Nonlinear Control Strategy of Split-Capacitor-Type Shunt Active Power Filter Based on EL Model

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1 Introduction

The Split-Capacitor-type Shunt Active Power Filter (2C SAPF) can be widely used in low-to-medium-power applications of three-phase four-wire system because its cost is lowest [1]. At present, a number of linear strategies for SAPF have been reported in the literature, but the mathematical model of SAPF is nonlinear [2]. In this paper, a nonlinear Passivity-Based Control (PBC) strategy based on EL model is used to achieve globally stable operation of 2C SAPF, which satisfies the current harmonic limits as specified by IEEE-519 [3, 4] and effectively maintains the stability of the DC bus voltage. The principle and comparison with the traditional strategies reveal the merits of the proposed strategy.

2 Modeling of 2C SAPF

The circuit in Fig. 1 is the considered system used to derive the model of 2C SAPF. Selecting the current flowing through the inductor (L_f), the different and the total DC bus voltage (ΔV_{dc} and $\sum V_{dc}$) as state variables, the Kirchhoff's law is used to

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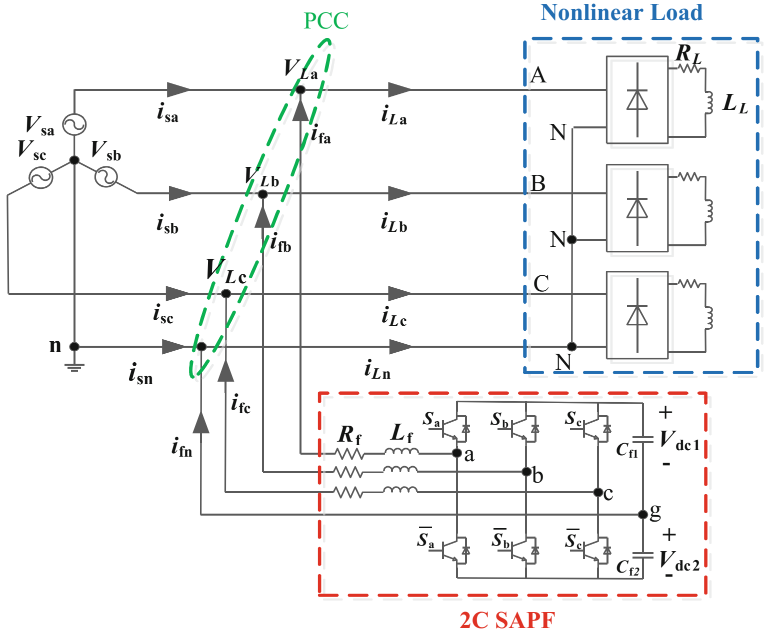


Fig. 1 The equivalent circuit of 2C SAPF

determine the mathematical model of 2C SAPF in *abc* stationary coordinate as shown in (2.1).

$$\begin{cases} L_f \dot{i}_{fa} = S_a \sum V_{dc} - R_f i_{fa} - V_{La} - \left(\sum V_{dc} - \Delta V_{dc}\right)/2 \\ L_f \dot{i}_{fb} = S_b \sum V_{dc} - R_f i_{fb} - V_{Lb} - \left(\sum V_{dc} - \Delta V_{dc}\right)/2 \\ L_f \dot{i}_{fc} = S_c \sum V_{dc} - R_f i_{fc} - V_{Lc} - \left(\sum V_{dc} - \Delta V_{dc}\right)/2 \\ C_f \Delta \dot{V}_{dc} = -(i_{fa} + i_{fb} + i_{fc}) \\ C_f \sum \dot{V}_{dc} = i_{fa} + i_{fb} + i_{fc} - 2(S_a i_{fa} + S_b i_{fb} + S_c i_{fc}) \end{cases} \tag{2.1}$$

where ΔV_{dc}, $\sum V_{dc}$ and C_f are given by: $\Delta V_{dc} = V_{dc1} - V_{dc2}$, $\sum V_{dc} = V_{dc1} + V_{dc2}$, $C_f = C_{f1} = C_{f2}$. And the switching function S_j (for j = a, b, c) is defined as:

$$S_j = \begin{cases} 1, S_j \text{ is on and } \bar{S}_j \text{ is off} \\ 0, S_j \text{ is off and } \bar{S}_j \text{ is on} \end{cases} \tag{2.2}$$

