Reactive Power Compensation and Resonance Damping for Three-Phase Buck-Type Dynamic Capacitor

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Abstract—**Dynamic capacitor (D-CAP) is able to provide dynamic reactive power and harmonic compensation for industrial plants. Previous papers have introduced the principles and control strategies of D-CAP. However, there is no paper to focus on resonance conditions of D-CAP. In this paper, based on three-phase Buck-type D-CAP, basic structure and principle are introduced. Then, through the modeling of D-CAP impedance and grid impedance, the reason of resonance is analyzed, and the corresponding resonance points are calculated. In order to suppress the harmonics near the resonant frequency, this paper presents an active damping method that the capacitance voltage of D-CAP is detected as feedback quantity to solve this problem. At last, a hybrid control strategy for reactive power compensation, harmonic suppression and resonance damping is proposed. Through this strategy, grid current harmonic distortion obtains good inhibition and its THD meets the IEEE std519-1992. The experimental results verify the validity of the theoretical analysis.**

Keywords—dynamic capacitor; reactive power compensation; harmonic suppression; resonance damping; hybrid control strategy

I. INTRODUCTION

In low or medium voltage power distribution system, there are growing demands of using reactive power compensation equipment. This is caused by the application of inductive loads such as inductive-motor, transformer and air-conditioning which can lead to significant reactive problems[1][2].

Well known reactive power compensation device, such as Static VAR Compensator (SVC), has been widely used in power grid. It could dynamically adjust reactive power, and its cost is low. However, SVC could bring harmonic pollution to grid. Another type of VAR compensation device with superior performance is Static Synchronous Compensator (STATCOM) based on DC/AC converter. STATCOM's performance is faster than SVC, and it causes fewer harmonics. But price and maintain cost of STATCOM are costly for industrial users to correct power factor [3]. Compared with above devices, dynamic capacitor, which is designed based on the AC/AC converter, is used to implement dynamic VAR compensation and harmonic compensation with cost-effective and flexible characteristics [4][5].

At present, many literatures have designed reactive power compensation control function for single-phase and three-phase D-CAP[5][6]. In order to make D-CAP have the ability of harmonic compensation, some papers designed the harmonic suppression function. Literature [7] proposed an Even Harmonic Modulation(EHM) strategy, which made D-CAP suppress the harmonics when it was implementing reactive power compensation. Furthermore, based on single-phase Buck-type D-CAP, literature [8] proposed a strategy that D-CAP could generate controlled harmonic current in order to improve itself corresponding output current waveform quality.

Resonance is a problem that cannot be ignored when D-CAP is realizing VAR compensation. Until now, there is no literature to analyze the resonance condition of D-CAP. In this paper, according to the modeling analysis of impedance, the device would cause resonance problem effected by background harmonics in grid voltage. This resonance problem could cause current distortion of grid in PCC, which further affects the application of D-CAP in the industrial field.

For the resonance problem, traditional passive damping method will lead to huge power consumption, so active damping methods have been wildly used in damping resonance[9]. An active damping way is realizing voltage or current feedback control at the resonance frequencies[10][11]. Another type way to realize active damping is using combined control strategies to suppress specified harmonic currents and selectively damp corresponding resonance [12]-[14].

In this paper, a capacitance-voltage-feedback active damping method is proposed to solve resonance problem in Section II. Though this method, resonance damping loops are designed to selectively suppress the corresponding resonance harmonics. By using EHM strategy, harmonic suppression loops are designed to selectively suppress the grid current harmonics. Finally, a hybrid control strategy for reactive power

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compensation, harmonic suppression and resonance damping is proposed in Section III. Experimental verification is carried out to verify the theoretical analysis in Section IV.

II. ACTIVE DAMPING METHOD

A. Basic structure and principle of Buck-type D-CAP

As shown in Fig.1(a), per phase of the basic circuit structure of Buck-type D-CAP is mainly composed of power capacitor C, buffer inductor L_{F1}, two converters S_1 and S_2, and filter $L_{F2}C_F$. In Fig.1(b), bidirectional switch S_1 is composed of two common-collector IGBTs in series, while S_2 is made up of two common-emitter IGBTs in series. In Fig.1(c), the switches S_1 and S_2 are turned on complementarily, their duty ratios are D and 1-D respectively.

