Proceedings of the
2005 IEEE Conference on Control Applications
Toronto, Canada, August 28-31, 2005

Adaptive Saturation Scheme to Limit the Capacity of a Shunt Active Power Filter

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Abstract: When the current reference of a Shunt Active Power Filter (SAPF) changes quicker than the output current can change, the output of the APF cannot precisely track the current reference. Undesired harmonics will be generated by the APF due to the controller saturation. Based on detailed analysis of the reason and consequences of the controller saturation problem, this paper proposes an adaptive saturation scheme to suppress the effect of saturation by using the feedback of the current error signal. The proposed scheme can adaptively adjust the capacity of the APF according to different load conditions. The adjusted reference is still in phase with the original calculated harmonics and contains no extra undesired harmonics. Also, this algorithm has no risk of affecting the reference when there is no saturation. Simulation results show that the proposed scheme can operate effectively and the effect of saturation is greatly reduced.

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

1. Introduction

In the past few years there has been widespread proliferation of electric loads that contain electric drives, power converters and other nonlinear devices. These loads often introduce harmful harmonic currents and reactive power into the power system. This has led to research in methods to suppress the contamination of power quality at the point of coupling. One attractive approach to mitigate harmonics and improve power factor is to implement a shunt Active Power Filter (APF) in the power distribution systems.

The idea of a shunt APF is to connect an inverter in parallel with a power source or nonlinear load. The APF injects an appropriate current of the same amplitude and negative phase to that of the unwanted components of the load current. Thus, unwanted harmonics are canceled out and the source current becomes sinusoidal as desired. Further, with proper APF controllers, the source current has same phase as the source voltage, thus maintaining unity power factor (i.e. no reactive power) [1-10]. Because APFs only need to compensate for the reactive and harmonic currents, they handle just a fraction of the total power. Thus, utilization of the shunt APF is an attractive solution for high power application. To achieve high reliability and effective compensation, various control algorithms have been developed for APFs [1-5].

Figure 1 is a diagram of a shunt APF. The control part of the APF calculates the current reference for the inverter, and the current controller adjusts the output current of the inverter to follow the current reference.

Ideal compensation occurs when the output current of the APF can exactly follow the reference. In this case, the shunt APF is able to inject currents to cancel out the unwanted load current harmonics. The ideal result is a sinusoidal source current in phase with the source voltage [1-5].

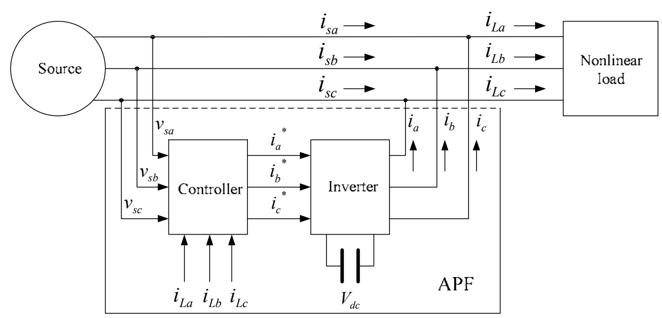
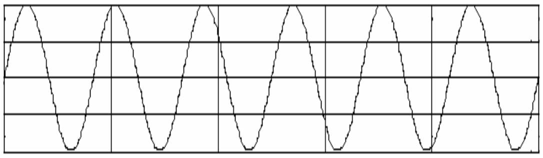


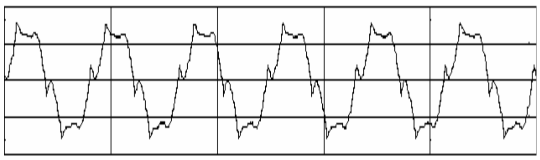
Fig. 1 Diagram of a shunt APF

However, in practice the output current in an APF cannot precisely track its reference. Specifically, there has been research demonstrating that power capacity limitations [6-7] in the APF sometimes cause controller errors. Likewise, more recent research has shown that controller delays [8-10] also cause current errors in an APF. Selective harmonic compensations have been proposed to cope with the controller delay of the current loop [11-12]. In this case, control accuracy is improved since the delay of the current control is compensated for. Further, the instabilities or interactions with the possible dynamic component of the load are reduced, and the rating of the APFs can be reduced.

