Letters

A Fast Positive-Sequence Component Extraction Method With Multiple Disturbances in Unbalanced Conditions

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***Abstract*—Fast and accurate acquisition of current components is a key factor for an active power filter to realize transient control under unbalanced conditions. In this letter, a robust real-time algorithm, which rapidly separates the positive-sequence component (PSC) from multiple decaying dc (DDC) components, dc bias component, negative-sequence component, and harmonics, is proposed. To this end, first, the multiple DDC components are detected in the multiple disturbance and unbalanced grid context, by making use of the periodicity of remaining components. The dc bias can be obtained accordingly, followed by the detection of a compound signal encompassing the positive-sequence component, negative-sequence component, and harmonics. Specifically, the compound signal can be extracted precisely, based on the detected DDC and dc bias components, with one grid cycle response time, or approximately, within half grid cycle. A switching logic of the two approaches is designed to shorten the overall convergence time and improve steady-state accuracy. The PSC is then effectively extracted by constructing the virtual orthogonal signal of the compound signal and using *dq*-frame filtering. Compared with the existing transient control techniques, the proposed scheme guarantees one grid cycle response time and simultaneously suppresses multiple disturbances. Finally, experimental results verify the effectiveness of the proposed method.**

***Index Terms*—DC bias, decaying dc (DDC), positive-sequence component (PSC), transient impact current, unbalanced condition.**

I. Introduction

DUE to the presence of power electronic devices, unbalanced loads, and impact loads in three-phase distributed systems, a large faulty current, including negative sequence and exponential decay components, can flow into the grid [1]. Specifically, the decaying dc (DDC) component associated with the switching action can be dominant over the unbalanced components and harmonics, leading to a transient current amplitude as large as twice that during the steady state [2]. The compound impact current severely jeopardizes the safe and stable operation of power grids and electrical equipment, causing the undesired relay protection and economic loss.

To suppress the transient current involving the DDC components, the traditional solution resorts to the addition of passive components. For instance, the solution by increasing line impedance was used to cope with DDC components; however, this occupies a large area, has a high cost, and will affect the parameters of the circuit. Conversely, an active solution can serve as an efficient alternative, as long as the fast responding converter, e.g., the active power filter (APF), is controlled to generate the suitable compensation current that counteracts the undesired current components.

Under the active solution framework, an effective compensation requires the information of positive-sequence component (PSC) from the transient signal; the remaining component can then be served as the converter reference for compensation. The detection of DDC component is a prerequisite to this target. Prior to this letter, several methods, e.g., [3]–[6], were proposed in the literature for this purpose. For instance, a numerical approximation method, with a long dynamic response time of 2.25 power grid cycles, was proposed in [3] to accurately estimate the DDC component. To reduce the extraction time, an adaptive algorithm was proposed in [4], but at the expense of computational efficiency. In [5], a volterra model combined with an LMS/fourth-filter was used to extract DDC components in a three-phase system. However, the algorithm needs to compromise between accuracy and response time. For better generality, a DFT-based algorithm was proposed in [6] to extract the dc offset and multiple DDC components. These methods, though effective in the relay protection scenarios, cannot be directly applied to converter applications, due to the detection time, accuracy, or computing resource constraint of the embedded controller.

In the past few years, several efforts [2], [7], [8] have been made to address these issues, mainly by considering the analytical expression of multiple components in the transient signal. The method in [7] was able to separate the DDC component from the harmonic environment within one grid cycle. Under the same condition, Xiong *et al.* [8] improved the dynamic response time to half grid cycle, by exploiting the half-wave symmetry of grid signal. Xiong *et al.* [2] extended these analytical models, and was able to effectively extract the amplitude/phase information