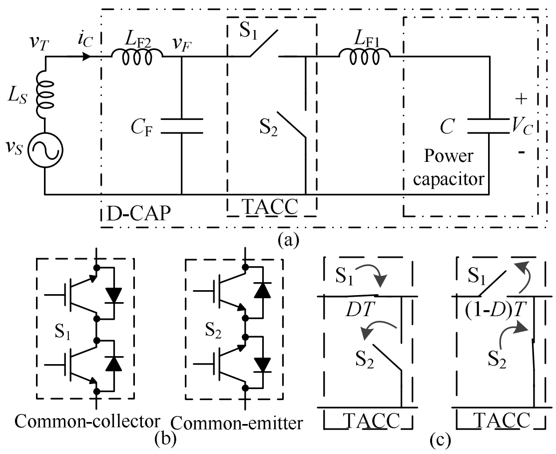


Fig.1 Buck-type D-CAP (a)Basic topology structure (b)Bidirectional switches (c)Two complementary switching states

It is defined that $i_{C(t)}$ is output current of D-CAP, $D(t)$ is duty ratio of S_1. When duty ratio is adjusted as a constant D_0 in every switching period, literature [8] deduces the basic control equation (1) of Buck-type D-CAP in detail.

$$i_C(t) = D_0^2 C \frac{dv_T(t)}{dt} \tag{1}$$

According to (1), D-CAP can be equivalent to a variable capacitor $D_0^2 C$. By adjusting the duty ratio D_0, the reactive compensation current i_C is changed dynamically. This is the principle of reactive power compensation of Buck-type D-CAP.

B. Resonance analysis of Buck-type D-CAP

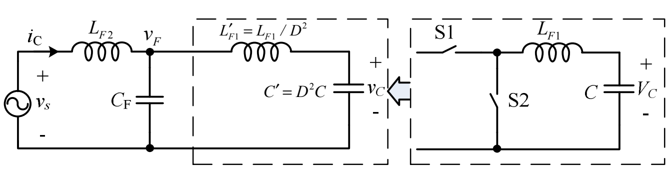


Fig.2 Buck-type D-CAP equivalent circuit

It is defined that power capacitor voltage is V_C. After equivalent deducing in Fig.2, it is assuming that L_{F2} contains the grid inductance L_S and equivalent power capacitor voltage is v_C. Fig.3 shows the block diagram that can be used to analyze the dynamic behavior of the topology structure in Fig.1(a).

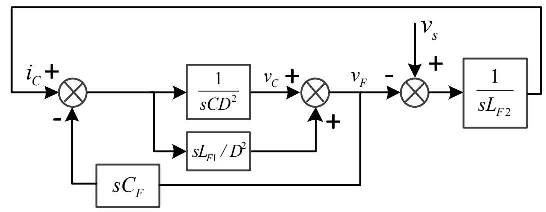


Fig.3 The block diagram representation of Buck-type D-CAP

Based on Fig.3, the following transfer function can be deduced in (2).

$$G_1(s) = \frac{I_C(s)}{V_S(s)} = \frac{L_{F1}C_F C s^3 + (C_F + D^2 C)s}{L_{F1}L_{F2}C_F C s^4 + (L_{F1}C + L_{F2}C_F + L_{F2}CD^2)s^2 + 1} \tag{2}$$

Then the amplitude-frequency characteristic of $G_1(s)$ with different duty ratio D is in shown in Fig.4.

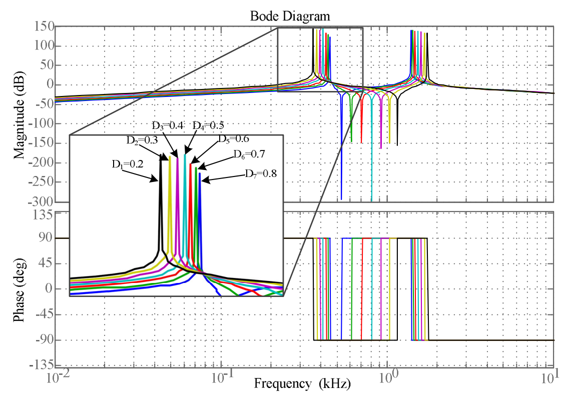


Fig.4 Buck-type D-CAP equivalent circuit Bode diagram

With the increase of duty ratio D from 0.2 to 0.8, the low series resonance frequency of $G_1(s)$ increases from 360hz to 452hz(7^{th}~8^{th} harmonics), and the high series resonance frequency is near 1530hz(30^{th} harmonics). These series resonance frequency can be calculated accurately by equation(3).

