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Comparative Study of PQ theory and DQ Control Method for Shunt Active Harmonic Filter

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Abstract

Active harmonic filters (AHFs) are devices that can mitigate harmonic distortion and improve power quality in electrical systems. This paper compares two popular control methods for AHFs: the instantaneous real and imaginary power theory (PQ) and the synchronous reference frame method (DQ). The performance of both methods is evaluated in terms of harmonic compensation, reactive power control, and voltage regulation under different load and source conditions. The simulation results show that the DQ method has better dynamic response and stability than the PQ method, especially under unbalanced and distorted source voltages. The DQ method also requires less computational effort and tuning parameters than the PQ method. The paper concludes that the DQ method is more suitable for AHFs in modern power systems with nonlinear and variable loads.

Introduction

Harmonic distortion is a common problem in modern power systems, caused by the widespread use of nonlinear and time-varying loads, such as power electronic converters, adjustable speed drives, and arc furnaces. Non-linear loads are electrical loads that draw current in a non-sinusoidal manner, meaning that their current waveform does not follow the same shape as the applied voltage waveform. Non-linear loads can cause harmonic distortion, which is the presence of higher frequency components in the voltage and current signals. Harmonic distortion can degrade the power quality and efficiency of the system, as well as damage the equipment and cause interference with communication devices. Therefore, it is essential to mitigate the harmonic distortion and improve the power quality in electrical systems.

One of the effective solutions for harmonic mitigation is the use of active harmonic filters (AHFs), which are power electronic devices that inject compensating currents to cancel out the harmonic currents drawn by the nonlinear loads. AHFs can also provide reactive power compensation and voltage regulation, thus enhancing the system performance and stability. AHFs can be classified into shunt, series, or hybrid types, depending on the connection mode and configuration. Among them, shunt AHFs are the most widely used, as they can compensate for both current and voltage harmonics.

The performance of shunt AHFs depends largely on the control method used to generate the reference compensating currents. Various control methods have been proposed in the literature, such as the instantaneous real and imaginary power theory (PQ), the synchronous reference frame method (DQ), and the conservative power theory (CPT). Each method has its own advantages and disadvantages, depending on the system conditions and requirements. Therefore, it is important to compare and evaluate the different control methods for shunt AHFs, in order to select the most suitable one for a given application.

This paper aims to compare two popular control methods for shunt AHFs: the PQ method and the DQ method. The PQ method is based on the Clarke transformation and calculates the reference currents from the instantaneous values of the load currents and voltages. The DQ method is based on the Park transformation and the phase-locked loop (PLL) and calculates the reference currents from the synchronous components of the load currents and voltages. The comparison criteria include the harmonic compensation, the reactive power control, and the voltage regulation capabilities of each method, under different load and source conditions. The simulation results are obtained using MATLAB/Simulink and show the advantages and disadvantages of each method.

Methodology:

Instantaneous PQ theory:

PQ theory is a method for generating reference currents for active harmonic filters, based on the instantaneous real and imaginary power components of the load currents and voltages. PQ theory was proposed by Akagi et al. and is also known as the instantaneous power theory or the p-q theory. The main steps of PQ theory are:

1. Transform the three-phase load currents and voltages from the a-b-c frame to the alpha-beta frame using the Clarke transformation.

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -{}^{1}/_{2} & -\perp_{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \text{................}(1)$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -{}^{1}/_{2} & -\perp_{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \text{................}(2)$$

Where,

$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$ represent the three-phase voltages at the a-b-c coordinate respectively,

$\begin{bmatrix} \mathrm{i_a} \\ \mathrm{i_b} \\ \mathrm{i_c} \end{bmatrix}$ represent the three-phase currents at the a-b-c coordinate respectively,

$\begin{bmatrix} \mathrm{v_0} \\ \mathrm{v_\alpha} \\ \mathrm{v_\beta} \end{bmatrix}$ refer to the three-phase voltages at the 0-α-β coordinate,

$\begin{bmatrix} \mathrm{i_0} \\ \mathrm{i_\alpha} \\ \mathrm{i_\beta} \end{bmatrix}$ refer to the three-phase currents at the 0-α-β coordinate.