This paper proposes an adaptive saturation scheme to deal with another mechanism that can cause errors between the actual and desired APF output currents. Specifically, when the reference changes quicker than the output current can change, the output of the APF cannot precisely track the current reference. In this case over-modulation may occur, which is due to the saturation effects on the control vector. When saturation occurs, the APF cannot provide the proper compensation. *Some undesired new harmonics will be* *generated by the APF.* These limitations on the speed response of the APF, which can cause serious extra current error, have received little attention in the literature.

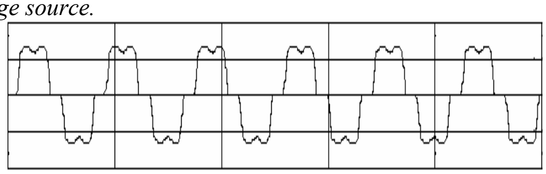


(a) Source voltage v_{sa}

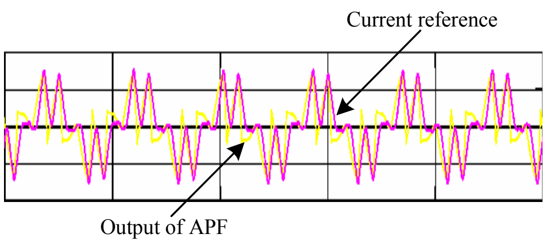


(b) Source current i_{sa} (20A/div)

The source current contains unwanted harmonics which are unable to be compensated for by APF due to the saturation of control. Ideally, the source current is sinusoidal and in phase with the voltage source.

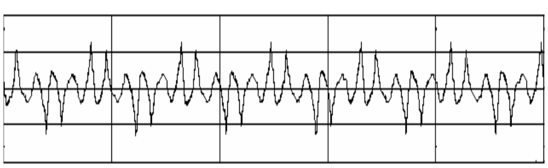


(c) Load current i_{La} (20A/div)

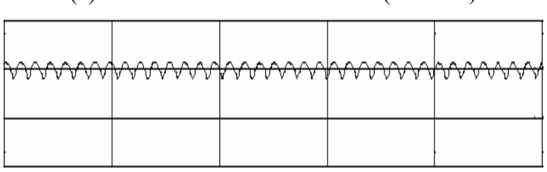


(d) Reference i_a^* and output of APF i_a (10A/div)

The output of APF cannot precisely track the reference. APF produces undesired harmonics besides generating the compensation.



(e) Harmonics of source current (10A/div)



(f) V_dc (from 400V to 550V, 50V/div)

Fig. 2 Waveforms when saturation occurs

Figure 2 shows an example when this type of saturation occurs using known shunt APF controller approach. The simulation uses a thyristor rectifier as the nonlinear load. The load current contains more harmonics than APF can compensate for. Thus, the output of the APF cannot change quickly enough to follow the reference. Therefore, a large error between the output and the reference arises. The current reference shown in Fig. 2(d) represents the harmonic distortion of the load current. Comparing the harmonic distortion of the source current after compensation in Fig. 2(e) with the load harmonic distortion, there is not a considerable improvement with the application of the APF. This means that the performance of the APF is affected due to a large compensation error which entails saturation on the control.

The limitation process due to saturation in a shunt APF is very involved. It is related with the load current condition, the APF inductance value, the source voltage value and the DC side voltage of the APF. Thus, the problem cannot be solved by directly limiting the amplitude of the current reference or the error amplifier output. (Other new problems may occur.)

Selective harmonic compensations [11-12] may have some benefits of reducing the influence of saturation, since the selected harmonics are just part of the distortion and have slower variation. However, even those selected harmonic components may have fast change and exceed the capacity of the APFs. This motivates the need to develop better controllers to deal with this type of APF limitation to avoid saturation.

Section 2 of this paper explains the reasons/mechanisms that cause the control vector to saturate. Section 3 proposes a saturation scheme that introduces a closed loop controller to adaptively limit the reference current to the APF. Section 4 presents simulations to verify the approach. Section 5 gives conclusions.

2. Understanding when the saturation on the control vector occurs

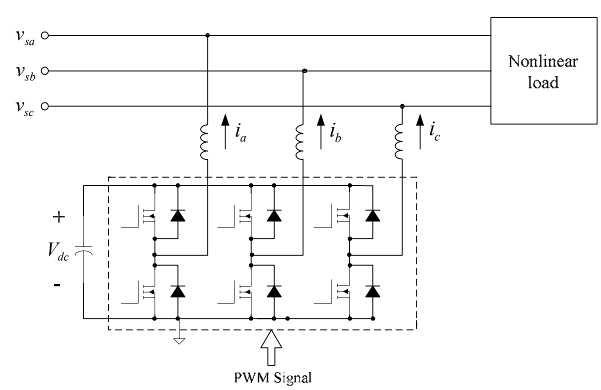


Fig. 3 Diagram of a three-phase power inverter used for APF

Figure 3 shows the diagram of a three-phase power inverter used for APF. The PWM signal controls the switches of the inverter, thus creates desired output currents.