In the future work, the *dq*0 approach is used to describe the control strategy of 2C SAPF. Therefore, the mathematical model in (2.1) can be transformed into (2.3) by using equal power transformation.

$$\begin{cases} L_\mathrm{f}\dot{i}_\mathrm{fd} = S_\mathrm{d}\sum V_\mathrm{dc} - R_\mathrm{f}i_\mathrm{fd} - V_{L\mathrm{d}} + \omega L_\mathrm{f}i_\mathrm{fq} \\ L_\mathrm{f}\dot{i}_\mathrm{fq} = S_\mathrm{q}\sum V_\mathrm{dc} - R_\mathrm{f}i_\mathrm{fq} - V_{L\mathrm{q}} - \omega L_\mathrm{f}i_\mathrm{fd} \\ L_\mathrm{f}\dot{i}_\mathrm{f0} = (S_0 - \sqrt{3}/2)\sum V_\mathrm{dc} - R_\mathrm{f}i_\mathrm{f0} - V_{L0} + \sqrt{3}\Delta V_\mathrm{dc}/2 \\ C_\mathrm{f}\Delta\dot{V}_\mathrm{dc}/2 = -\sqrt{3}i_\mathrm{f0}/2 \\ C_\mathrm{f}\sum\dot{V}_\mathrm{dc}/2 = -S_\mathrm{d}i_\mathrm{fd} - S_\mathrm{q}i_\mathrm{fq} - (S_0 - \sqrt{3}/2)i_\mathrm{f0} \end{cases} \tag{2.3}$$

where, ω is the angular frequency of the power supply.

Letting us choose $x = [x_1, x_2, x_3, x_4, x_5]^\mathrm{T} = [i_\mathrm{fd}, i_\mathrm{fq}, i_\mathrm{f0}, \Delta V_\mathrm{dc}, \sum V_\mathrm{dc}]^\mathrm{T}$, and then rewriting (2.3) into the form of EL equation [5], as shown in (2.4).

$$\boldsymbol{M}\underline{\boldsymbol{x}} + \boldsymbol{J}\boldsymbol{x} + \boldsymbol{R}\boldsymbol{x} = \boldsymbol{u} \tag{2.4}$$

where $\boldsymbol{M}$, $\boldsymbol{J}$, $\boldsymbol{R}$ and $\boldsymbol{u}$ are given by:

$$\begin{gathered} \boldsymbol{M} = \mathrm{diag}\{L_\mathrm{f}, L_\mathrm{f}, L_\mathrm{f}, C_\mathrm{f}/2, C_\mathrm{f}/2\}, \quad \boldsymbol{R} = \mathrm{diag}\{R_\mathrm{f}, R_\mathrm{f}, R_\mathrm{f}, 0, 0\}, \\ \boldsymbol{J} = \begin{bmatrix} 0 & -\omega L_\mathrm{f} & 0 & 0 & -S_\mathrm{d} \\ \omega L_\mathrm{f} & 0 & 0 & 0 & -S_\mathrm{q} \\ 0 & 0 & 0 & -\sqrt{3}/2 & -(S_0 - \sqrt{3}/2) \\ 0 & 0 & \sqrt{3}/2 & 0 & 0 \\ S_\mathrm{d} & S_\mathrm{q} & (S_0 - \sqrt{3}/2) & 0 & 0 \end{bmatrix} \boldsymbol{u} = \begin{bmatrix} -V_{L\mathrm{d}} \\ -V_{L\mathrm{q}} \\ -V_{L0} \\ 0 \\ 0 \end{bmatrix} \end{gathered} \tag{2.5}$$

3 Principle and Design of PBC Based on EL Model

The proposed strategy is based on passivity-based method. The main idea is that of proving that the total increased energy of the system is less than that of the external injection.

