

Comparative Analysis of FBD and dq Current Detection Methods

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Abstract

Current detection is the key to improve the power quality by using the active power filter. From two aspects which are algorithm of principle complexity and compensation for current harmonic content, this paper investigates to analyze and compare two novel harmonic current detection methods called FBD method and dq method. The results show that harmonic current can be well compensated by applications of the shunt active power filter with two methods. But FBD method has better prospects of a practical application for simpler algorithm, better real-time, and lower harmonic content after compensation.

Keywords: APF; FBD; dq; harmonic compensation

1. Introduction

For the detection method of APF harmonic current, theories proposed by scholars at home and abroad are mostly based on the instantaneous reactive power theory [2-4]. Reference [2] presented the pq method with the good compensation flexibility. This method has been less used because it only applies to the harmonic and reactive current detection under the condition that three-phase grid voltage was symmetrical and no distortion. Reference [3] introduced the ip-iq method which is developed on the basis of the theory of pq theory. It needs to decompose the current of the single-phase circuit and then constructs the three-phase current. Finally, the instruction current can be detected by the ip-iq method in three-phase circuit. Thereby the algorithm is too complex. Reference [4] described the dq method widely used which is not affected by the voltage and can be applied to the case of the asymmetric load current.

For three-phase three-wire power system, this paper studies the dq method and FBD method[5] which are relatively new in harmonic current detection. The theoretical principles of two methods are discussed. Furthermore, two algorithms are used to model and simulate in PSCAD/EMTDC for shunt APF in three-phase three-wire system. The compensation performances are compared under the three uncontrollable full-bridge rectifiers with RL and RC loads.

2. The dq Theory

The dq theory is simplified from the theory of the d-q-0 synchronized rotating coordinate transform, In essence, it uses Park transform to turn the three-phase current from the a-b-c coordinate system to the d-q-0 coordinate system. Thus it can separate the fundamental current component or the positive sequence component of any harmonic current [6]. The load current includes harmonic components of positive sequence, negative sequence and zero sequence. After performing Park transform on the above three components, zero sequence component turns to zero. The zero sequence component does

not participate in Park transform process. Park transform performed on the three-phase load current as:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = C_{dq} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} i_{1n} \sin[(n-1)\omega t + \varphi_{1n}] \\ -i_{1n} \cos[(n-1)\omega t + \varphi_{1n}] \end{bmatrix} + \begin{bmatrix} i_{2n} \sin[(n+1)\omega t + \varphi_{2n}] \\ -i_{2n} \cos[(n+1)\omega t + \varphi_{2n}] \end{bmatrix} \quad (1)$$

Where park transformation matrix is:

$$C_{dq} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos \omega t & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \\ -\sin \omega t & -\sin(\omega t - \frac{2\pi}{3}) & -\sin(\omega t + \frac{2\pi}{3}) \end{bmatrix} \quad (2)$$

The currents of d and q axis can be decomposed into DC and AC components by the transformation as:

$$i_{dq} = \begin{bmatrix} i_d \\ i_q \end{bmatrix} = C_{dq} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \bar{i}_d + \tilde{i}_d \\ \bar{i}_q + \tilde{i}_q \end{bmatrix} \quad (3)$$

With the symmetrical voltage system, the dq method is shown in Figure 1. Input currents of three-phase loads are i_a , i_b and i_c , which are transformed into d axis component i_d and q axis component i_q with dq transform, including DC components (\bar{i}_d and \bar{i}_q) and AC components (\tilde{i}_d and \tilde{i}_q). By the low pass filter (LPF), the DC components (\bar{i}_d and \bar{i}_q) can be obtained. After dq inverse transform, fundamental components of detection current (i_{af} , i_{bf} and i_{cf}) can also be got. The difference of load current and fundamental current component is the required harmonic detection current [7].