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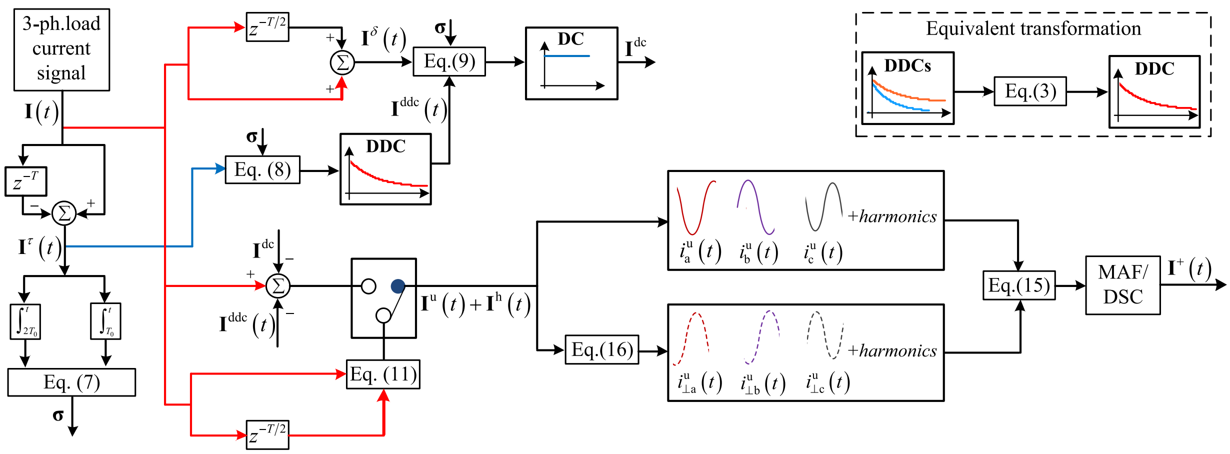

Fig. 1. Principle of the proposed PSC extraction method.

from a transient signal encompassing the DDC component and three-phase asymmetry. However, these methods make use of the half-wave symmetry of the grid signal, and are therefore not applicable to the more general scenario studied in this letter, where the dc bias component is present along with harmonics and grid asymmetries. As a matter of fact, the issue of dc bias component is occasionally encountered in practice, including the case of the grid faults [9]. Since the DDC components are usually associated with faults, it is sensible to also consider the presence of dc bias component during the transient.

After the separation of the DDC component, the PSC still needs to be extracted from the remaining signal. There are several works available in the literature for this purpose. For instance, in [10], the PSC in the unbalanced component was effectively extracted based on the moving average filter (MAF). The method is simple to calculate and can be applied to converter control. Similarly, in [11], a delayed signal cancellation (DSC) algorithm was proposed to extract the PSC within 0.25 power grid cycle. These methods alone cannot handle the DDC and dc bias components, and must be efficiently combined with the proposed method for DDC and dc components removal.

Hence, to effectively suppress the impact current by use of active compensation, this letter proposes a method of PSC component detection from the transient current signal encompassing multiple DDC components, dc bias component, negative-sequence component, and harmonics. The proposed method is characterized by rapid response and easy implementation. Compared with the similar active suppression method in [7], which used the transient power quality control (TPQC) mode for DDC component elimination, the proposed algorithm cannot only guarantee the smooth response, but also cope with multiple disturbances possibly present during the transient.

II. Proposed Detection Scheme

The overall diagram of the proposed PSC extraction scheme is shown in Fig. 1. The transient current, encompassing the DDC component starting at $t = 0$, as well as the dc bias component, negative-sequence component, and harmonics, is defined as

$$\mathbf{I}(t) = \mathbf{I}^{\mathrm{dc}} + \mathbf{I}^{+}(t) + \mathbf{I}^{-}(t) + \mathbf{I}^{\mathrm{h}}(t) + \mathbf{I}^{\mathrm{ddc}}(t) \qquad (1)$$

with $\mathbf{I}(t) = [i_a(t)\ i_b(t)\ i_c(t)]^{\mathrm{T}}$, $\mathbf{I}^{\mathrm{dc}} = [I_a\ I_b\ I_c]^{\mathrm{T}}$