Assuming that the storage energy of the 2C SAPF is given as:

$$H(\boldsymbol{x}) = \boldsymbol{x}^\mathrm{T}\boldsymbol{M}\boldsymbol{x}/2 \tag{3.1}$$

The system is globally asymptotically stable if $H(\boldsymbol{x})$ satisfies the following inequality:

$$\dot{H}(\boldsymbol{x}) \le \boldsymbol{u}^\mathrm{T}\boldsymbol{y} - Q(\boldsymbol{x}) \tag{3.2}$$

where, the $Q(\boldsymbol{x})$ is positive. Based on (2.4) and (3.1), $H(\boldsymbol{x})$ derivative can be expressed as:

$$\dot{H}(\boldsymbol{x}) = \boldsymbol{x}^{\mathrm{T}}\boldsymbol{M}\dot{\boldsymbol{x}} = \boldsymbol{x}^{\mathrm{T}}(\boldsymbol{u} - \boldsymbol{J}\boldsymbol{x} - \boldsymbol{R}\boldsymbol{x}) = \boldsymbol{u}^{T}\boldsymbol{x} - \boldsymbol{x}^{T}\boldsymbol{R}\boldsymbol{x} \tag{3.3}$$

From (3.2) and (3.3), we can see that if we choose $\boldsymbol{y} = \boldsymbol{x}$, $Q(\boldsymbol{x}) = \boldsymbol{x}^{\mathrm{T}}\boldsymbol{R}\boldsymbol{x}$, the 2C SAPF is globally asymptotically stable.

In order to achieve the purpose of PBC, that is to make each controlled variable gradually reach its expected value, the definition of the error of $\boldsymbol{x}$ is given as: $\boldsymbol{x}_{\mathrm{eg}} = \boldsymbol{x} - \boldsymbol{x}_{\mathrm{ref}} = [i_{\mathrm{fd}} - i_{\mathrm{fd}}^{*}, i_{\mathrm{fq}} - i_{\mathrm{fq}}^{*}, i_{\mathrm{f0}} - i_{\mathrm{f0}}^{*}, \Delta V_{\mathrm{dc}}, \sum V_{\mathrm{dc}} - \sum V_{\mathrm{dc}}^{*}]^{\mathrm{T}}$, where i_{fd}^{*}, i_{fq}^{*}, and i_{f0}^{*} are the reference currents extracted from the nonlinear load, and $\sum V_{\mathrm{dc}}^{*}$ is the reference voltage of $\sum V_{\mathrm{dc}}$. The equilibrium points of the system are found to be: $\boldsymbol{x}_{\mathrm{eg}} = 0$. Then, based on (2.4), we can get:

$$\boldsymbol{M}\dot{\boldsymbol{x}}_{\mathbf{eg}} + \boldsymbol{J}\boldsymbol{x}_{\mathbf{eg}} + \boldsymbol{R}\boldsymbol{x}_{\mathbf{eg}} = \boldsymbol{u} - (\boldsymbol{M}\dot{\boldsymbol{x}}_{\mathbf{ref}} + \boldsymbol{J}\boldsymbol{x}_{\mathbf{ref}} + \boldsymbol{R}\boldsymbol{x}_{\mathbf{ref}}) \tag{3.4}$$

Assuming that the error energy storage function of the 2C SAPF is given as:

$$H_{\mathrm{eg}}(\boldsymbol{x}) = \boldsymbol{x}_{\mathbf{eg}}^{\mathrm{T}}\boldsymbol{M}\boldsymbol{x}_{\mathbf{eg}} \Big/ 2 \tag{3.5}$$

As long as the $H_{\mathrm{eg}}(\boldsymbol{x})$ converges to 0, the $\boldsymbol{x}_{\mathbf{eg}}$ can converge to 0, and at this time, we can achieve the purpose of PBC.

