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IMPROVEMENT OF *P-Q* HARMONIC DETECTION METHOD FOR SHUNT ACTIVE POWER FILTER

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Abstract. *The effective operation of the shunt active power filter (SAPF) is decided by the harmonic detection method. The p-q theory method has been widely used in determining the harmonic current of SAPF. However, the p-q theory method depends on the source voltage and has the large overshoot and long transient duration at a large and rapid load change. Therefore, in this paper an improvement of p-q theory method based on fuzzy logic has been proposed, which aims to reduce the overshoot and transient time of the traditional p-q method. This has practical significance in improving the stability of SAPF. In order to compare the conventional and improved p-q theory methods, simulation results have demonstrated that: the proposed method has a shorter dynamic response time, an amplitude of the supply current in the transient duration is smaller, and a better ability to reduce overshoot in active and reactive power components.*
Keywords: Shunt active power filter, *p-q* theory, Fuzzy logic, Harmonic detection

1. **Introduction.** The shunt active power filter is known as a harmonic filter and reactive power compensation effectively [1-3]. However, the effectiveness of SAPF depends on many factors such as: filter structure, calculation parameters, control method, control strategy, and harmonics detection method. This paper deals with a key issue that decides the correct operation of SAPF. That is the harmonic current detection method.

Many harmonic detection methods have been proposed for SAPF. Traditional harmonic detection methods include: the low-pass filter (LPF), high-pass filter (HPF), fast Fourier transform and *p-q* theory. The low-pass and high-pass filters have slow response and only a slight variation of frequency will also result in a significant phase shifting [4]. The disadvantage of fast Fourier transform method is that it is not flexible to load changes because the sampling frequency has been fixed [5]. The most common is the *p-q* harmonic detection method (namely, *p-q* theory method) [6-9]. This method has the advantage of being simple, easy to implement. However, it also has many disadvantages, for example, transient time is large, result is inaccurate if the three-phase source is not ideal and the overshoot at the transient period is large if the load changes very quickly with great amplitude. The unideal three-phase source can be overcome by using the phase-locked loop (PLL) [10]. To improve the accuracy of the *p-q* harmonic detection method, a few articles have proposed by using the neural network [11,12] or fuzzy logic [13,14]. It only has the ability to improve accuracy in steady-state. However, these methods have a slow response and large overshoot when the load changes rapidly. Therefore, it is less used. Another is Fryze-Buchholz-Dpenbrock (FBD) method [15,16], which is based on the sliding-window iterative algorithm. This method has the advantage of not using phase-locked loop block and skip low-pass filter. Even so, it has the disadvantages of complexity and slow response.

In short, the above listed methods have disadvantages of large transient duration and it is difficult to reduce the current amplitude during transient period. In this paper, an improvement of the traditional *p-q* harmonic detection method is made. The purpose of this improvement is to reduce the transient overshoot and transient time. From the mathematical analysis of the traditional *p-q* method, we find that its disadvantage is that it depends on the source voltage and low-pass filters. From there, a fuzzy regulator is integrated into the traditional *p-q* method to adjust the direct current (DC) signals of the active power and reactive power to near the desired value. From this, the amplitude of the source current has not overshoot when the load changes rapidly and with a great amplitude, while the transient duration is reduced to very small.

The structure of the paper consists of four parts: part 1 gives an overview of the research problem, the *p-q* harmonic detection method and its disadvantage are analyzed in part 2, part 3 is the improved *p-q* harmonic detection method, part 4 is the results of simulation and discussion, and the conclusions are presented in part 5.

2. *P-Q* Harmonic Detection Method and Its Disadvantage.

The traditional *p-q* harmonic detection method is proposed by Akagi et al. [8] and can be summarized as in Figure 1.