$$\mathbf{I}^{+} = I_{\mathrm{m}}^{+}\begin{bmatrix}\sin\left(\omega t + \theta^{+}\right)\\ \sin\left(\omega t + \theta^{+} - \frac{2\pi}{3}\right)\\ \sin\left(\omega t + \theta^{+} + \frac{2\pi}{3}\right)\end{bmatrix},$$

$$\mathbf{I}^{-} = I_{\mathrm{m}}^{-}\begin{bmatrix}\sin\left(\omega t + \theta^{-}\right)\\ \sin\left(\omega t + \theta^{-} + \frac{2\pi}{3}\right)\\ \sin\left(\omega t + \theta^{-} - \frac{2\pi}{3}\right)\end{bmatrix}$$

$$\mathbf{I}_{\mathrm{h}}(t) = \sum_{k=3,5,7,\ldots}\mathbf{I}_k(t) = \sum_{k=3,5,7,\ldots} I_k\begin{bmatrix}\sin\left(k\omega t + \varphi_k\right)\\ \sin\left(k\omega t + \varphi_k - \frac{2\pi}{3}\right)\\ \sin\left(k\omega t + \varphi_k + \frac{2\pi}{3}\right)\end{bmatrix}$$

$$\mathbf{I}^{\mathrm{ddc}}(t) = \left[\sum_{k=1}^{n} I_{ak}^{\mathrm{ddc}} e^{-\sigma_{ak}t}\ \sum_{k=1}^{n} I_{bk}^{\mathrm{ddc}} e^{-\sigma_{bk}t}\ \sum_{k=1}^{n} I_{ck}^{\mathrm{ddc}} e^{-\sigma_{ck}t}\right]^{\mathrm{T}}$$

where I_s $(s = a, b, c)$ is the dc bias component, I_{m}^{+} and θ^{+} (I_{m}^{-} and θ^{-}) are the amplitude and initial phase of the positive- (negative-) sequence component, respectively, ω is the grid angular frequency, I_k and φ_k are the amplitude and initial phase of kth harmonic current, respectively, I_{sk}^{ddc} and σ_{sk} are the amplitude and decay coefficient of the kth DDC component, and n is the total number of terms of DDC components.

The unbalanced current $\mathbf{I}^{\mathrm{u}}(t)$ is defined as

$$\mathbf{I}^{\mathrm{u}}(t) = \mathbf{I}^{+}(t) + \mathbf{I}^{-}(t) = \left[i_a^{\mathrm{u}}(t)\ i_b^{\mathrm{u}}(t)\ i_c^{\mathrm{u}}(t)\right]^{\mathrm{T}}. \qquad (2)$$

The presence of multiple DDC components in (1) can be caused by the nonlinear characteristics of ferromagnetic elements. These components can be combined into one DDC component, yielding [2]

$$\sum_{k=1}^{n} I_{sk}^{\mathrm{ddc}} e^{-\sigma_{sk}t} = I_s^{\mathrm{ddc}} e^{-\sigma_s t} \qquad (3)$$

where I_s^{ddc} and σ_s represent the amplitude and decay coefficient of the compound DDC component, respectively. The detailed derivation process via mathematical induction, along with the relationship between the compound parameters and the individual ones, can be found in [2].

Based on the principle of active compensation, once the equivalent DDC component is known, it is unnecessary to extract parameters of each DDC component, hence reducing the algorithm complexity and transient response time. This equivalent DDC component is extracted first by considering the periodicity of the remaining signal. This gives (with T being the grid period)

$$\mathbf{I}^{\tau}(t) = \mathbf{I}(t) - \mathbf{I}(t-T) = (\mathbf{X} - e^{\boldsymbol{\sigma}T})\mathbf{I}^{\mathrm{ddc}}(t) \tag{4}$$

where $\mathbf{X} = \begin{bmatrix} 1 & & \\ & 1 & \\ & & 1 \end{bmatrix}$ and $\boldsymbol{\sigma} = \begin{bmatrix} \sigma_a & & \\ & \sigma_b & \\ & & \sigma_c \end{bmatrix}$.