In an attempt to increase the speed of convergence, the damping injection method can be used to speed up the system's energy dissipation, so as to increase the speed of the system's response. The injected damping dissipation can be expressed as:

$$\boldsymbol{R}_{\mathbf{d}}\boldsymbol{x}_{\mathbf{eg}} = (\boldsymbol{R} + \boldsymbol{R}_{\mathbf{a}})\boldsymbol{x}_{\mathbf{eg}} \tag{3.6}$$

where, the form of $\boldsymbol{R}_{\mathrm{a}}$ is the same as that of $\boldsymbol{R}$, is given as: $\boldsymbol{R}_{\mathrm{a}} = \mathrm{diag}\{r_{\mathrm{a1}}, r_{\mathrm{a2}}, r_{\mathrm{a3}}, 0,0\}$. Then, (3.4) becomes:

$$\boldsymbol{M}\dot{\boldsymbol{x}}_{\mathbf{eg}} + \boldsymbol{R}_{\mathbf{d}}\boldsymbol{x}_{\mathbf{eg}} = \boldsymbol{u} - (\boldsymbol{M}\dot{\boldsymbol{x}}_{\mathbf{ref}} + \boldsymbol{J}\boldsymbol{x} + \boldsymbol{R}\boldsymbol{x}_{\mathbf{ref}} - \boldsymbol{R}_{\mathbf{a}}\boldsymbol{x}_{\mathbf{eg}}) \tag{3.7}$$

In an effort to ensure the global asymptotic stability of the 2C SAPF, letting us choose the control law of hybrid PBC as:

$$\boldsymbol{u} = \boldsymbol{M}\dot{\boldsymbol{x}}_{\mathbf{ref}} + \boldsymbol{J}\boldsymbol{x} + \boldsymbol{R}\boldsymbol{x}_{\mathbf{ref}} - \boldsymbol{R}_{\mathbf{a}}\boldsymbol{x}_{\mathbf{eg}} \tag{3.8}$$

At this time, based on (3.5), (3.7) and (3.8), the derivative of $H_{\mathrm{eg}}(\boldsymbol{x})$ satisfies:

$$\dot{H}_{\mathrm{eg}}(\boldsymbol{x}) = \boldsymbol{x}_{\mathbf{eg}}^{\mathrm{T}}\boldsymbol{M}\dot{\boldsymbol{x}}_{\mathbf{eg}} = -\boldsymbol{x}_{\mathbf{eg}}^{\mathrm{T}}\boldsymbol{R}_{\mathbf{d}}\boldsymbol{x}_{\mathbf{eg}} < 0 \tag{3.9}$$

Then, based on (3.9), the switching function on $dq0$-frame can be deduced as:

$$\begin{cases} S_{\mathrm{d}} = \dfrac{V_{L\mathrm{d}} - \omega L_{\mathrm{f}} i_{\mathrm{fq}} + R_{\mathrm{f}} i_{\mathrm{fd}}^{*} - r_{\mathrm{a1}}(i_{\mathrm{fd}} - i_{\mathrm{fd}}^{*})}{\sum V_{\mathrm{dc}}} \\ S_{\mathrm{q}} = \dfrac{V_{L\mathrm{q}} + \omega L_{\mathrm{f}} i_{\mathrm{fd}} + R_{\mathrm{f}} i_{\mathrm{fq}}^{*} - r_{\mathrm{a2}}(i_{\mathrm{fq}} - i_{\mathrm{fq}}^{*})}{\sum V_{\mathrm{dc}}} \\ S_{0} = \dfrac{2V_{L0} - \sqrt{3}\Delta V_{\mathrm{dc}} + 2R_{\mathrm{f}} i_{\mathrm{f0}}^{*} - 2r_{\mathrm{a3}}(i_{\mathrm{f0}} - i_{\mathrm{f0}}^{*})}{2\sum V_{\mathrm{dc}}} + \dfrac{\sqrt{3}}{2} \end{cases} \tag{3.10}$$