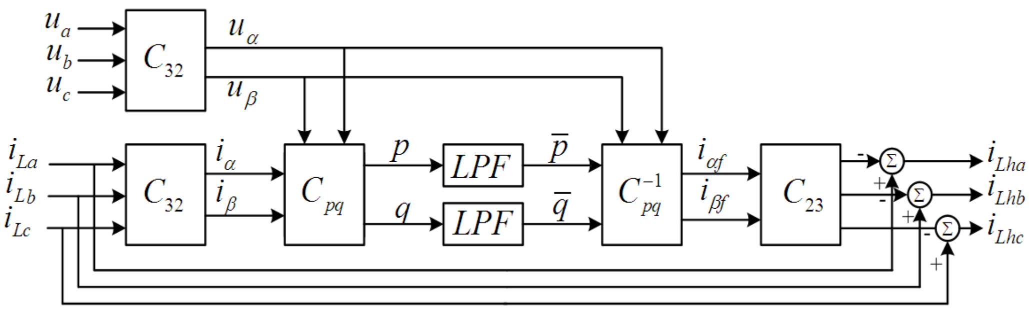


FIGURE 1. The principle diagram of *p-q* method

In Figure 1, u_a, u_b, u_c are three-phase instantaneous source voltages, i_{La}, i_{Lb}, i_{Lc} are three-phase instantaneous load currents, and $\bar{p}$, $\bar{q}$ are DC components of p and q instantaneous powers.

From Figure 1, we can calculate the fundamental harmonic current components of the i_{La}, i_{Lb}, i_{Lc} following formula as

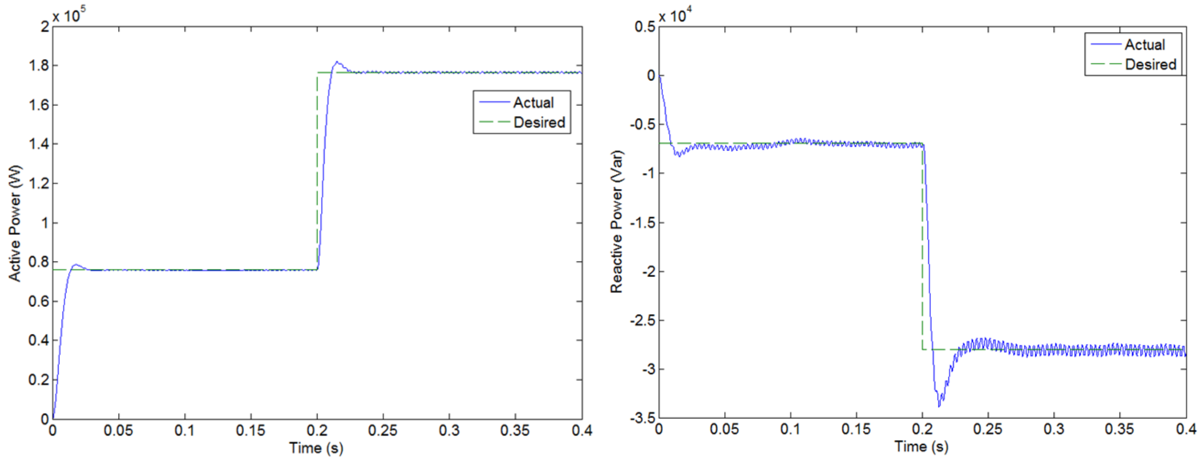
$$\begin{bmatrix} i_{Laf} \\ i_{Lbf} \\ i_{Lcf} \end{bmatrix} = \frac{1}{3U_1^2} C_{23} C_{pq}^{-1} \begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} \tag{1}$$

where $C_{32} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}$; $C_{23} = C_{32}^T$; $C_{pq} = \begin{bmatrix} u_\alpha & u_\beta \\ u_\beta & -u_\alpha \end{bmatrix}$.