$$f_{1,2} = \frac{1}{2\pi}\sqrt{\frac{(L_{F2}C_F + L_{F2}D^2 C + L_{F1}C) \pm \sqrt{\Delta}}{2L_{F1}L_{F2}C_F C}} \tag{3}$$

where $$\Delta = (L_{F2}C_F + L_{F1}C + L_{F2}D^2 C)^2 + 4L_{F1}L_{F2}C_F C \tag{4}$$

The series resonance is mainly caused by background harmonics in grid, and those harmonics frequency are relatively low, so the effect of high series resonant frequency and parallel resonant frequency could be ignored. Due to the resonance effect, D-CAP's reactive power compensation output current i_C would lead to serious distortion, and the grid current is also influenced at the same time. This paper mainly focuses on designing the active resonance damping method near 7th~8th harmonics.

C. Active damping method based on capacitance-voltage-feedback

To solve series resonance problem, it is feasible to employ the feedback of variables in the D-CAP capacitance for the purpose of damping the resonance. The variable for feedback quantity is sampled from equivalent capacitor voltage v_C in Fig.2 where $1/R_d$ is the damping coefficient for v_C in Fig.5.

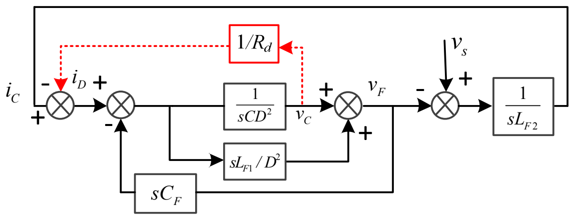


Fig.5 The block diagram representation of active damping method

The transfer function of i_C/v_S with damping coefficient $1/R_d$ can be deduced in (5).

$$G_2(s)=\frac{I_C(s)}{V_S(s)}= \frac{L_{F1}C_FCs^3+(C_F+D^2C)s+1/R_d}{L_{F1}L_{F2}C_FCs^4+(L_{F1}C+L_{F2}C_F+L_{F2}CD^2)s^2+L_{F2}s/R_d+1} \quad (5)$$

The Bode plot of equation (5) with different value of damping coefficient $1/R_d$ is in shown in Fig.6 (D=0.5).

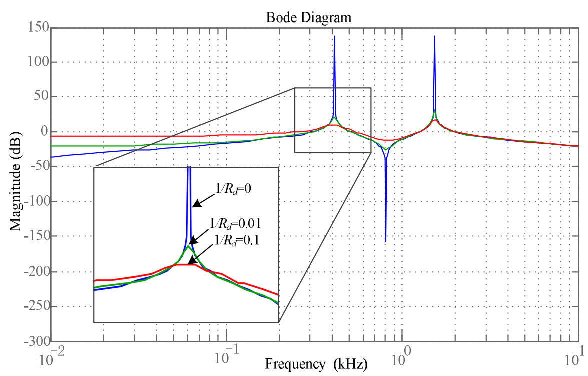


Fig.6 Active damping method Bode diagram

Damping coefficient $1/R_d$ is only generated at harmonic frequencies, so it does not consume active power at fundamental frequency. With the increase of $1/R_d$, the whole amplitude-frequency characteristic curve moves down. Although the harmonic suppression ability is weakened at low frequency, the damping loop allows the resonance peaks to get significantly attenuation and the system performance for resonance damping is improved.

III. HYBRID CONTROL STRATEGY

The three-phase Buck-type D-CAP system structure can be seen in Fig.7(a). The hybrid control architecture is designed in Fig.7(b). The reactive power compensation loop has been proposed in[5]. As shown in Fig.7(a), three-phase reactive power load current of i_{La}, i_{Lb}, i_{Lc} are detected. Though this loop in Fig.7(b), D-CAP can realize floating control of fundamental reactive current.

