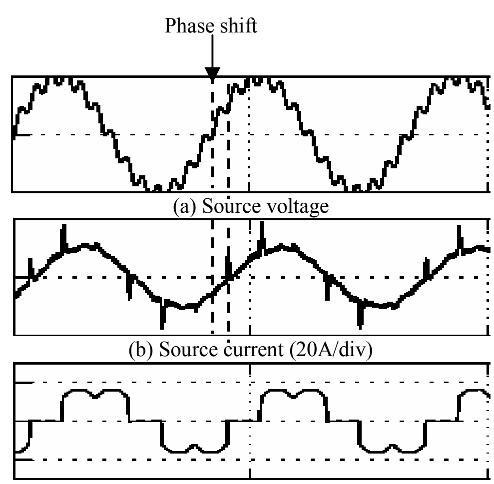
To verify the principle of the proposed phase adjustment scheme in the case of SRF based control, Fig. 9 and Fig. 10 show the simulation results. A seriously distorted 120V voltage with nominal line frequency of 60 Hz is utilized as the power supply. Figure 9 shows the results based on conventional SRF control. LPF is utilized to suppress the voltage distortion to prevent the false synchronization of the PLL. Therefore, it causes the phase shift in source current after compensation and the power factor is affected. Fig. 10 shows the results when the proposed approach is utilized. The waveforms show that the phase shift in source current is effectively adjusted to zero.



(a) Source voltage
(b) Source current (20A/div)
(c) Load current (20A/div)
Fig. 7 Conventional IRP based control
Notice significant source current distortion



(a) Source voltage
(b) Source current (20A/div)
(c) Load current (20A/div)
Fig. 8 Proposed scheme is applied to IRP control – Notice significant
Notice source current distortion has been reduced



(a) Source voltage
(b) Source current (20A/div)
(c) Load current (20A/div)
Fig. 9 Conventional SRF based control
Notice the phase shift between source voltage and current

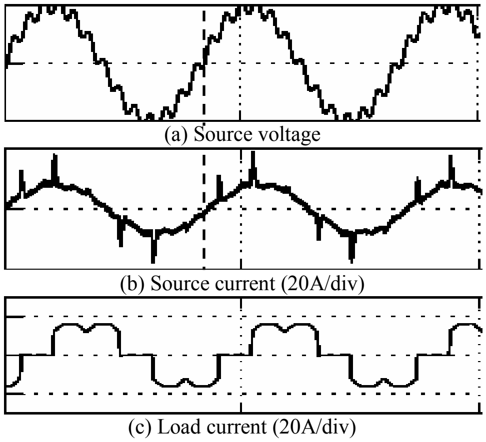


Fig. 10 Proposed scheme is applied to SRF control
Notice the source voltage and source current have the same phase

IV. CONCLUSION

Source voltage distortion is common in most distributed power systems. This paper describes the effects of the source voltage distortion on the current reference of SAPFs. It is shown that the source voltage distortion causes extra harmonics for IRP based control and affects the precise synchronization for SRF based control. An adaptive algorithm to compensate for the distortion problem is presented. The scheme is suitable for either the synchronous reference frame or for the instantaneous reactive power theory and is able to remove the phase shift caused by the utilization of low pass filter. Example applications verify the principle of the method.

For conventional control methods, SRF based control may be more preferable than IRP based methods, since they tend to be less sensitive to voltage perturbations. However, similar performance for the suppression of voltage distortion can be obtained when applying the proposed method of this paper to either the SRF or the IRP based control. Therefore, the preference of the two options depends on other factors. For example, SRF based harmonic detection only needs voltage information from one phase voltage, and thus saves two voltage sensors. On the other hand, the IRP based method has no need to utilize a phase locked loop (PLL).

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