From here, the harmonic current components can be determined as:

$$\begin{cases} i_{Lah} = i_{La} - i_{Laf} \\ i_{Lbh} = i_{Lb} - i_{Lbf} \\ i_{Lch} = i_{Lc} - i_{Lcf} \end{cases} \tag{2}$$

From (1) we can see that: the traditional *p-q* method has the disadvantages of depending on the supply voltage and LPF. When source voltage is not ideal, PLL block must be used [10]. When the load changes rapidly in amplitude and phase angle, the LPFs will produce components $\bar{p}$ and $\bar{q}$ that contain unwanted components. As a result, the active and reactive power components will change significantly. However, actual power always changes because load changes. The difference between the actual value and the reference value $\bar{p}$ is called Δp. Similarly, the difference between the actual value $\bar{q}$ and the reference value $\bar{q}$ is called Δq. Desired and actual variation of $\bar{p}$ and $\bar{q}$ are shown in Figure 2.



(a) Desired and actual variation of $\bar{p}$ (b) Desired and actual variation of $\bar{q}$

FIGURE 2. Desired and actual variation of $\bar{p}$ and $\bar{q}$

From Figure 2, we can see that: in the transient duration there is overshooting, and there is a discrepancy between the actual value and the reference value. When the load changes, the overshoot is high, which results in a sudden increase in the amplitude of the supply current, leading to system easy instability.

3. Improved *P-Q* Harmonic Detection Method. In the p-q method, LPFs determine the accuracy of the method, when the cut-off frequency is chosen to be large, the transient duration will decrease but the overshoot increases and the error is large. The cut-off frequency is small, the overshoot will decrease and the error in steady-state is small but the transient duration will be very large. In real-time applications, load changes rapidly over time, and components $\bar{p}$ and $\bar{q}$ will change at different frequencies.

To improve transient overshoot and reduce the dynamic response time of the traditional p-q method. An improvement of the traditional p-q harmonic detection method is proposed in Figure 3.

The p and q components after passing LPF will obtain the DC components $\bar{p}$ and $\bar{q}$. A fuzzy adjustor is added to control the $\bar{p}$ and $\bar{q}$ components whenever there is a change of load.

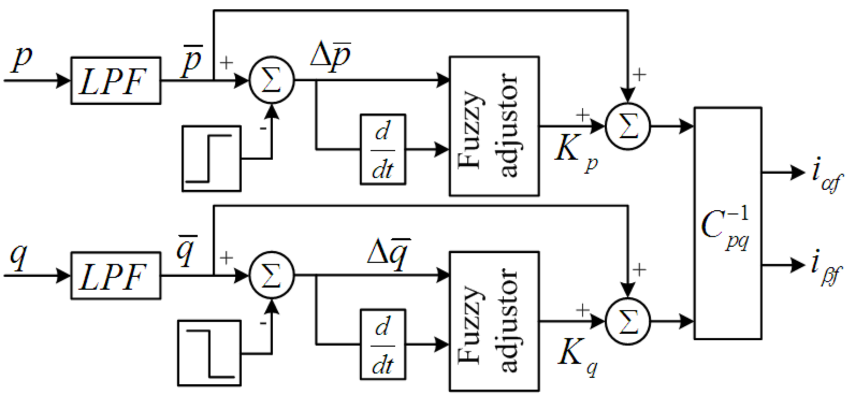


FIGURE 3. Improved p-q harmonic detection method

Accordingly, Formula (1) can be rewritten as follows:

$$\begin{bmatrix} i_{Laf} \\ i_{Lbf} \\ i_{Lcf} \end{bmatrix} = \frac{1}{3U_1^2} C_{23} C_{pq}^{-1} \begin{bmatrix} \bar{p}_{new} \\ \bar{q}_{new} \end{bmatrix} \tag{3}$$

where $\begin{cases} \bar{p}_{new} = \bar{p} + K_p \\ \bar{q}_{new} = \bar{q} + K_q \end{cases}$, and $\bar{p}$ and $\bar{q}$ will have step response. K_p and K_q are parameters controlled by fuzzy adjustor.

The error between the actual value and the reference value of $\bar{p}$ and $\bar{q}$ is $\Delta\bar{p}$ and $\Delta\bar{q}$, namely $\Delta(.)$ and its rate d/dt is the inputs of the fuzzy regulator, and the outputs of the fuzzy regulator are K_p and K_q.

The inputs and outputs of the fuzzy regulator are shown into seven membership functions: Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z0), Positive Small (PS), Positive Medium (PM), Positive Big (PB) as shown in Figure 4.