Based on EHM, the corresponding harmonic suppression loops are established to realize harmonic suppression in Fig.7(b). In order to suppress n order harmonic component of PCC current, it is needed to regulate n-1 order harmonic component of duty ratio D(t), thus D-CAP could generate controlled n order harmonic current with the same amplitude and reversed phase of compensated harmonic current[8].

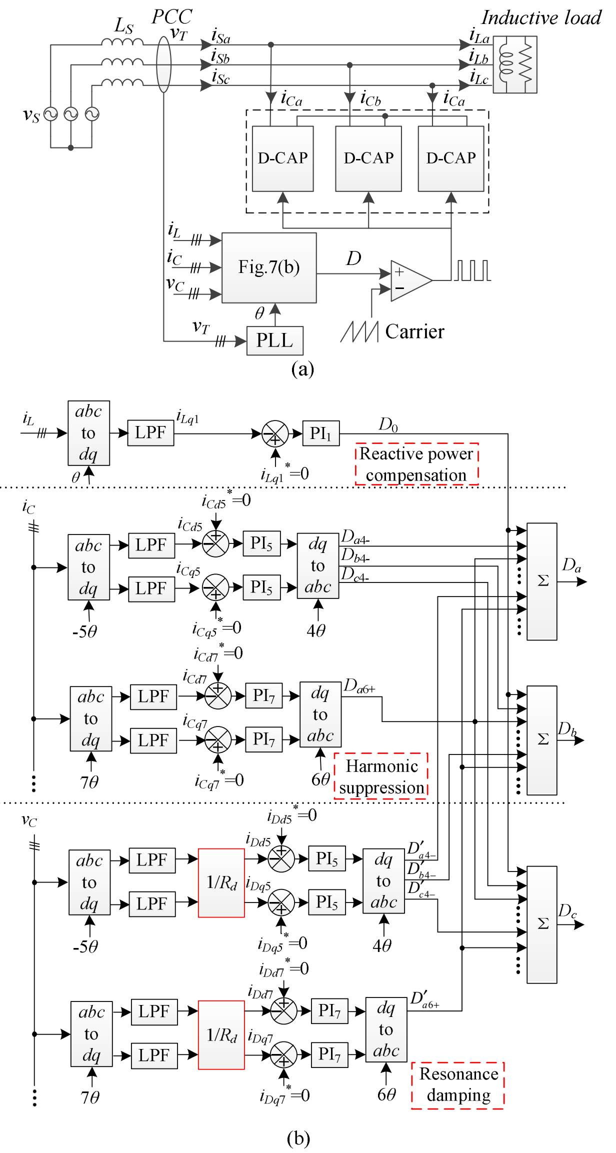


Fig.7 System structure of three-phase Buck-type D-CAP (a)Main circuit (b)Hybrid control strategy

At last, the resonance damping loops are proposed as shown in Fig.7(b). To realize the active resonance damping method, by using equation (6), each of the resonance damping loop at the resonance frequency consists of the "*abc*" capacitance voltages to "*dq0*" transformation. Then by low pass filter (LPF) and damping coefficient $1/R_d$ that turn all three "*abc*" voltages components to i_{Ddk} and i_{Dqk} currents components. Meanwhile, damping coefficient $1/R_d$ is closed-loop regulated and its design method could refer to [12][13]. The followed by corresponding PI_k controller cooperate with i_{Ddk}* and i_{Dqk}* instructs that drive i_{Ddk} and i_{Dqk} currents components to zero. Based on EHM and corresponding equation (7), the "*dq0*" output of the PI_k controller back to "*abc*" coordinate space in order to obtain $(k\text{-}1)^{th}$ resonance damping duty ratio reference D'.

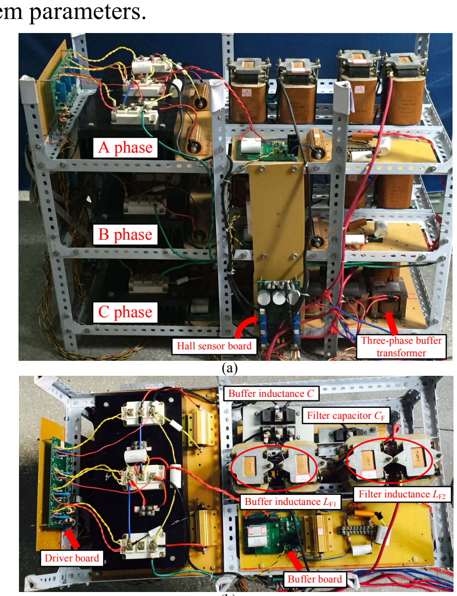
$$C_{abc/dq}^{k} = \frac{2}{3}\begin{bmatrix} \sin\left((-1)^n k\omega t\right) & \sin\left((-1)^n k\omega t - 2\pi/3\right) & \sin\left((-1)^n k\omega t + 2\pi/3\right) \\ \cos\left((-1)^n k\omega t\right) & \cos\left((-1)^n k\omega t - 2\pi/3\right) & \cos\left((-1)^n k\omega t + 2\pi/3\right) \end{bmatrix} \tag{6}$$