At this time, according to (2.3) and (3.10), we can get:

$$\begin{cases} i_{\mathrm{fd}}^{*} = i_{\mathrm{fd}} + \frac{L_{\mathrm{f}}}{R_{\mathrm{f}} + r_{\mathrm{a1}}} \dot{i}_{\mathrm{fd}} \\ i_{\mathrm{fq}}^{*} = i_{\mathrm{fq}} + \frac{L_{\mathrm{f}}}{R_{\mathrm{f}} + r_{\mathrm{a2}}} \dot{i}_{\mathrm{fq}} \\ i_{\mathrm{f0}}^{*} = i_{\mathrm{f0}} + \frac{L_{\mathrm{f}}}{R_{\mathrm{f}} + r_{\mathrm{a3}}} \dot{i}_{\mathrm{f0}} \end{cases} \tag{3.11}$$

It's easy to see that the control law of PBC of (3.8) can make the compensating current completely decoupled.

From (2.1) and (2.3), it can be seen that the compensating current and DC bus voltage is closely related, so a regulation of the DC bus voltage is required. In order to keep ΔV_{dc} stable at 0 and $\sum V_{\mathrm{dc}}$ stable at $\sum V^{*}$ dc, an outer control loop is designed by a suitable PI regulator. The output of the ΔV_{dc} controller is added to the d-component harmonic current $i_{L\mathrm{dh}}$ and the output of the $\sum V_{\mathrm{dc}}$ controller is added to the *0*-component harmonic current $i_{L0\mathrm{h}}$ as shown in Fig. 2.

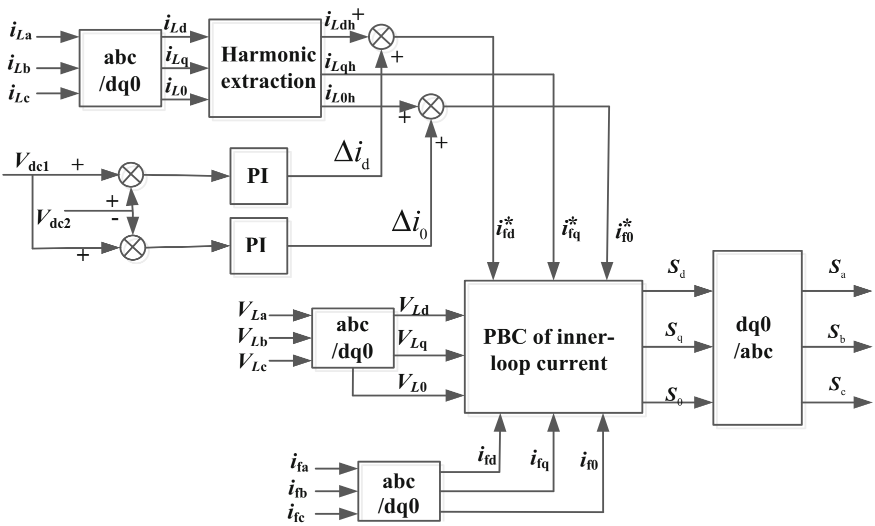


Fig. 2 Block diagram of the proposed control scheme

4 Simulation Results

To verify the merits of the proposed strategy, a system of 2C SAPF based on this and traditional strategy is simulated under the Matlab/Simulink environment, and the THD of the source current under varying load and unbalanced voltage source conditions is taken as the performance index. The simulation parameters are: the nonlinear load $R_{\mathrm{L}} = 5\ \Omega$, $L_{\mathrm{L}} = 20$ mH; filter inductor and resistance $L_{\mathrm{f}} = 5$ mH, $R_{\mathrm{f}} = 0.3\ \Omega$; capacitor of DC bus $C_{\mathrm{f}} = 5$ mF; $\sum V_{\mathrm{dc}}^{*} = 800$ V; injection damping $r_{\mathrm{a1}} = r_{\mathrm{a2}} = r_{\mathrm{a3}} = 600\ \Omega$; the simulation time is 0.55 s.