As previously mentioned, saturation due to rapid load current changes has yet to be examined in the literature, and hence, it is important to model and understand the reasons they occur: Undesired harmonics will be produced when the change rate of load current exceeds the maximum change rate of the APF output current. Assume that v_{no} is a constant. The maximum and minimum rates of change of the power inverter output current are:

$$(\frac{di_i}{dt})_{\max} = \frac{V_{dc} - v_{si} - v_{no}}{L} \quad (1)$$

$$(\frac{di_i}{dt})_{\min} = \frac{-v_{si} - v_{no}}{L} \qquad (i = a, b, c) \quad (2)$$

v_{no} is the voltage between the neutral point of the source and the ground of the inverter, V_{dc} is the DC side voltage of the inverter, v_{si} represents the source voltage. From (1) and (2), the following conclusions can be obtained: First, since v_{no} is related to the switching condition of the three phases, the current rate of change is affected by the condition of all three phases. Second, V_{dc} has restricted maximum value according to the various component ratings of the APF, for example, the dc bus capacitor.

The output current rate of change will be limited by V_{dc}. Third, the value of the inductor L is limited by the requirement of current ripple. Finally, the maximum rate of change also varies according to the value of the source voltage within one line cycle.

To simplify the analysis, we change the variables from a-b-c coordinates to $\alpha\beta$ coordinates.
Consider

$$L\begin{bmatrix} di_a/dt \\ di_b/dt \\ di_c/dt \end{bmatrix} = \begin{bmatrix} v_{ao} \\ v_{bo} \\ v_{co} \end{bmatrix} - \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} - \begin{bmatrix} v_{no} \\ v_{no} \\ v_{no} \end{bmatrix} \quad (3)$$

where $\begin{bmatrix} v_{ao} \\ v_{bo} \\ v_{co} \end{bmatrix} = \begin{bmatrix} V_{dc} \cdot v_{cona} \\ V_{dc} \cdot v_{conb} \\ V_{dc} \cdot v_{conc} \end{bmatrix}$

and $v_{cona}, v_{conb}, v_{conc}$ represent the duty ratio of the control signal.

Using the Park transformation [1-5],

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \quad (4)$$

(3) can be transformed into two phases as follows:

$$L\begin{bmatrix} di_\alpha/dt \\ di_\beta/dt \end{bmatrix} = V_{dc}\begin{bmatrix} v_{con\alpha} \\ v_{con\beta} \end{bmatrix} - \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \quad (5)$$

Ideally, the output current should be equal to the current reference. Assume the switching cycle is small enough. The output current rate of change will be the same as the reference rate of change. Accordingly, the ideal, or equivalent, duty ratio is:

$$\begin{bmatrix} v_{con\alpha}^* \\ v_{con\beta}^* \end{bmatrix} = \frac{L}{V_{dc}}\begin{bmatrix} di_\alpha^*/dt \\ di_\beta^*/dt \end{bmatrix} + \frac{1}{V_{dc}}\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \quad (6)$$

where i_α^*, i_β^* represent the current reference in $\alpha\beta$ coordinates. If larger (or smaller) duty ratio is available to obtain a higher output current rate of change, the output current can converge to the reference no matter how big the current error is. To guarantee the tracking performance, the above condition should be satisfied at each point of the line cycle. Thus, to avoid saturation, the derived ideal duty ratio should be within the range that the control circuit can provide. The concept of the space vector makes it much easier to discuss the saturation of the duty ratio. For a three-phase control signal, a space vector (in $\alpha\beta$ frame) inside the region of the hexagon shown in Fig. 4 can represent a duty cycle that the controller can provide. Equation (7) shows the saturation condition.

$$\sqrt{(v_{con\alpha}^*)^2 + (v_{con\beta}^*)^2} \cdot \cos(\theta + 30^o - n \cdot 60^o) \le \frac{\sqrt{3}}{2} \quad (7)$$

where $\cos\theta = \frac{v_{con\alpha}^*}{\sqrt{(v_{con\alpha}^*)^2 + (v_{con\beta}^*)^2}}$,

$\sin\theta = \frac{v_{con\beta}^*}{\sqrt{(v_{con\alpha}^*)^2 + (v_{con\beta}^*)^2}}$,

$n = 1, 2, \cdots 6$ represents the region where the vector locates.