Here, the system is considered as three phase , three wire system, therefore zero sequence component is absent.

2. Calculate the instantaneous real power (p) and the instantaneous imaginary power (q) from the alpha-beta currents and voltages.

In the α-β coordinate, the complex sum of the active and reactive powers (P and Q) can be represented by,

$S = P + jQ = v_{\alpha\beta} i^*_{\alpha\beta}$ ……………(3)

Instantaneous real power is given by,

$P(t) = v_a i_a + v_b i_b + v_o i_o$

$P(t) = v_\alpha i_\alpha + v_\beta i_\beta + v_o i_o$

$P(t) = P_\alpha + P_\beta + P_o$

$P(t) = P_{\alpha\beta} + P_o$ …………………(4)

Instantaneous reactive power is given by,

$Q(t) = v_\alpha i_\alpha - v_\beta i_\beta$ …………………(5)

$$\begin{bmatrix} \mathrm{P_0} \\ \mathrm{P_{\alpha\beta}} \\ \mathrm{Q_{\alpha\beta}} \end{bmatrix} = \begin{bmatrix} v_o & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i^*_0 \\ i^*_\alpha \\ i^*_\beta \end{bmatrix} \text{……….(6)}$$

3. Separate the p and q components into their average and oscillating parts using a low-pass filter.

With the presence of nonlinear loads, the instantaneous active and reactive power components are decomposed of their AC and DC parts as,

$P = \bar{p} + \tilde{p}$

$Q = \bar{q} + \tilde{q}$

The DC component ($\bar{p}$) of the instantaneous real power (P) signifies the fundamental components of voltage and current, and it is associated with the power that is transferred from the source to the load. The AC component ($\tilde{p}$) is related to the energy that is exchanged between the source and the load. The average or DC component of the instantaneous real power, which should be the only power supplied by the three-phase AC source, is derived using a high-order low-pass filter. In terms of the instantaneous reactive power component (Q), $\bar{q}$ and $\tilde{q}$, represent the fundamental and harmonic components respectively, which are responsible for the energy flow between the phases of the load.

To generate the harmonic reference currents, the AC component ($\bar{p}$) of the active power and the total reactive power (Q) are required. To recompose the voltage source inverter switching losses, and to reserve the DC-link voltage at the required level, the shunt active power filter consumes a small amount of real power ($\bar{p}_{loss}$) from the three phase ac source or an external power supply. Therefore, the ac component ($\tilde{p}$) of the active power is measured as,

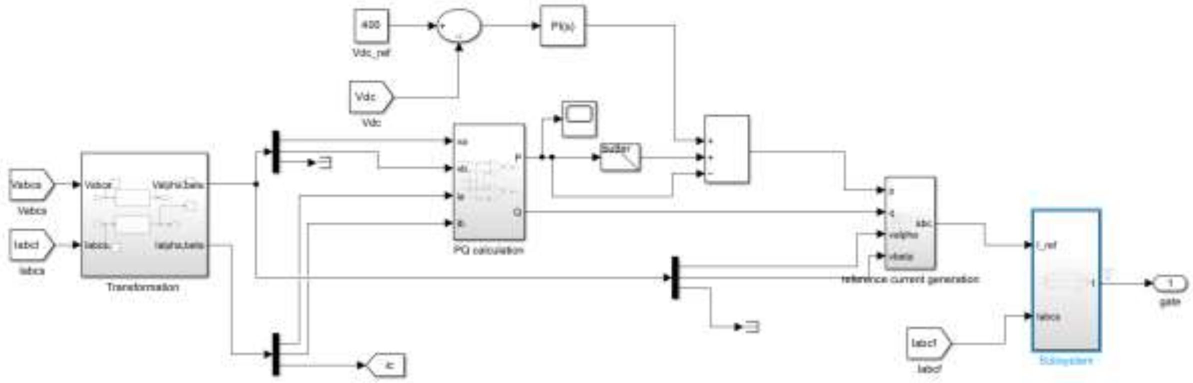
$$\tilde{p} = P - \bar{P} + \bar{p}_{loss} \ldots\ldots\ldots\ldots\ldots\ldots(7)$$

4. Calculate the reference currents for the active harmonic filter

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \frac{1}{\left(v_\alpha^2+v_\beta^2\right)} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p} \\ Q \end{bmatrix} \ldots(8)$$

5. Transform the reference currents from the alpha-beta frame to the a-b-c frame using the inverse Clarke transformation.