$$C_{dq/abc}^{k-1} = \begin{bmatrix} \sin\left((k-1)\omega t\right) & \cos\left((k-1)\omega t\right) \\ \sin\left((k-1)\omega t - 2\pi/3\right) & \cos\left((k-1)\omega t - 2\pi/3\right) \\ \sin\left((k-1)\omega t + 2\pi/3\right) & \cos\left((k-1)\omega t + 2\pi/3\right) \end{bmatrix} \tag{7}$$

Finally, the every loop duty ratio reference is added to obtain total duty ratio reference D_a, D_b, and D_c. Thus, by adjusting the duty ratio, D-CAP is able to provide both active harmonic suppression and resonance damping function when the reactive power compensation is realized.

IV. Experiment Results

An experimental test with three-phase three-wire 33kVA Buck-type D-CAP is carried out for the performance of the hybrid control strategy. The system configuration is shown in Fig.7 and the test prototype is shown in Fig.8. Tab.I shows the main system parameters.



(b)

Fig.8 Test prototype(a)Three-phase Buck-type D-CAP (b) Experimental platform of A phase

TABLE.I The Main Parameters

Parameters	Value
Grid voltage v_S	380 V
Grid frequency f	50 Hz
Grid inductance L_S	10μH
Load inductance L_1	42.4mH
Load resistance R_1	12.5Ω
Filtering capacitor C_F	160μH
Filtering inductance L_{F2}	80μF
Buffer inductance L_{F1}	180μH
Power capacitor C	660μF
Switching frequency f_S	9.6kHz

The experimental results mainly contain the waveforms in PCC and output current of D-CAP. Buck-type D-CAP operates in following A~D four different modes.

A. D-CAP is not connected to the system

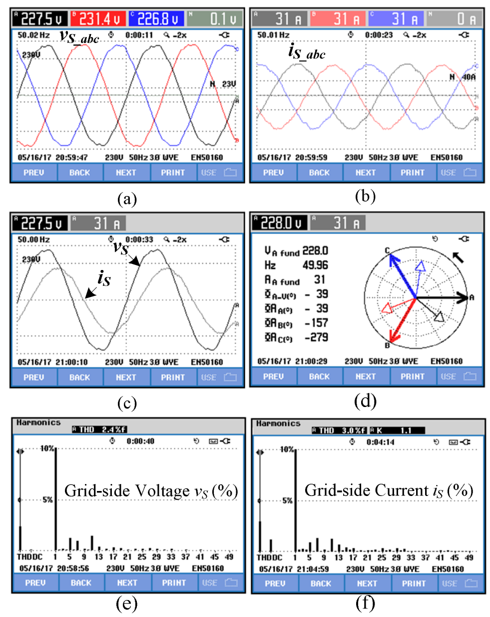


Fig.9 D-CAP is not connected to the system(a)PCC voltage (b)Grid current (c)v_S&i_S waveform (d)v_S&i_S phase relation (e)PCC voltage THD (f)Grid current THD

When D-CAP is not connected to the system, experimental results are shown in Fig.9. The background harmonic in grid voltage is constructed by nonlinear load and its THD is near 2.4% in experiment. As shown in Fig.9(f), grid current THD is 3.0% that meets the IEEE std519-1992[15]; The grid current waveform is obviously lagging behind the PCC voltage waveform in Fig.9 (c)(d), therefore, the power factor caused by inductive load needs to be corrected.