The condition can also be expressed as:

$$|v_{con\alpha}| \cdot \frac{\sqrt{3}}{2} + |v_{con\beta}| \cdot \frac{1}{2} \le \frac{\sqrt{3}}{2} \quad (8)$$

when $|v_{con\beta}| < \sqrt{3}|v_{con\alpha}|$ (in region 1,3,4,6);

$$|v_{con\beta}| \le \frac{\sqrt{3}}{2} \quad (9)$$

when $|v_{con\beta}| \ge \sqrt{3}|v_{con\alpha}|$ (in region 2,5).

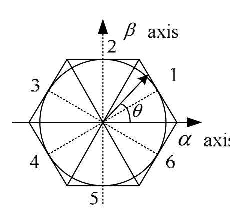


Fig. 4 The space vectors

When the ideal duty ratio satisfies the equation (8) and (9), the control signal does not exceed the maximum limitation. However, when (8) and (9) are not satisfied, the circuit is unable to provide sufficient duty ratio. Then, the excess of the control vector is cut off, and the output is affected.

3. Adaptive saturation scheme

Since the parameters of the power design, such as V_{dc} and L, are fixed for each APF, the limitation of the output current rate of change is not adjustable according to (1) and (2). Therefore, adjusting the current reference is a good choice. Because the current reference represents the harmonic distortion that the load current contains, properly reducing the harmonics is reasonable consideration to limit the reference rate of change.

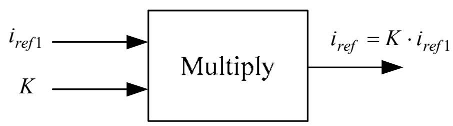


Fig. 5 Providing part of the compensation

To guarantee an appropriate operation of the APF, we propose to compensate only for a reduced amount that is proportional to the harmonic distortion during saturation. A simple method is to multiply the current reference by a value K (0<K<1) to reduce reference rate of change (as shown in Fig. 5). Thus, the rate of change will also be multiplied by K. Notice that, a small value of K would keep the APF underemployed, while a large value of K may produce saturation. This paper will propose how to properly adjust K with closed loop control.

The proposed approach (as shown in Fig. 6) has the following advantages:

- *The proposed scheme can adaptively adjust its capacity according to different load conditions.*
- *The new approach keeps the final reference in phase with the original calculated harmonics without causing any phase shift at steady state. Thus, the power factor will not be affected.*
- The proposed scheme does not affect the reference when there is no risk of saturation.
- The effect of control delay can also be reduced with lower di/dt.

To prevent the APF from producing new undesired harmonics, we propose to *adaptively adjust the gain K by using the feedback of* $|\Delta i|$. As previously discussed, the output current of the APF cannot precisely track the current reference when the current reference rate of change is too high. So, $\Delta i = i_f - i_{ref}$ will not be close to zero, and $\overline{|\Delta i|}$ will be large if the saturation problem is serious. (i_f is the current produced by the APF. $\overline{|\Delta i|}$ is the averaged value of $|\Delta i|$. When no saturation occurs, Δi and $\overline{|\Delta i|}$ are almost zero.). By controlling $|\Delta i|$ in a closed loop, we can keep $\overline{|\Delta i|}$ to a small value.

a. Basic principle:

Figure 6 shows the diagram of the scheme. i_{ref1} is the original reference calculated from the load current, i_{ref} is the final reference that APF will use. Parameter k_1 is a relatively small (ideally zero) value which is set to limit $\overline{|\Delta i|}$. When saturation occurs, $\overline{|\Delta i|}$ is bigger than k_1 at the beginning, and the output of the integrator increases. Then the value of K and the reference i_{ref} will also gradually decrease until $\overline{|\Delta i|}$ reaches k_1. When $\overline{|\Delta i|}$ is smaller than k_1, K gradually increase to get back the capacity.