The decay coefficient in (4) can be algebraically calculated. Taking phase a as an example, we have

$$A_1 = \int_{t-T_0}^{t} I_a^{\tau}(t)\mathrm{d}t = \frac{I_a}{\sigma_a}(1 - e^{\sigma_a T})\left(e^{\sigma_a T_0} - 1\right)e^{-\sigma_a t} \tag{5}$$

$$A_2 = \int_{t-2T_0}^{t} I_a^{\tau}(t)\mathrm{d}t = \frac{I_a}{\sigma_a}(1 - e^{\sigma_a T})\left(e^{2\sigma_a T_0} - 1\right)e^{-\sigma_a t} \tag{6}$$

$$\sigma_a = \frac{1}{T_0}\ln(A_2/A_1 - 1) \tag{7}$$

where T_0 is a short time period properly selected to compromise between random noise and detection speed. The larger this value, the better the suppression of high-frequency noise, but the longer the calculation time.

Afterward, the DDC component can be obtained by (4) as

$$i_a^{\mathrm{ddc}}(t) = \frac{I_a^{\tau}(t)}{1 - e^{\sigma_a T}}. \tag{8}$$

Then, the DSC method is used to solve for the dc bias component. This gives

$$\mathbf{I}^{\delta}(t) = \mathbf{I}(t) + \mathbf{I}\left(t - \frac{T}{2}\right) = 2\mathbf{I}^{\mathrm{dc}} + \left(\mathbf{X} + e^{\boldsymbol{\sigma}T/2}\right)\mathbf{I}^{\mathrm{ddc}}(t). \tag{9}$$

By combining (1), (2), and (9), the sum of unbalanced current and harmonics can be written as

$$\mathbf{I}^{\mathrm{u}}(t) + \mathbf{I}^{\mathrm{h}}(t) = \mathbf{I}(t) - \frac{\mathbf{I}^{\delta}(t) - \left(e^{\boldsymbol{\sigma}T/2} - \mathbf{X}\right)\mathbf{I}^{\mathrm{ddc}}(t)}{2}. \tag{10}$$

The transient current incorporating DDC component is severe when the decay coefficients are small (i.e., the damping effect is weak). This is the specific case to be addressed in this letter. In this case, (10) can be simplified as

$$\mathbf{I}^{\mathrm{u}}(t) + \mathbf{I}^{\mathrm{h}}(t) \approx \frac{\mathbf{I}(t) - \mathbf{I}(t - T/2)}{2}. \tag{11}$$

The method in (10), resorting to (4) for accurate DDC component calculation, has a dynamic response time of one grid cycle. Conversely, though the provided result is less accurate, the simplified expression in (11) requires merely half grid cycle. This greatly reduces the overall convergence time, if a quick detection is needed.

To limit the overall response time and guarantee the detection performance, a two-step control is used in this letter.

1) *In the First Stage (After the Disturbance to One Grid Cycle):* The simplified expression (11) is adopted for rough detection and elimination of the DDC component. Under the framework of active compensation, this helps the shunt APF to approximately compensate for the surge current at the early stage, which is critical during the transient.
2) *In the Second Stage (After One Grid Cycle):* The complete detection algorithm in (10) is used along with the following procedure. This ensures a better steady-state performance.