Figure 3 shows the transient responses of 2C SAPF that adopted the proposed strategy for a 100% step increase and decrease of the load at $t_1 = 0.2$ s and

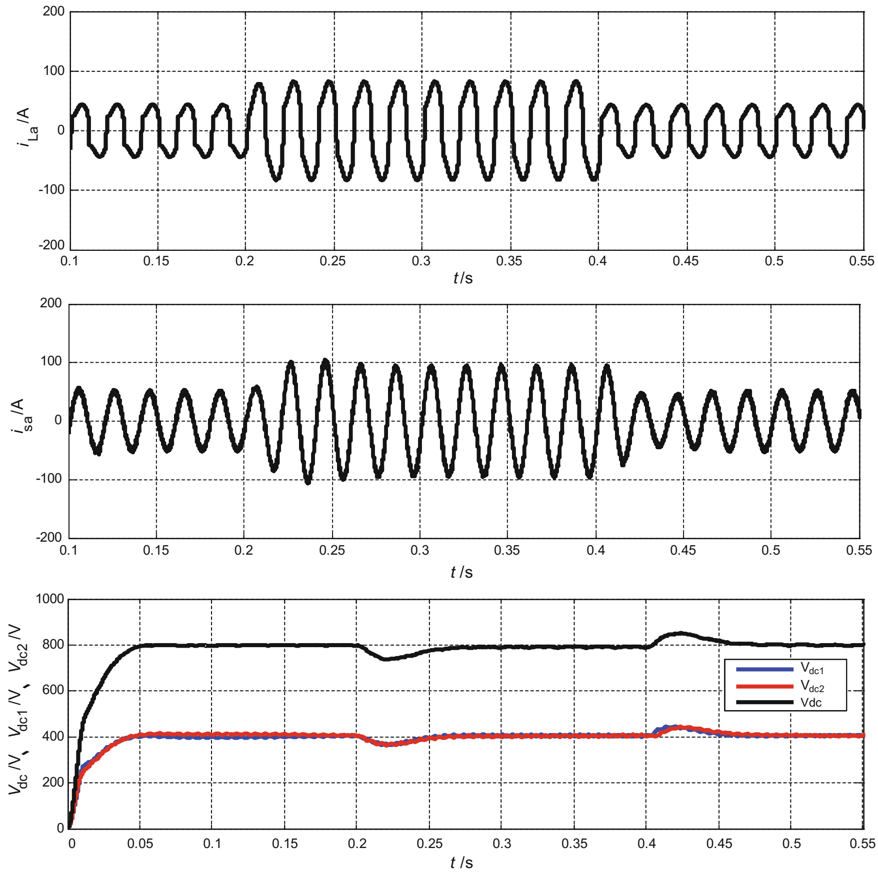
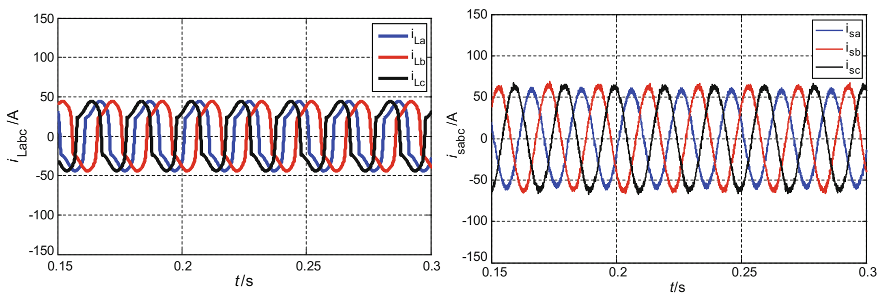


Fig. 3 Dynamic response of the 2C SAPF

$t_2 = 0.4$ s, respectively. It can be seen that both the supply current and the DC bus voltage exhibit a fast transient response under this sudden variation of load, achieving stable operation of the 2C SAPF.