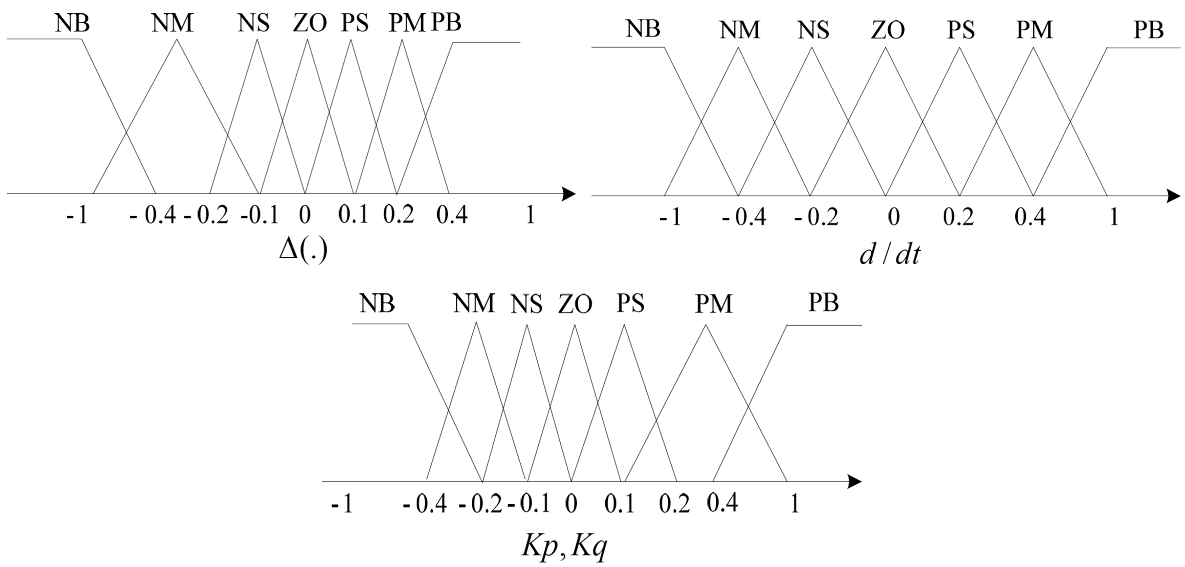


Figure 4. Membership functions of input/output

Based on Figure 2 and Figure 3, we have the control laws of K_p and K_q as follows:

1) If $\Delta(.) = 0$, then K_p, K_q must be zero.
2) If $\Delta(.)$ is NS or PS, then K_p, K_q should be zero.
3) For large value of $\Delta(.)$, a small K_p, K_q is required and for small value of $\Delta(.)$, a large K_p, K_q is required.
4) For positive values of $\Delta(.)$ and d/dt, negative values of K_p, K_q are required and for negative values of $\Delta(.)$ and d/dt, positive values of K_p, K_q are required.
5) For positive values of $\Delta(.)$ and negative values of d/dt, negative values of K_p, K_q are required and for negative values of $\Delta(.)$ and positive values of d/dt, positive values of K_p, K_q are required.

The fuzzy rules are shown clearly in Table 1.

4. **Simulation Results and Discussion.** To demonstrate the effectiveness of the improved and traditional *p-q* harmonic detection methods, simulation results were performed on a three-phase 380V-50Hz SAPF system. The SAPF single-phase equivalent circuit is shown in Figure 5.

Nonlinear loads of the model are modelled by a three-phase uncontrolled bridge rectifier with RL load ($0 \div 0.2$s) and then the load changes (0.2s $\div$ 0.4s). Total harmonic distortion (THD) of the load current i_L before change is 28.6% and after change is 27.53%.