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} \ldots\ldots.(9)$$



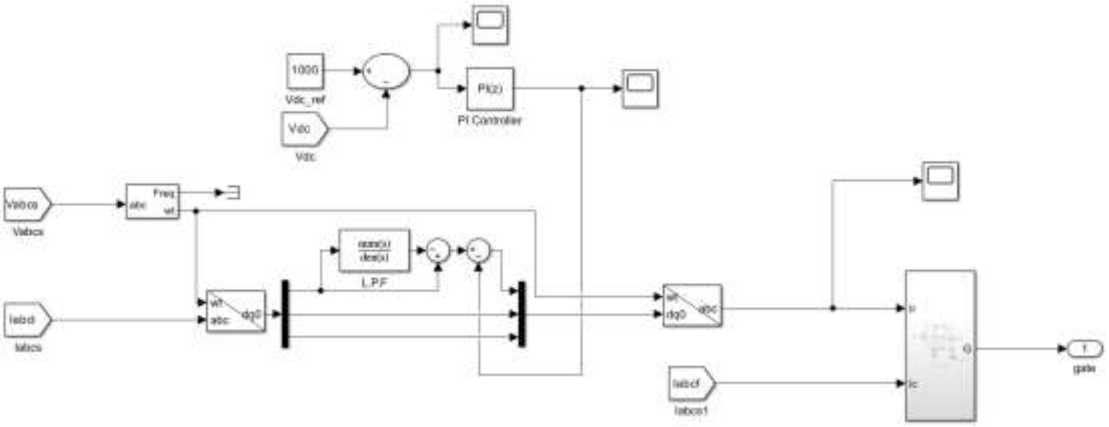
DQ Control technique:

DQ control technique is a method for generating reference currents for active harmonic filters, based on the synchronous reference frame components of the load currents and voltages. DQ control technique was proposed by Bhattacharya and is also known as the synchronous reference frame method or the d-q method.

Transform the three-phase load currents and voltages from the a-b-c frame to the d-q frame using the Park transformation and a phase-locked loop (PLL).

The a-b-c frame equations can be transformed according to α-β theory,

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \text{……..(10)}$$



PI controller in the synchronous reference frame uses integrators to remove the steady state error of the reference signal’s DC components in the d−q coordinates. According to the d−q frame theory, the current harmonics appear as DC components in their respective reference frame, and the integrators cancel out the steady state error of each harmonic component. The PI controller removes the steady state error and produces the desired controlled reference signal. The algorithm then converts the voltage reference signal in the d−q rotating frame back to the a−b−c stationary frame, which is the reference signal for the Pulse Width Modulation.

DQ control technique can compensate for both current and voltage harmonics, as well as reactive power and unbalance. It has some advantages over PQ theory, such as better dynamic response and stability, less computational effort and tuning parameters, and robustness under distorted and unbalanced source voltages. However, DQ control technique also has some limitations, such as sensitivity to errors in the PLL and the Park transformation, difficulty in compensating for zero-sequence harmonics, and requirement of a large DC link capacitor.