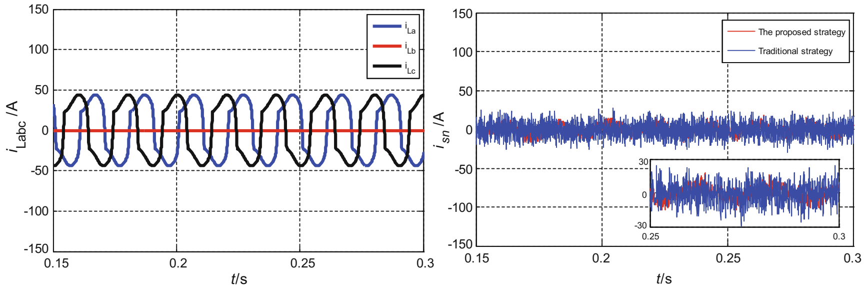
Figure 4 shows the steady-state simulation results of 2C SAPF that adopted the proposed strategy before and after compensation when the phase of supply voltage is 0°, −90°, 60°, respectively. The corresponding THD of the supply current has reduced from 24.89 to 2.50, 2.32, 2.60%, which shows the effectiveness of the proposed strategy.

Figure 5 shows the simulation results of 2C SAPF that adopted the proposed and traditional strategy before and after compensation at b-phase grounding. The corresponding THD of the supply current using the proposed strategy has reduced from 24.89 to 3.04, 2.67, 2.90%, while using traditional strategy in each phase of THD decreased to 6.72, 7.58 and 6.62% respectively. In addition, the results further show that compared with traditional strategy, the time of reaching steady state can be reduced from 0.1 to 0.05 s when using the proposed strategy. They both show the availability and significant advantage of the proposed strategy.

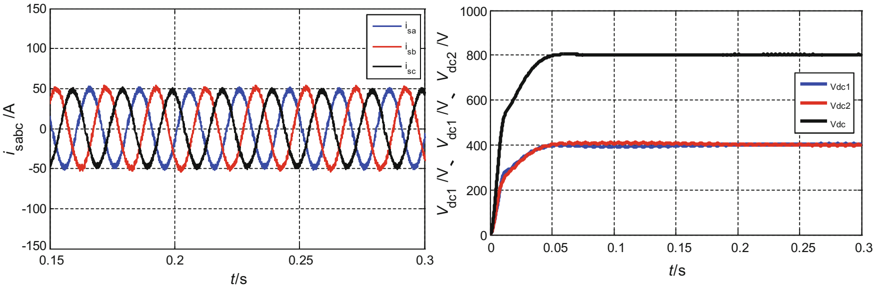


(a) Current supply before compensation (b) Current supply after compensation

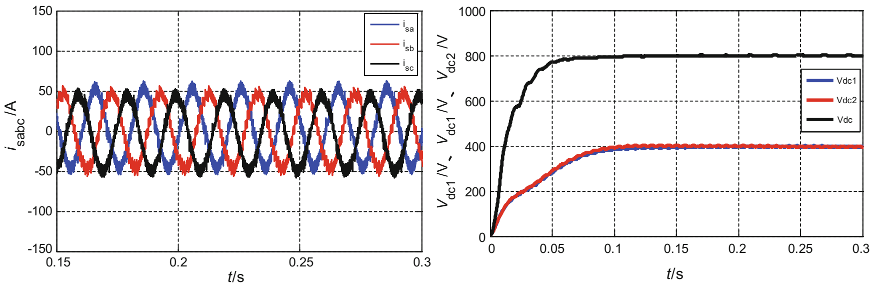
Fig. 4 Response of 2C SAPF when the phase of power supply is unbalanced



(a) Supply currents before compensation (b) Neutral current after compensation



(c) Simulation results adopted the proposed strategy



(d) Simulation results adopted traditional strategy

Fig. 5 Response of 2C SAPF at b-phase grounding

5 Conclusion

A hybrid PBC strategy for 2C SAPF has been proposed and implemented in this paper. The observed performance has demonstrated the ability of the proposed strategy of 2C SAF to compensate the current harmonics effectively under varying loads and unbalanced power supply. It has also been shown that the proposed strategy has a faster and better dynamic response than traditional strategy and is able to keep the THD of the supply currents well below the mark of 5% specified in the IEEE-519 standard.

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