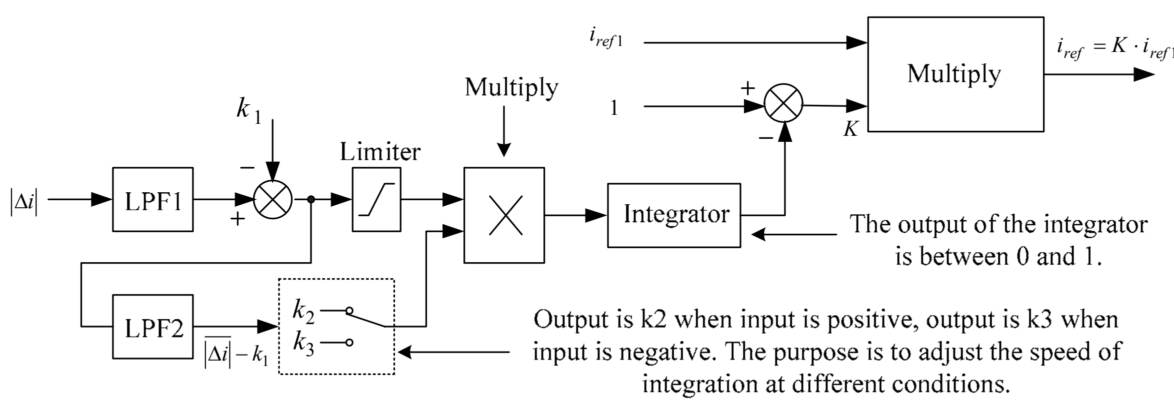


Fig. 6 A method to reduce the effect of saturation by using the feedback of $|\Delta i|$

When no saturation occurs or when its effect is imperceptible, $|\bar{\Delta i}|$ is smaller than k_1. Variable K and the reference i_{ref} will increase until $i_{ref} = i_{ref1}$ (*K is clamped to 1*). APF provides the total compensation. The proposed scheme does not affect the control and operation of APF at that time.

b. More detailed description:

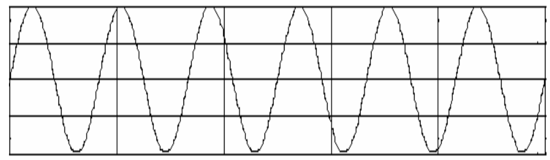
In Fig. 6, the value of $|\Delta i|$ is measured and fed back. LPF1 is utilized to suppress the high frequency noise of $|\Delta i|$. The cut-off frequency has been set to 500 Hz for nominal line frequency of 60Hz. Then, the output of LPF1 minus k_1 is used to realize the closed loop control. Since the value of $|\Delta i|$ can be large before coming into steady state, a limiter is utilized.

The integrator in Fig. 6 has two functions: First, it computes the averaged value. Second, it regulates as a PI controller. To obtain the averaged value and prevent the controller from affecting the steady state operation, the integration constant is designed to be very low. In simulation, the integrating time is 100ms which is much larger than the line cycle (16.7ms). Thus, the value of K can be considered to be nearly a constant in a line cycle at steady state. Also, the output of the integrator should be clipped between 0 and 1 to keep the value of K within the proper range. The purpose of the scheme is to adjust $|\bar{\Delta i}|$ to a substantially small value k_1 during saturation. (k_1 *is set sufficiently small to make* $|\bar{\Delta i}|$ *close to zero.*) In simulation, k_1 is set to be 5% of the source current peak.

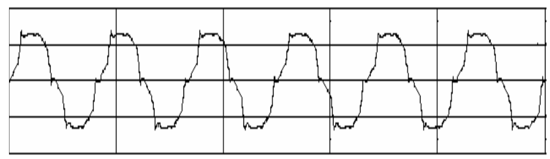
To improve the response during a load change, the integration constant should be adjusted for different conditions. For example, when $|\bar{\Delta i}|$ is larger than k_1, the added controller will decrease the value of K to avoid saturation. At that time, the value of $\overline{|\Delta i|} - k_1$ can be much bigger than k_1, and the effect of the feedback signal $|\Delta i|$ can be large when the error is large. On the other hand, the controller increases K when $|\bar{\Delta i}|$ is smaller than k_1. Since $\overline{|\Delta i|} - k_1$ will be a substantially small value within the range of $[-k_1, 0]$ in that condition, the effect of $|\Delta i|$ will be small even when the K is far away from the anticipated value. Thus, the integration speed cannot be the same for these two conditions.

The purpose of *LPF2* is to obtain the averaged value of $|\Delta i| - k_1$ (The cut-off frequency is set to 30Hz). By judging the value of $\overline{|\Delta i|} - k_1$, the integration mode is determined. Mode 1 is utilized when $\overline{|\Delta i|} - k_1 > 0$. k_2=1 is sent to the multiply. Mode 2 will be utilized when $\overline{|\Delta i|} - k_1 < 0$. In this case, k_3=5 is sent to the multiply to accelerate the integration.