Simulation and results:

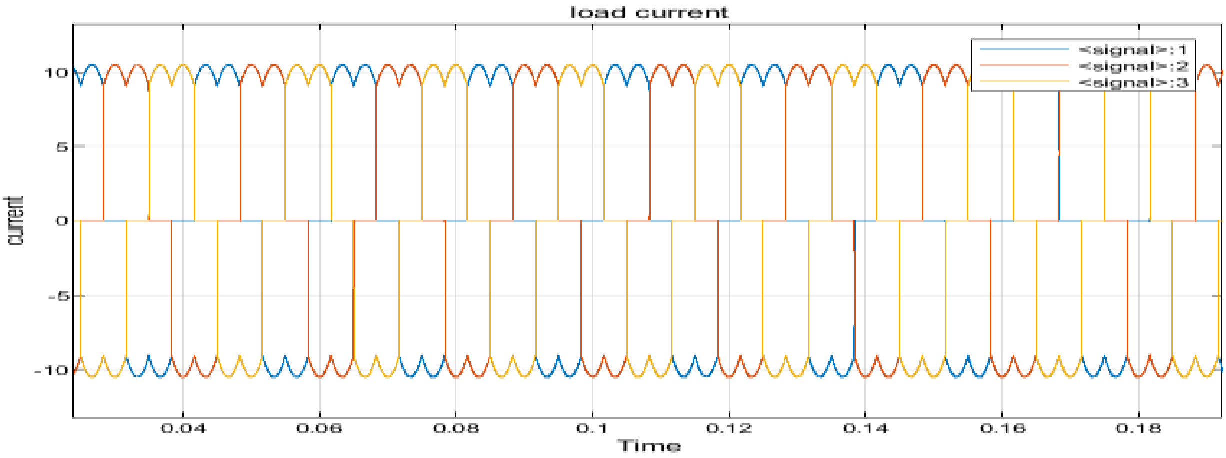


Figure :Load Current

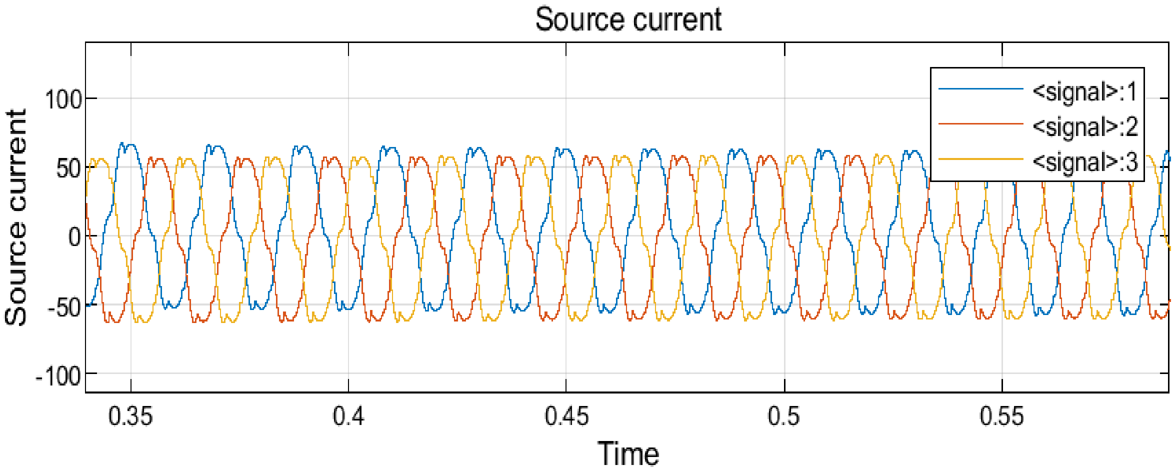


Figure : Source currrent after compensation (using PQ theory)