B. D-CAP realizes reactive power compensation

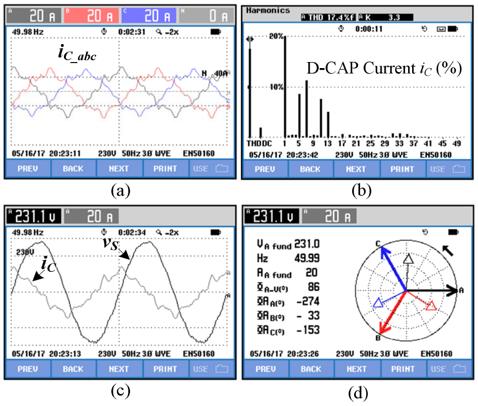


Fig.10 D-CAP realizes reactive power compensation (a)Output current of D-CAP (b)THD of output current (c)v_S&i_C waveform (d)v_S&i_C phase relation

According to Fig.10(c)(d), D-CAP would output 20A capacitive current i_C, its phase-angle is leading 86° of PCC voltage v_S. However, as shown in Fig.10(a)(b), the harmonic distortion of D-CAP output current is very serious, its THD reaches to 17.4%. Its harmonics mainly concentrate in 5th, 7th, 11th and 13th, among them, 7th harmonic content is the maximum. It verifies the previous analysis that resonance occurs near 7th harmonic when D-CAP is connected to system.

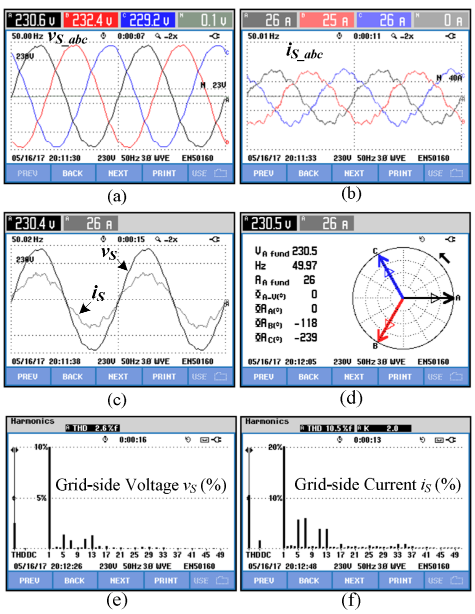


Fig.11 D-CAP realizes reactive power compensation (a)PCC voltage (b)Grid current (c)v_S&i_S waveform (d)v_S&i_S phase relation (e)PCC voltage THD (f)Grid current THD

Fig.11(e)(f) show the waveforms of PCC voltage and grid current, their THDs are 2.6% and 10.5% respectively. It is obvious to see that grid current is distorted, meanwhile, its spectra reveals that resonance frequency is around 7th. Fig.11(c)(d) show the power factor is corrected well by D-CAP.

C. D-CAP realizes reactive power compensation and harmonic suppression

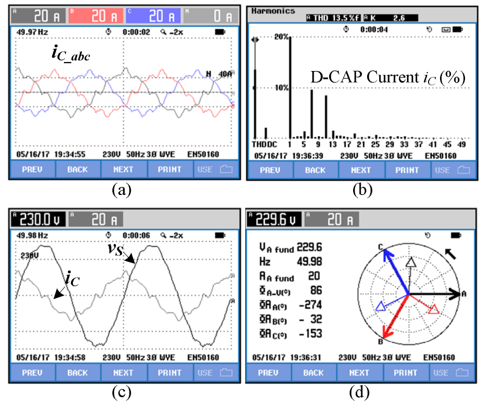


Fig.12 D-CAP realizes reactive power compensation and harmonic suppression(a)Output current of D-CAP (b)THD of output current (c)v_S&i_C waveform (d)v_S&i_C phase relation

In this compensation mode, as shown in Fig.12(b), it is clear that 5th and 13th harmonic distortion of D-CAP output current is suppressed well. Its THD decreases to 13.5%. The 7th and 11th harmonics are still relatively high.