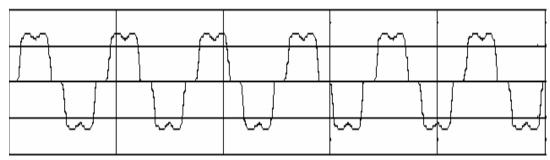
4. Examples



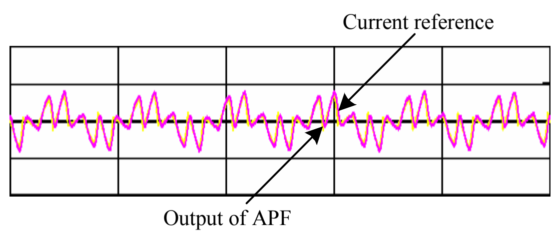
(a) Source voltage



(b) Source current (20A/div)

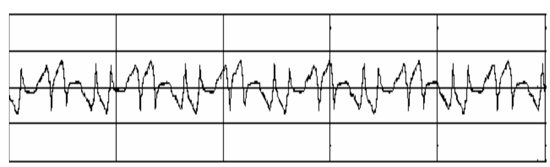


(c) Load current (20A/div)

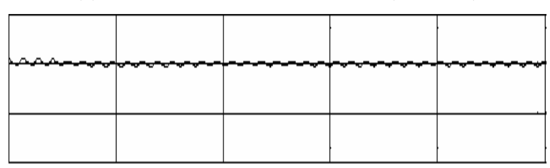


(d) Reference and output of APF (10A/div)

As desired, the output of APF almost superimposes the adaptively adjusted current reference. Thus, the APF does not generate undesired harmonics.



(e) Harmonics of source current (10A/div)



(f) V_dc (from 400V to 550V, 50V/div)

Fig. 7 Waveforms when the proposed scheme is applied

To verify the performance of the proposed adaptive saturation scheme, simulation models are built to compare the results. The source is a three-phase power supply of

120V. The major parameters of the APF are as follows: DC bus voltage is 500V, the value of DC bus capacitor is 470uF, and the value of the inductor is 15mH. Typical thyristor rectifier is utilized as the nonlinear load.

Figure 2 and Fig. 7 compare the simulation results before and after the application of the proposed scheme to deal with the saturation problem. Fig. 2 shows the waveforms when saturation occurs. The results are obtained based on the conventional operation approach [1-5] of APF. From Fig. 2(d), we observe that there is noticeable difference between the reference and the output of the APF. In this case the APF generates noticeable undesired harmonics. Thus, source current contains the undesired harmonics, as shown in Fig.2(e). Fig. 7 shows the waveforms when the proposed scheme is applied. From Fig. 7(d), we observe that the output current of the APF is close to the adjusted reference. The APF operates properly and has no risk of creating harmful undesired harmonics. Figure 7(b) and Fig. 7(d) shows that the compensation results are improved by the proposed algorithm during saturation when compared with Fig. 2(b) and Fig. 2(d).

Comparing the waveforms between Fig. 2 and Fig. 6, the following advantages of the new scheme can be seen:
(1) The maximum amplitude of the harmonics of the source current decreased from 12.7A to 7.2A when the saturation is adaptively limited in our proposed scheme.
(2) The APF only provides part of compensation instead of dealing with all the harmonic distortion during saturation. The amplitude of the APF output current reduces from 15.2A to 7.9A when the proposed scheme is applied (compare Fig. 2(e) and Fig. 6(e)) without causing more distortion. Thus, the power rating on the APF can be reduced.
(3) The THD value of the source current reduces from 20.1% to 17.3% when the adaptive saturation scheme is utilized. THD is the ratio between the total root-mean-square (RMS) value of the harmonic distortion of the signal and the overall RMS value of the signal. The THD value of the source current can represent the effectiveness of the compensation.
(4) Voltage ripple of the DC side in the APF decreased from 3.2% to 1.2% when the proposed scheme is used.

5. Conclusion

This research analyzes the reasons and consequences of the controller saturation problem caused by the rapid change of load current. Possible solutions and challenges are discussed. Based on detailed analysis, a scheme to reduce the effect of the saturation problem is presented. The proposed approach can adaptively adjust the compensation according to different load conditions. Matlab simulation verifies the principle of the new approach.

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