After the extraction of the compound current including the unbalanced current and harmonics, the PSC can be obtained by *abc*/*dq* transformation and using the corresponding filter [10]. However, this extraction method requires a response time of at least 0.15 grid cycles. To reduce the overall response time, this letter resorts to the symmetrical component method to solve for the PSC, eliminating the need for the design of the corresponding filter. To this end, the virtual current phasors are constructed, yielding

$$\dot{\mathbf{I}}_{\mathrm{v}}^{+}(t) = \dot{\mathbf{T}}\dot{\mathbf{I}}_{\mathrm{v}}(t) \tag{12}$$

where $\dot{\mathbf{I}}_{\mathrm{v}}(t)$ and $\dot{\mathbf{I}}_{\mathrm{v}}^{+}(t)$ are the phasors of the virtual compound current and its positive-sequence decomposition, respectively, and $\dot{\mathbf{T}}$ is the positive-sequence transformation matrix, given by

$$\dot{\mathbf{T}} = \frac{1}{3}\begin{bmatrix} 1 & e^{\mathrm{j}2\pi/3} & e^{\mathrm{j}4\pi/3} \\ e^{\mathrm{j}4\pi/3} & 1 & e^{\mathrm{j}2\pi/3} \\ e^{\mathrm{j}2\pi/3} & e^{\mathrm{j}4\pi/3} & 1 \end{bmatrix}.$$

Similar to the design of orthogonal signals in the phase-locked loop, a vector of virtual orthogonal currents $\mathbf{I}_{\perp}^{\mathrm{u}}(t)$ is constructed from the compound current $\mathbf{I}^{\mathrm{u}}(t)$ solved by (10) or (11). The constructed virtual current phasors $\dot{\mathbf{I}}_{\mathrm{v}}(t)$ and $\dot{\mathbf{I}}_{\mathrm{v}}^{+}(t)$ can be expressed as

$$\dot{\mathbf{I}}_{\mathrm{v}}(t) = \left[\mathbf{I}^{\mathrm{u}}(t) + \mathbf{I}^{\mathrm{h}}(t)\right] + j\left[\mathbf{I}_{\perp}^{\mathrm{u}}(t) + \mathbf{I}_{\perp}^{\mathrm{h}}(t)\right] \tag{13}$$

$$\dot{\mathbf{I}}_{\mathrm{v}}^{+}(t) = \left[\mathbf{I}^{+}(t) + \mathbf{I}^{\mathrm{h}}(t)\right] + j\left[\mathbf{I}_{\perp}^{+}(t) + \mathbf{I}_{\perp}^{\mathrm{h}}(t)\right] \tag{14}$$

where $\mathbf{I}_{\perp}^{+}(t)$ is the orthogonal current vector of the PSC.

By combining (12)–(14) and considering the correspondence of the equation two sides, the sum current of the PSC and harmonics can be obtained, namely

$$\mathbf{I}^{+}(t) + \mathbf{I}^{\mathrm{h}}(t) = \mathbf{A}_{\alpha}\left[\mathbf{I}^{\mathrm{u}}(t) + \mathbf{I}^{\mathrm{h}}(t)\right] + \mathbf{A}_{\beta}\left[\mathbf{I}_{\perp}^{\mathrm{u}}(t) + \mathbf{I}_{\perp}^{\mathrm{h}}(t)\right] \tag{15}$$

where

$$\mathbf{A}_{\alpha} = \frac{1}{6}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \mathbf{A}_{\beta} = \frac{\sqrt{3}}{6}\begin{bmatrix} 0 & 1 & -1 \\ -1 & 0 & 1 \\ 1 & -1 & 0 \end{bmatrix}.$$