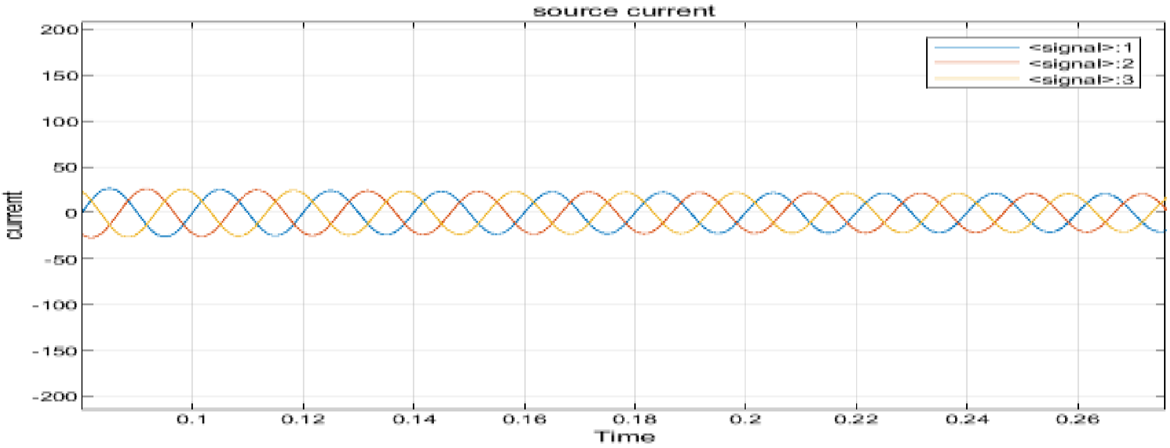


Figure : Source currrent after compensation (using DQ theory)