TABLE 1. Fuzzy rules

K_p, K_q		d/dt						
		NB	*PM*	*NS*	*Z0*	*PS*	*PM*	*PB*
$\Delta(.)$	*NB*	PB	PM	PM	PM	PS	PS	PS
	NM	PM	PM	PS	PS	PS	PS	PS
	NS	PS	Z0	Z0	Z0	Z0	Z0	PS
	Z0	Z0	Z0	Z0	Z0	Z0	Z0	Z0
	PS	NS	Z0	Z0	Z0	Z0	Z0	NS
	PM	NM	NM	NS	NS	NS	NS	NS
	PB	NB	NM	NM	NM	NS	NS	NS

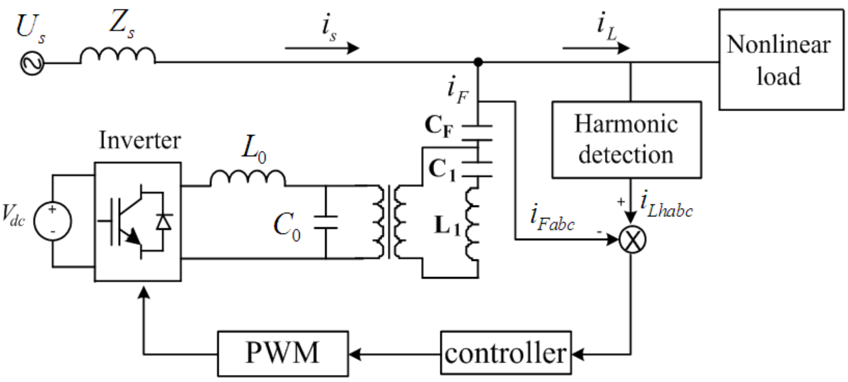


FIGURE 5. SAPF single-phase equivalent circuit

DC components of active power and reactive power before and after load change are shown in Figure 6.

Example: from Figure 6(a), we can calculate the transient duration and overshoot of $\bar{p}$ following as: At $t = 0.2$s, load changes, $\bar{p}$ increases to 1.82×10^5(W) and then reaches the steady-state value at 1.74×10^5(W) in 0.05s. Therefore, the transient duration is 0.05s and overshoot is 4.59%.

The difference between the traditional and improved *p*-*q* methods is summarized in Table 2 and Table 3 as follows.

TABLE 2. Response of $\bar{p}$

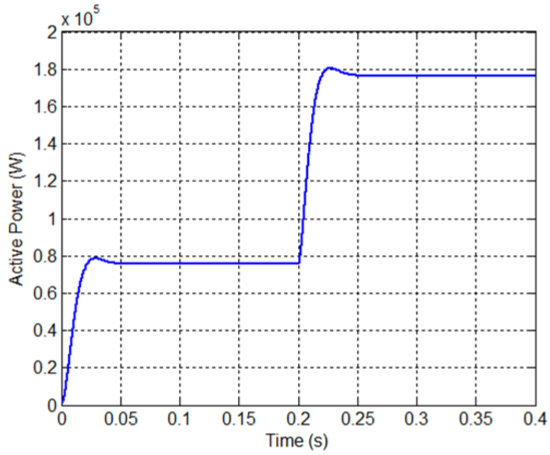
	0.0s ÷ 0.2s		0.2s ÷ 0.4s	
	transient duration	overshoot	transient duration	overshoot
Traditional *p*-*q*	0.05s	3.96%	0.05s	4.59%
Improved *p*-*q*	0.016s	0.3%	0.025	0.5%

TABLE 3. Response of $\bar{q}$

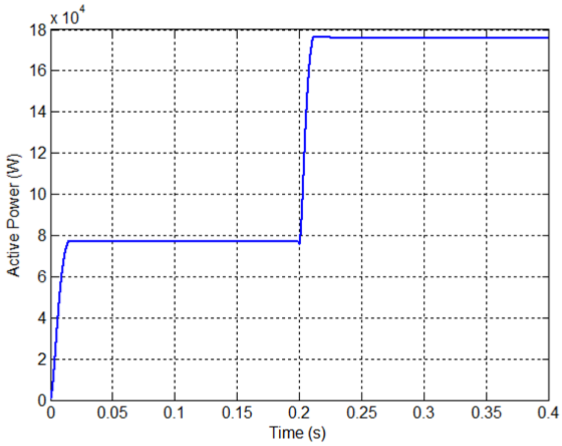
	0.0s ÷ 0.2s		0.2s ÷ 0.4s	
	transient duration	overshoot	transient duration	overshoot
Traditional *p*-*q*	0.025s	18.4%	0.04s	21.13%
Improved *p*-*q*	0.02s	0.42%	0.02s	2%

The dynamic response of the waveforms with the traditional and improved *p*-*q* methods is shown in Figure 7 and Figure 8.