The coefficient matrices $\mathbf{A}_{\alpha}$ and $\mathbf{A}_{\beta}$ are fixed, hence the key to solving the compound current in (15) is to solve $[\mathbf{I}^{\mathrm{u}}(t) + \mathbf{I}^{\mathrm{h}}(t)]$ through (10) or (11), and construct the orthogonal current $[\mathbf{I}_{\perp}^{\mathrm{u}}(t) + \mathbf{I}_{\perp}^{\mathrm{h}}(t)]$. The traditional scheme adopts the delay method or the differential method to construct the orthogonal signals. However, the delay method takes too long and affects the transient response capability of the system; the differential method cannot be directly applied to the measurement of unbalanced current. In this letter, an improved orthogonal signal construction scheme in [12] is adopted. Taking the phase a as an example, we have

$$i_{a\perp}^{\mathrm{u}}(t) + i_{a\perp}^{\mathrm{h}}(t) = \frac{1}{\sin(\omega T_{\mathrm{d}})}\left\{\left[i_a^{\mathrm{u}}(t) + i_a^{\mathrm{h}}(t)\right]\cos(\omega T_{\mathrm{d}}) - \left[i_a^{\mathrm{u}}(t - T_{\mathrm{d}}) + i_a^{\mathrm{h}}(t - T_{\mathrm{d}})\right]\right\} \tag{16}$$

where T_{d} is a short time period for calculation. This value should be properly chosen to balance the generation speed and noise immunity [12].

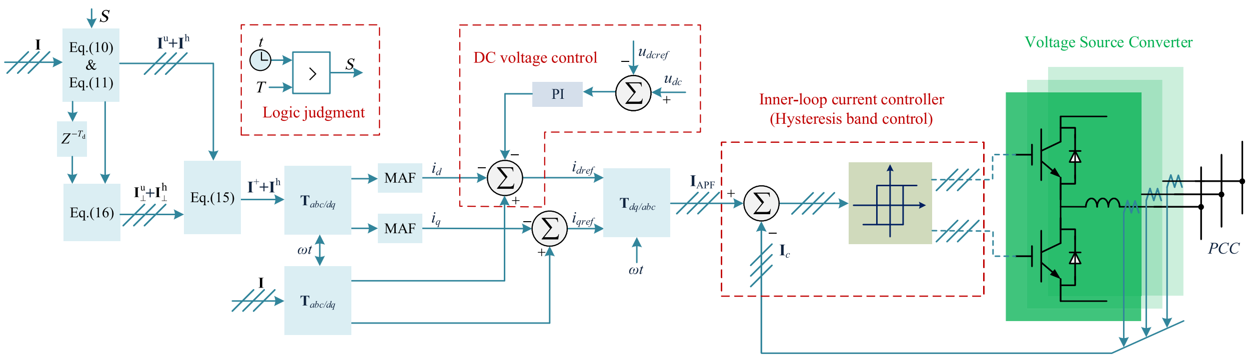

Fig. 2. Control diagram of the proposed method.

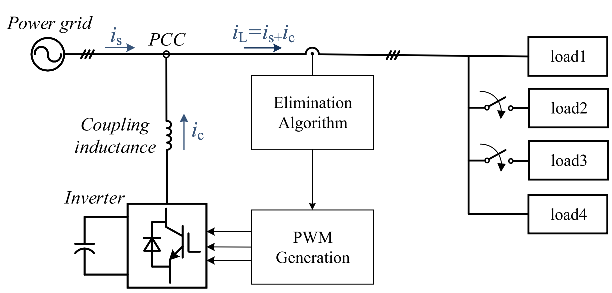

Fig. 3. Experiment system diagram.

Finally, after the sum current of PSC and harmonics is calculated, the PSC can be readily separated by using the *abc*/*dq* transformation and removing the ac components. To achieve the elimination of odd harmonics (which is the general case in grid), the MAF with a window length of half grid cycle can be simply used for the *d*-/*q*-axis components. This theoretically adds half grid cycle to the dynamic response time. Considering also the aforementioned two-step procedure to extract the intermediate current, the entire PSC detection process takes nearly one grid cycle. However, if the orders of major harmonic components can be preliminarily decided, multiple DSC blocks can be used instead of the MAF block, in order to further reduce the overall dynamic time.