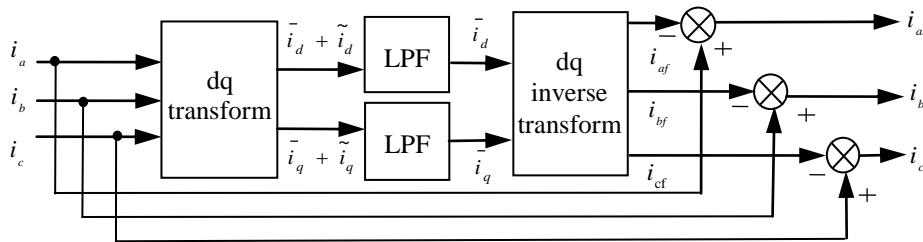


Figure 1. Schematic Diagram of dq Detection Method

3. The FBD Theory

FBD is a kind of the harmonic detection method in the time domain and based on FBD instantaneous reactive power theory. It is first proposed by Fryze and further improved by Buchholz [8]. The basic idea of FBD method is that the actual load is equivalent to ideal conductance component in a circuit. Power in the circuit is consumed on the equivalent conductance. The energy is transmitted from the source system to the load system without other energy loss. The equivalent conductance decomposes the system current into the active power component and reactive power component. According to these components harmonic current is calculated [9].

The three-phase reference voltages are:

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = \begin{bmatrix} U \sin \omega t \\ U \sin(\omega t - 120^\circ) \\ U \sin(\omega t + 120^\circ) \end{bmatrix} \quad (4)$$

The currents of three-phase three-wire system contains the positive sequence component and negative sequence component which are expressed in the subscript 1 and 2, respectively. The currents of a, b and c are shown as:

$$\begin{cases} i_a = \sum_{n=1}^{\infty} [I_{1n} \sin(n \omega t + \phi_{1n}) + I_{2n} \sin(n \omega t + \phi_{2n})] \\ i_b = \sum_{n=1}^{\infty} [I_{1n} \sin(n \omega t + \phi_{1n} - 120^\circ) + I_{2n} \sin(n \omega t + \phi_{2n} + 120^\circ)] \\ i_c = \sum_{n=1}^{\infty} [I_{1n} \sin(n \omega t + \phi_{1n} + 120^\circ) + I_{2n} \sin(n \omega t + \phi_{2n} - 120^\circ)] \end{cases} \quad (5)$$

Three-phase instantaneous active conductance is shown as:

$$G_p(t) = \frac{e_a i_a + e_b i_b + e_c i_c}{e_a^2 + e_b^2 + e_c^2} = \sum_{n=1}^{\infty} \{I_{1n} \cos[(n-1)\omega t + \phi_{1n}] - I_{2n} \cos[(n+1)\omega t + \phi_{2n}]\} \quad (6)$$

After LPF, the active conductance becomes:

$$G_p = \overline{G_p(t)} = I_{11} \cos \phi_{11} \quad (7)$$

Where ϕ_{11} is the angle between a-phase voltage and the fundamental positive sequence current, I_{11} is the amplitude of fundamental positive sequence current. Three-phase active current components of fundamental positive sequence currents are obtained by multiplying the output of LPF with the reference voltage in the same phase. They are written as:

$$\begin{cases} i_{a1,p} = I_{11} \cos \phi_{11} \sin \omega t \\ i_{b1,p} = I_{11} \cos \phi_{11} \sin(\omega t - 120^\circ) \\ i_{c1,p} = I_{11} \cos \phi_{11} \sin(\omega t + 120^\circ) \end{cases} \quad (8)$$

In a similar way, three-phase instantaneous reactive conductance components ($i_{a1,q}$, $i_{b1,q}$ and $i_{c1,q}$) are achieved. Because of the balanced load, three-phase fundamental positive sequence current components can be got by combining its active component with its reactive component. Hence the fundamental positive sequence currents are the fundamental currents. The fundamental positive sequence currents are shown as:

$$\begin{cases} i_{a1} = i_{a1,p} + i_{a1,q} = I_{11} \sin(\omega t + \phi_{11}) \\ i_{b1} = i_{b1,p} + i_{b1,q} = I_{11} \sin(\omega t + \phi_{11} - 120^\circ) \\ i_{c1} = i_{c1,p} + i_{c1,q} = I_{11} \sin(\omega t + \phi_{11} + 120^\circ) \end{cases} \quad (9)$$

The principle of FBD detection method is illustrated in Figure 2.