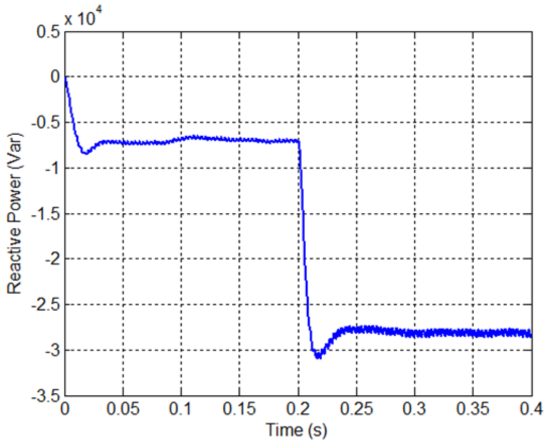
From Figure 7 and Figure 8 we find that: with traditional *p*-*q* method, the transient duration is 0.05s (0.0s ÷ 0.2s) and 0.04s (0.2s ÷ 0.24s), the overshoot of supply current



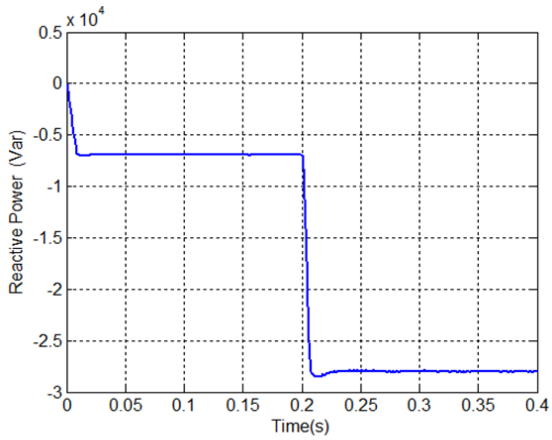
(a) Actual variation of $\bar{p}$ with the traditional *p*-*q* method