The proposed method enables an efficient detection of the PSC in the presence of multiple disturbances, and can be applied to several scenarios, e.g., phase synchronization, fault ride-through, etc. In this letter, the active compensation for the transient current is achieved by using the shunt APF. Based on the operation principle of the APF, the control command can be set to

$$\mathbf{I}_{\mathrm{APF}}(t) = \mathbf{I}(t) - \mathbf{I}^{+}(t). \tag{17}$$

Considering the general implementation of converter control in the *dq*-frame, the overall control diagram can be obtained as shown in Fig. 2.

III. Experimental Verification

With reference to the circuit diagram in Fig. 3 and the main parameters in Table I, a microgrid system with load switching, which generates the impulsive transient current, is used, in order to verify the effectiveness of the proposed method. Specifically, four loads are connected to the point of common coupling (PCC).

TABLE I
Main Parameters of System

Parameter	Value	Parameter	Value
Three-phase voltage (ph-ph)	380 Vrms	Grid frequency	50 Hz
APF DC voltage	650 V	Filter inductance	20 mH
Load 2	8 Ω + 0.5 H	Load 3	2.5 Ω + 0.125 H
Load 4	500 Ω + 2 H		

TABLE II
Settings of Controlled Current Source (Load 1)

Comp.	Ph.	Before disturbance (A)	After disturbance (A)
$\mathbf{I}^{-}$	a	$5\sin(\omega t)$	$5\sin(\omega t)$
	b	$5\sin(\omega t + 2\pi/3)$	$5\sin(\omega t + 2\pi/3)$
	c	$5\sin(\omega t - 2\pi/3)$	$5\sin(\omega t - 2\pi/3)$
$\mathbf{I}^{\mathrm{h}}$	a	$3\sin(3\omega t + 5\pi/9) + \sin(5\omega t + 5\pi/9)$	$\sin(3\omega t + 5\pi/9) + 0.5\sin(5\omega t + 5\pi/9)$
	b	$3\sin(3\omega t + 5\pi/9 - 2\pi/3) + \sin(5\omega t + 5\pi/9 - 2\pi/3)$	$\sin(3\omega t + 5\pi/9 - 2\pi/3) + 0.5\sin(5\omega t + 5\pi/9 - 2\pi/3)$
	c	$3\sin(3\omega t + 5\pi/9 + 2\pi/3) + \sin(5\omega t + 5\pi/9 + 2\pi/3)$	$\sin(3\omega t + 5\pi/9 + 2\pi/3) + 0.5\sin(5\omega t + 5\pi/9 + 2\pi/3)$
$\mathbf{I}^{\mathrm{dc}}$	a	0	2
	b	0	2
	c	0	-3.5

Load 1 is a controlled current source, whose reference signal includes three-phase harmonics, negative-sequence component, as well the dc bias component (see Table II). This controlled source changes its output current before and after the disturbance time. Loads 2–4 are resistive–inductive. At the disturbance time, the switches of loads 2 and 3 are closed simultaneously, thereby inducing a significant DDC component during the transient. A detailed description of the experiment platform can be found in [2], and is therefore not repeated here for brevity.

The experiment result of load current is shown in Fig. 4(a), where the green curve represents the disturbance status. After the disturbance, the load current includes not only the DDC component caused by switching the linear loads, but also the dc bias component, unbalanced current, and harmonics induced by the controlled source. The peak amplitude of the transient current reaches 23 A, whose value is about twice than that of the steady state, making it easy to trigger the corresponding relay protection if no countermeasures were adopted.