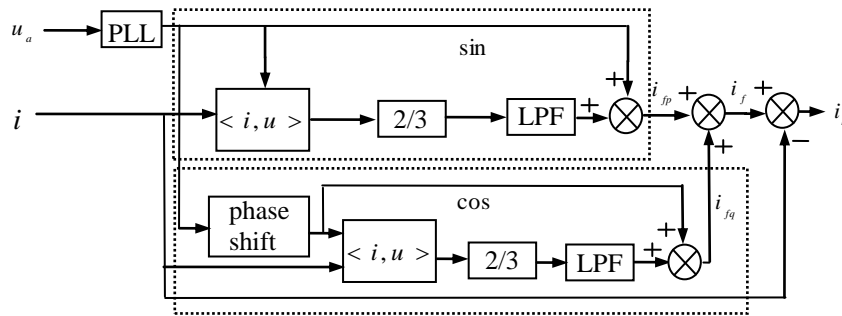


Figure 2. Block Diagram of FBD Detection Method

In Figure 2, the upper box and lower box are used to detect the active and reactive components of the fundamental positive sequence current, respectively. According to the equivalent conductance decomposition characteristic of the current, the compensation current can be calculated. The reference voltage which has the same phase with three-phase grid voltages can be got by the phase-locked loop (PLL), and then it is shifted 90° to get two reference voltages. The two voltages are multiplied by the load current, and divided by the sum of squared voltages which are simplified into a fixed value $3/2$. DC conductivity (G_p and G_q) of the two components can be received after LPF, respectively. Afterwards, they are multiplied by two voltages. Thus, the active and reactive components of the fundamental positive sequence current are further gained, and combined into the fundamental positive sequence current of the load. Because of the symmetric system, there is no negative and zero sequence current. The harmonic currents are determined by subtracting the fundamental positive currents from the load current [10, 11].

4. Comparative Analysis of Two Theories

The algorithm structure and the numbers of devices with two methods are shown in Table 1.

Table 1. Comparison of Algorithm Structure and Number of Devices

Content	dq	FBD
Matrix transform	Park transform and its inverse transform	no
Multiplier	12	7
Adder	10	9
Low-pass filter	3	2

As can be seen from Table 1, FBD method has smaller amount of calculation than that of dq and has no matrix transform. Meanwhile, the required amounts of multipliers and adders are less than that of dq so that it is relatively easy for hardware implementation. Therefore, in consideration of cost requirements, FBD method is more suitable. LPF will bring a certain delay to the detection circuit. dq method requires three LPFs, while FBD theory only needs two. In addition, taking into account that FBD method has no matrix transform, it is better than that of dq method in the real-time performance. FBD method applies not only to the three-phase three-wire system, but also to the three-phase four-wire system. For measuring the single-phase distortion current, FBD theory can also achieve a good result [12].

5. Construction of Simulation Model

The three-phase full-bridge inverter circuit is used as the main circuit of the active power filter. For, the three-phase uncontrollable full-bridge rectifier with RL and RC are selected as the loads of the three-phase three-wire system, respectively. PWM signals are generated by the triangular wave comparison control to drive IGBTs of the main circuit. The FBD theory and dq theory are used as harmonic current detection method, respectively. PSCAD / EMTDC software is adopted to simulate. The basic parameters of the simulation system are shown in Table 2.

Table 2. APF Simulation Parameters

Variable / Unit	Parameter
Grid voltage /V	380
Switching frequency /kHz	6
AC side inductance /mH	2
Load resistance (inductive load)/Ω	2
Load inductance (inductive load)/mH	2
Load resistance (RC load)/Ω	2
Load capacitance (RC load)/ μF	0.2
DC side capacitance /μF	3300

Figure 3 shows the simulation models of dq method and FBD method which are built upon the above principles.