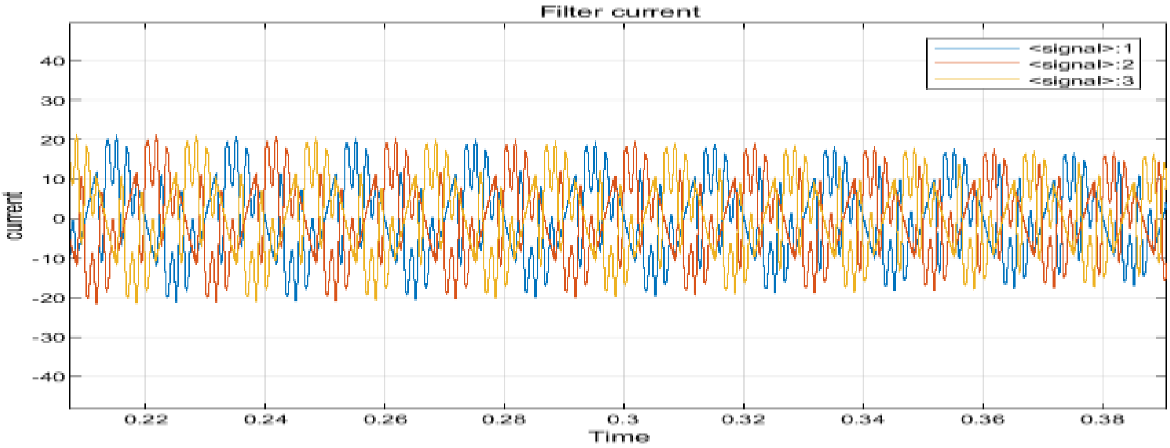


Figure : Compensated current generated by filter

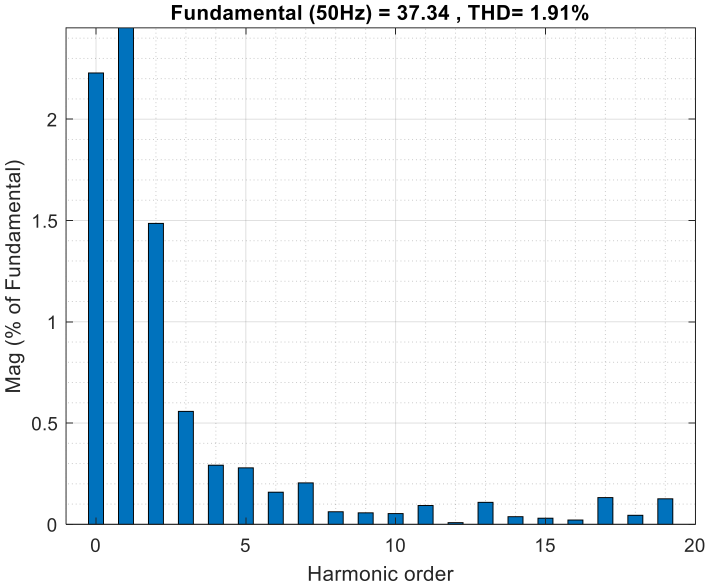
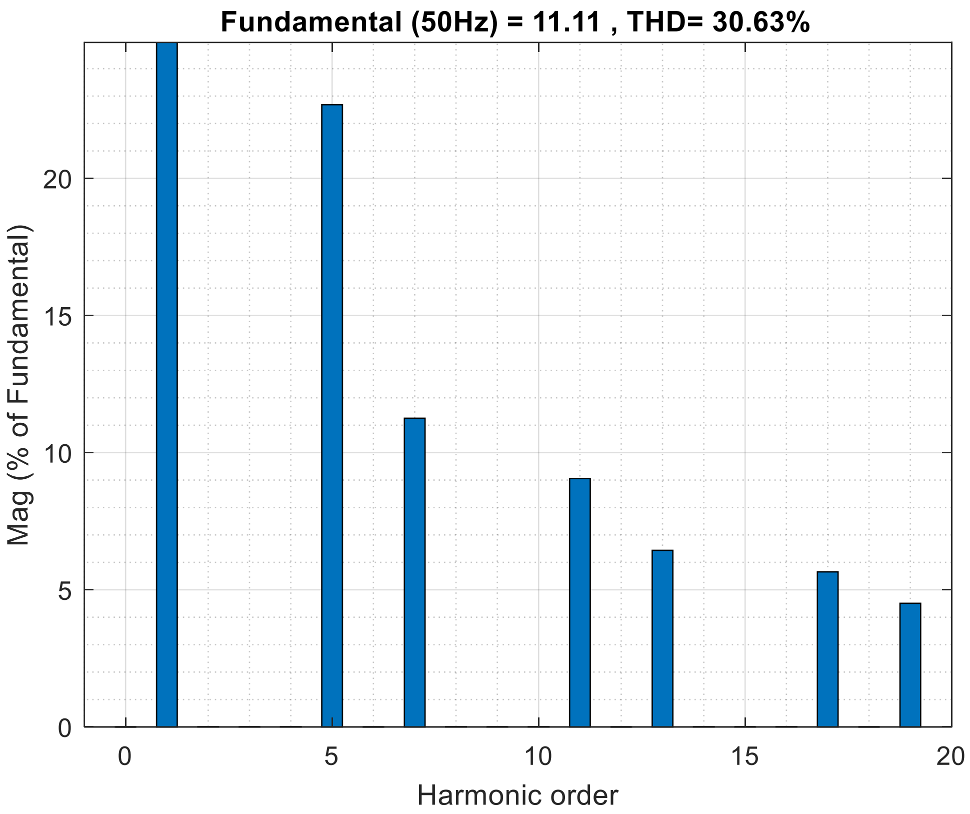


Figure : THD of Source current from DQ method



THD of load Current

Control Scheme	THD
DQ	**1.91%**
PQ	**3.8%**

Table: Comparision of THD values of DQ and PQ

Conclusion:

Both the p-q and d-q control methods are effective strategies for active harmonic filters in power systems, each with its unique advantages and applications.

The p-q method, which is grounded in Clarke transformation, is a fundamental approach for mitigating system harmonics by extracting reference currents. On the other hand, the d-q method employs Park transformation and a phase locked loop (PLL) for reference current extraction, and is typically paired with a Proportional-Integral (PI) controller to optimize the performance of the Shunt Active Filter (SAF).

When it comes to performance, both methods yield identical results under conditions of balanced source voltage. However, the d-q method outperforms the p-q method when dealing with unbalanced source voltage. Therefore, the selection between the p-q and d-q methods should be guided by the specific needs of the system, such as the balance of the source voltage.

Furthermore, the efficacy of these methods can be enhanced by employing techniques like hysteresis and Pulse Width Modulation (PWM) across various non-linear loads. These techniques contribute to improvements in Total Harmonic Distortion (THD), power quality, and reduction in switching losses.

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