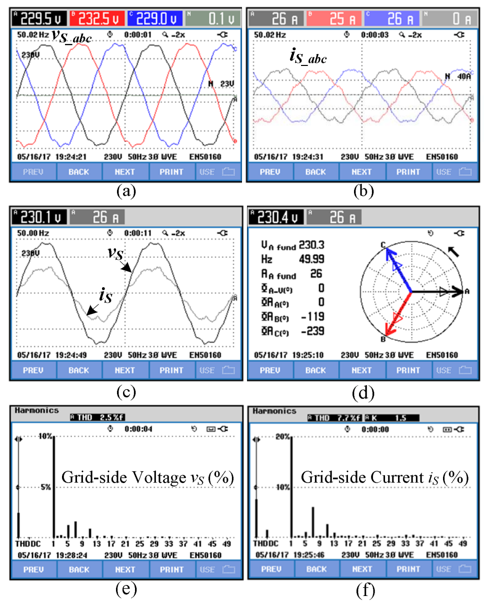


Fig.13 D-CAP realizes reactive power compensation and harmonic suppression (a)PCC voltage (b)Grid current (c)v_S&i_S waveform (d)v_S&i_S phase relation (e)PCC voltage THD (f)Grid current THD

As shown in Fig.13, PCC voltage THD and grid current THD are 2.5% and 7.7% respectively. The 5th and 13th harmonic distortions are sufficiently suppressed, and the power factor is corrected well. Due to the resonance effect, the 7th and 11th harmonics need to be further compensated.

D. D-CAP realizes hybrid control

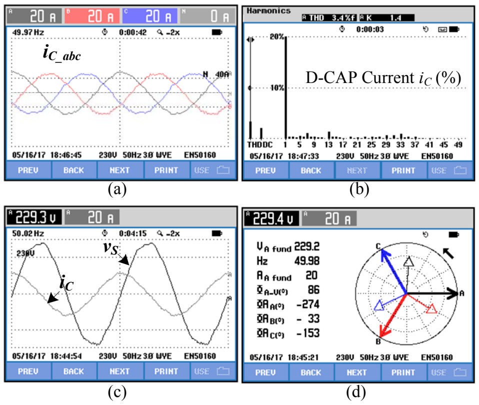


Fig.14 D-CAP realizes hybrid control (a)Output current of D-CAP (b)THD of output current (c)v_S&i_C waveform (d)v_S&i_C phase relation

In hybrid control mode, as shown in Fig.14(b), 5th ,7th 11th and 13th harmonics are all suppressed well. Resonance distortion of D-CAP output current has been improved, and its THD decreases to 3.4%.

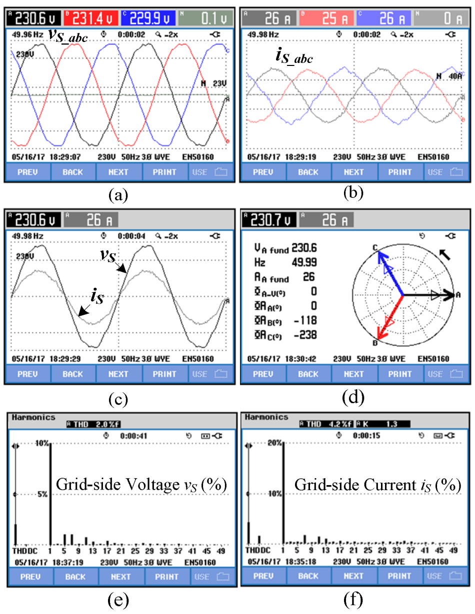


Fig.15 D-CAP realizes hybrid control (a)PCC voltage (b)Grid current (c)v_S&i_S waveform (d)v_S&i_S phase relation (e)PCC voltage THD (f)Grid current THD

As shown in Fig.15, PCC voltage THD and grid current THD are 2.0% and 4.2% respectively. Both of them meet the IEEE std519-1992. The resonance distortion is sufficiently suppressed and the power factor is corrected well, which proves the effectiveness of hybrid control strategy.

V. Conclusions

This paper focuses on resonance problem when three-phase Buck-type D-CAP realizes reactive compensation. The following conclusions are obtained through the experimental verification.

1) Under the influence of the background harmonic of the power grid, output current of D-CAP would cause resonance problem that would lead to current distortion in PCC. The corresponding resonance points are calculated.

2) Based on the capacitance-voltage-feedback, a kind of resonance damping loop is designed. By joining the harmonic suppression and resonance damping loops, a hybrid control strategy is proposed to selectively inhibit the resonance harmonic components. Experimental results demonstrate the validity of the active damping method, and the grid current THD meets IEEE std519-1992.

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