(b) Actual variation of $\bar{p}$ with the improved *p*-*q* method



(c) Actual variation of $\bar{q}$ with the traditional *p*-*q* method



(d) Actual variation of $\bar{q}$ with the improved *p*-*q* method

FIGURE 6. Actual variation of $\bar{p}$ and $\bar{q}$

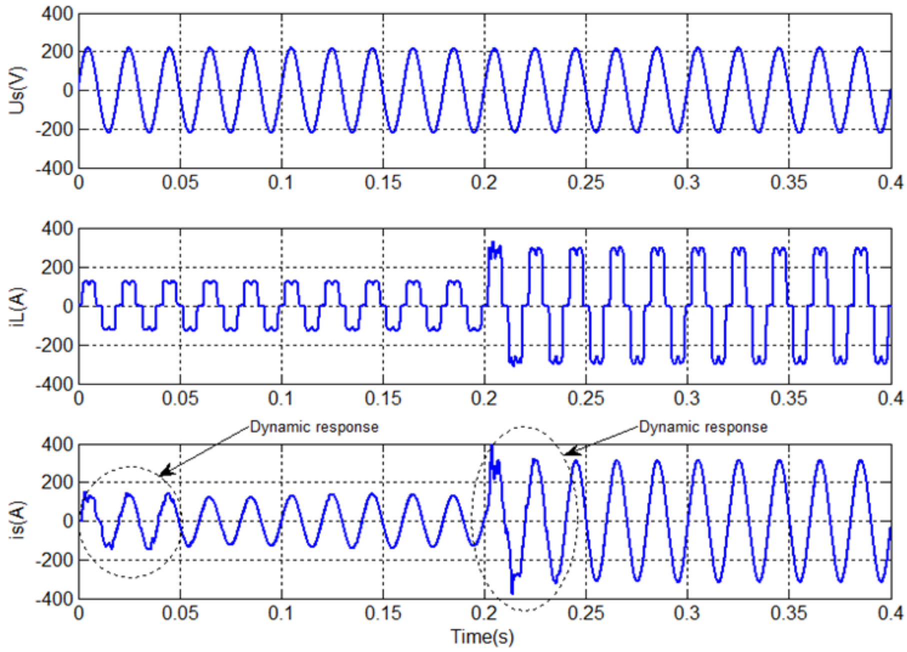


FIGURE 7. Dynamic response of waveforms with the traditional *p*-*q* method

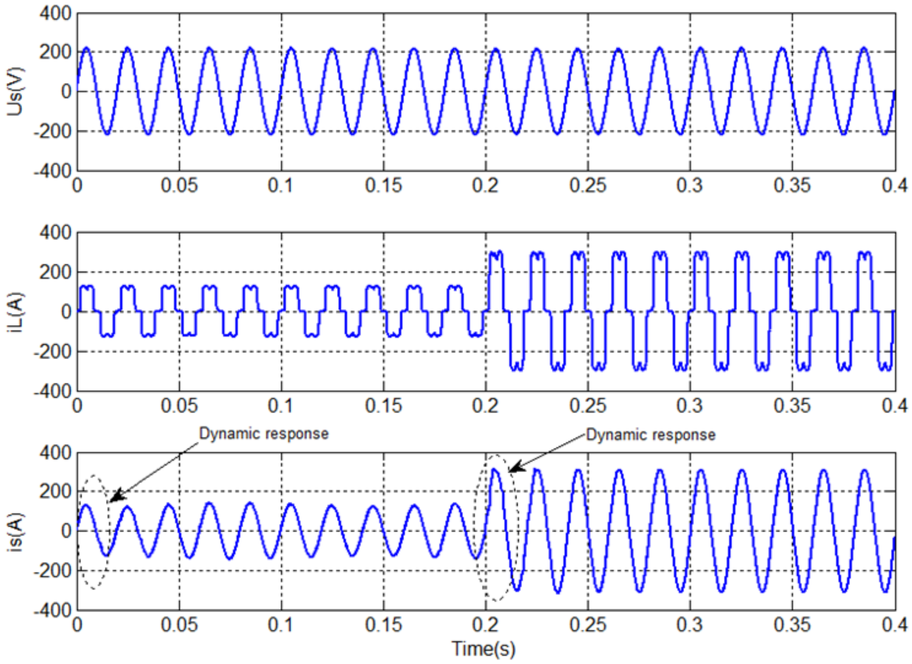


Figure 8. Dynamic response of waveforms with the improved *p*-*q* method

i_s when the load change is 27.67%, and THD of the supply current i_s in steady-state is 1.44% (0.1s ÷ 0.2s) and 1.2% (0.3s ÷ 0.4s). When the improved *p*-*q* method is used, the transient duration is almost zero (0.0s ÷ 0.2s) and 0.02s (0.2s ÷ 0.24s), the overshoot of i_s is almost zero when the load before and after change, and THD of i_s in steady-state is 1.44% (0.1s ÷ 0.2s) and 1.2% (0.3s ÷ 0.4s).

In summary, the simulation results demonstrated the effectiveness of the improved and traditional *p*-*q* harmonic detection method in reducing the transient time and overshoot. This has great significance in improving the stability of the SAPF system.

5. Conclusions.

This paper has made an improvement to the traditional *p*-*q* harmonic detection method. This improvement aims to reduce the dynamic response time, overshoot in the transient duration of the traditional *p*-*q* method. Furthermore, this study also contributed to improving the stability of the SAPF system when the load suddenly changes with a large amplitude. This approach will be a good solution for high speed power control applications.

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