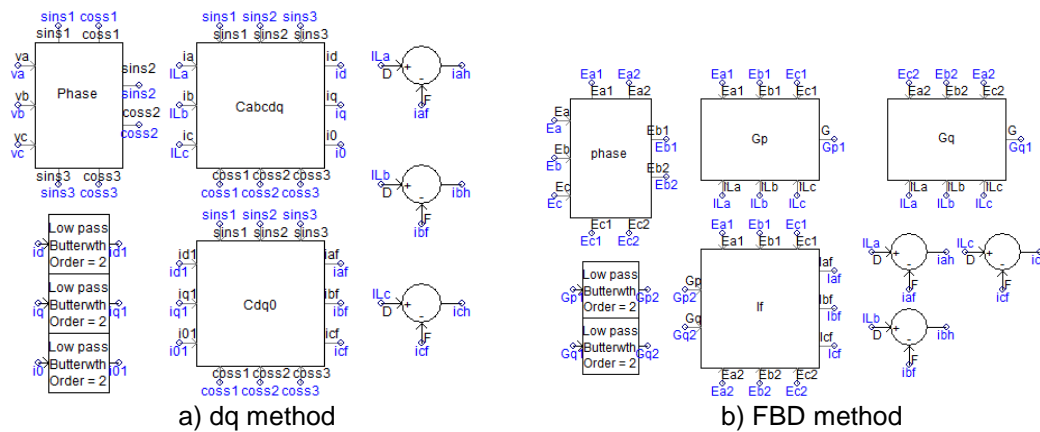


Figure 3. Simulation Models of Two Detection Methods

In the absence of dq harmonic current detection module in the software, simulation modules of abc-dq and dq-abc coordinate transformation subsystems are constructed in Figure 3 a) model. And they form the harmonic current detection model of the dq method with the voltage acquisition module and LPF together.

Similarly, voltage acquisition module, three-phase instantaneous active conductance (G_p) module, three-phase instantaneous reactive conductance (G_q) module and two LPF modules are put up to form the FBD harmonic current detection model, shown in Figure 3 b).

6. Analysis of Simulation Results

The simulation time is set to 1s. The simulation is shown with example of a-phase. Figure 4 and Figure 5 show of grid-side current waveforms of two methods with the RL load and RC load.

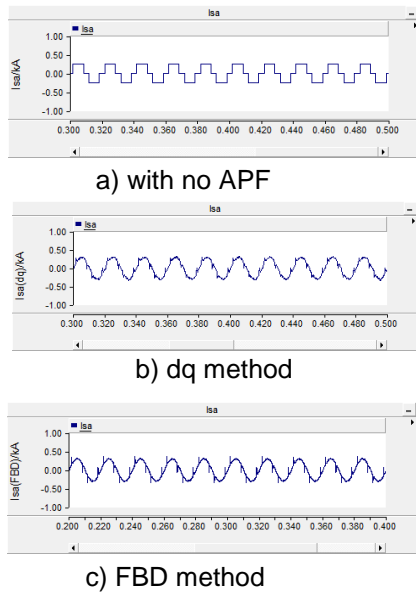


Figure 4. Grid-side Current Waveforms

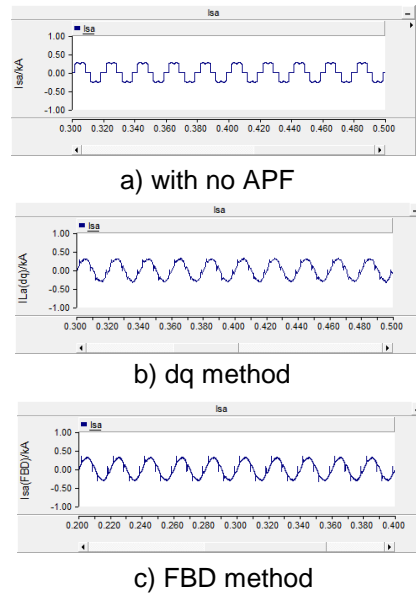
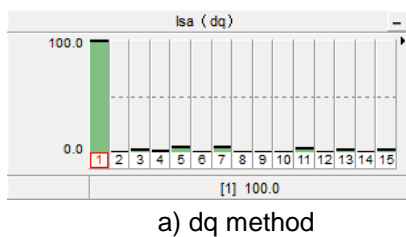