The undesired transient current components can be mitigated through the use of shunt APF connected to the PCC. To this end, the load current (i_{L} in Fig. 3) is sensed and the suitable method can be used to generate the compensation current (i_{c} in Fig. 3). If the hybrid mode operation in [7] incorporating

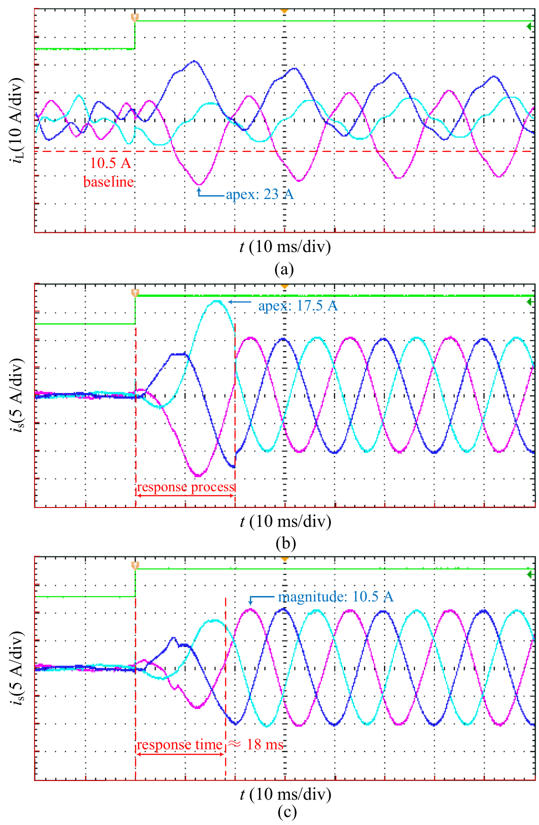

Fig. 4. Experimental results of enhanced APF. (a) Load current. (b) Grid current using the TPQC method in [7]. (c) Grid current using the proposed algorithm.

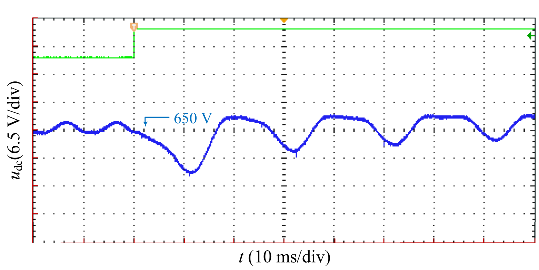

Fig. 5. Experimental result of dc-link voltage.

the TPQC mode is adopted, the resulting source current (i_s in Fig. 3) can be obtained in Fig. 4(b). This algorithm can alleviate the amplitude of fluctuation during the transient state to a certain extent. However, since the algorithm does not consider the asymmetry and dc components, the grid current still exhibits excessive amplitude during the transient (with the peak amplitude being about 1.7 times than that of the steady state), and the steady-state performance is compromised. Conversely, the grid current result, obtained using the proposed method [see Fig. 4(c)], shows a satisfactory mitigation of surge load current after the disturbance. Compared to the previous scheme, the proposed strategy not only slightly reduces the convergence time, but also smooths the grid current, lowering the maximum ac amplitude from 17.5 to 10.5 A. Note that here the result converged before the theoretical dynamic response time, which is the complete time that guarantees steady-state performance. Besides, the harmonics during the entire process have been effectively mitigated.

Finally, the voltage of dc-link capacitor is shown in Fig. 5. Despite minor fluctuations in the dc voltage during the transient, it has been proven that the classic PI controller (see Fig. 3) can satisfactorily regulate the dc-link capacitor, maintaining the stable operation of the APF.

IV. Conclusion

In this letter, a detection scheme of the PSC was proposed to address the transient signal with multiple disturbances and three-phase asymmetry. When the proposed method was adopted for active compensation using the APF, the transient response time was about one grid cycle. Compared to the existing scheme that also addresses the DDC component, the proposed algorithm supports operation under the full range of possible interference signals, and can quickly and accurately filter out the undesired components during the entire process.

Although not shown here for brevity, in practical applications where the grid frequency fluctuates within a narrow range (usually within 1 Hz limited by the pertinent grid code/standard), the influence of system frequency deviation on the proposed PSC detection scheme can be neglected. In this case, the major interference, i.e., the DDC component during the transient, can still be effectively suppressed.

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