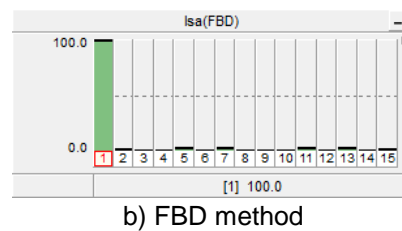
Figure 5. Grid-side Current Waveforms

From the simulation waveforms, it is seen that two kinds of non-linear loads causes serious the current distortion to the system. Two detection methods can be used to measure the harmonic current well, and they compensate the harmonic caused by the loads effectively. In comparison, the dq method has more waveform glitches than those of FBD.

Total harmonic distortion (THD) is a fundamental index of evaluating the performance of APF. To further analyze the effect of compensation, THDs of a-phase grid-side current with RL load and RC load by two methods in APF are illustrated in Figure 6 and 7.

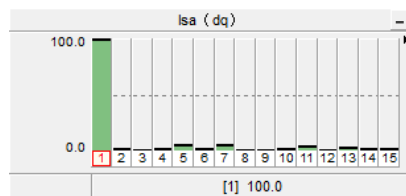


a) dq method

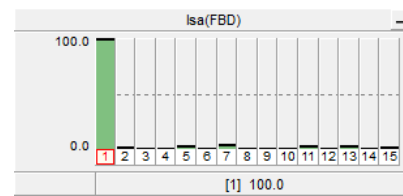


b) FBD method

Figure 6. THDs of the Grid-side Current by Two Methods with RL Load



a) dq method



b) FBD method

Figure 7. THDs of the Grid-side Current by Two Methods with RC Load

Figure 6 and Figure 7 indicate that no matter which kind of loads is on, the harmonic content of the grid-side current is small after APF. And it states that APF based on these two methods can effectively compensate for harmonic which is generated by the load of the three uncontrollable full-bridge rectifiers with RL or RC load. The total harmonic distortion of grid-side current before and after compensation, the harmonic component of

fundamental wave after compensation and the main higher harmonic content after compensation are shown in Table 3.

Table 3. Harmonic Contents by Two Methods

THD /%		RL load		RC load	
		dq	FBD	dq	FBD
Before	Grid-side current	25.62	25.62	33.45	33.45
After	Grid-side current	1.925	1.205	1.752	1.224
	Fundamental current	0.016	0.013	0.014	0.012
	5th harmonic	0.535	0.387	0.512	0.410
	7th harmonic	0.602	0.327	0.735	0.356
	11th harmonic	0.314	0.206	0.342	0.258
	13th harmonic	0.241	0.128	0.379	0.112

From Table 3, for the RL or RC load, the harmonic current content of grid-side current is significantly reduced to below 5% of the state standard by using two methods. In contrast of THD values after APF compensation with other condition unchanged, the results indicate that in the aspects which are the harmonic components of fundamental current, the THD value of network side current and high harmonic content, filtering effect of APF by FBD method is significantly better than that of dq method.

7. Conclusions

Starting from the real-time performance of the system and compensation accuracy, the two current detection methods are analyzed and compared in APF of three-phase three-wire balanced system in this paper.

According to the above theoretical analysis, FBD method has no Park matrix transform and its inverse transform of dq algorithm can significantly improve computing speed. Thus, the cost of processors can be saved. Compared with dq method, the amount of devices used by FBD method is reduced, which can also optimize the real-time performance of the system. Simulation results indicate that the accuracy detecting the harmonic current is basically consistent with both detection methods. After compensating, THDs of the grid-side current and main harmonic contents by FBD is less than that of dq method.

Acknowledgements

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