A Capacitive-coupled Transformerless Active Power Filter with Coupling Current Feedback Control

Chi-Seng Lam, Man-Chung Wong
Faculty of Science and Technology
University of Macau
Macau, SAR, P. R. China
cslam@umac.mo

***Abstract*—This paper presents a low rating capacitive-coupled transformerless active power filter (APF) for reactive power, current harmonics and neutral current compensation in three-phase four-wire distribution power system. Besides the benefits of APF's rating and initial cost reduction, it can lessen the switching loss and electromagnetic interference (EMI) problems, without significantly deteriorates the compensation capability. A novel control strategy is also proposed to strengthen the system damping and stability. Thus, the capacitive-coupled APF is characterized by low capacity, economical cost, stable and good filtering performance. Finally, simulation results are given to verify the viability and effectiveness of the APF and its control.**

I. INTRODUCTION

According to the proliferation and development of power electronics equipments in automatic production line, computer centre, hospital, etc; the power quality problems such as reactive power, current harmonics and neutral current in power distribution system is deteriorated [1]–[3]. Since the concept "Active ac Power Filter" was first developed by L. Gyugyi in 1976 [4], the research studies and practical usages of active power filters (APFs) for improving the power quality are prospering since then [5], [6]. APFs have the ability to overcome the abovementioned power quality problems. However, the initial and running costs are high due to the costs of semiconductor devices, digital controller, etc.

In this paper, a capacitive-coupled transformerless APF for three-phase four-wire power system is presented. With the usual APF functionalities, it requires a lower inverter rating than the conventional APF as in Fig. 1. Moreover, the proposed control strategy can strengthen the system damping and stability. Finally, simulation results are presented to verify its compensation capability and the proposed control strategy.

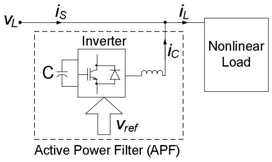


Figure 1. Active Power Filter (APF).

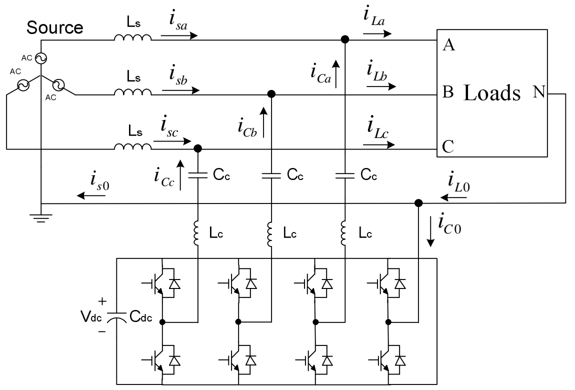


Figure 2. A capacitive-coupled transformerless APF.

II. CAPACITIVE-COUPLED TRANSFORMERLESS ACTIVE POWER FILTER IN THREE-PHASE FOUR-WIRE SYSTEM

Fig. 2 shows a three-phase four-wire capacitive-coupled transformerless APF. L_S is the system side inductance, C_c, L_c and C_{dc} are the coupling capacitance, inductance and dc capacitance and V_{dc} is the dc voltage. L_c and C_c values can be chosen via (1) and (2), where E is the inverter output voltage difference between two voltage level, T_S is the period of PWM, ΔI_{ripple} is the maximum output current ripple, k is a scale factor between 0.3 ~ 0.6. Q is the single-phase reactive power of the load, and $C = 1/\omega_f X_c$, where ω_f is the fundamental frequency.

$$L = k \cdot \frac{E \cdot T_S}{\Delta I_{ripple}} \qquad (1) \qquad \left(\frac{1}{X_c - X_L}\right) = \frac{Q}{V_s^2} \qquad (2)$$

III. ANALYSIS OF SYSTEM STABILITY AND DAMPING WITH FEEDBACK CONTROL STRATEGY

Fig. 3 (a) shows a single-phase equivalent circuit of the capacitive-coupled APF with no L_S consideration. Since the load impedance connected to the point of coupling is usually larger than L_S. Therefore, the loading effect can be neglected in order to simplify the analysis. And the control block diagram model is shown in Fig. 4(a). From Fig. 4 (a),

$$\frac{I_i(s)}{V_i(s)} = G_i(s) = \frac{sC_c}{s^2 L_c C_c + 1} \qquad (3)$$

With two poles and zero: $s_{p1,2} = \pm j / \sqrt{L_c C_c}$ and $s_z = 0$.

The harmonic resonance frequency can be expressed as:

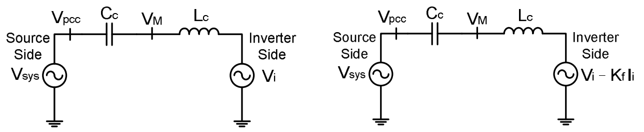
$$\omega_r = 1 / \sqrt{L_c C_c} \qquad (4)$$

For damping the LC structure, the usual method is by adding a damping resistor. However, the resistor value may not be enough to prevent the harmonics resonance. Even though increasing the damping resistance can increase the system damping, however, the loss will increase too. This paper replaces the function of the damping resistance by implement a coupling current feedback control strategy K_f. Fig. 3 (b) shows the single-phase equivalent circuit of the capacitive-coupled APF with current feedback control. From the control block diagram as shown in Fig. 4 (b),

$$\frac{I_i(s)}{V_i(s)} = G_i^{'}(s) = \frac{sC_c}{s^2 L_c C_c + sK_f C_c + 1} \qquad (5)$$

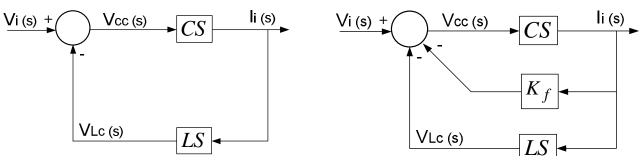
With two poles and zero:

$$s_{p1,2} = \frac{-K_f}{2L_c} \pm \frac{\sqrt{(K_f C_c)^2 - 4L_c C_c}}{2L_c C_c} \text{ and } s_z = 0.$$



(a) (b)

Figure 3. Single-phase equivalent circuit of the capacitive-coupled APF (a) without K_f control, (b) with K_f control.



(a) (b)

Figure 4. Control block diagram model of the capacitive-coupled APF (a) without K_f control, (b) with K_f control.

When K_f control is implemented, the poles $s_{p1,2}$ are being moved away from the jω axis, which enhances the system stability. Then, the harmonic resonance frequency is:

$$\omega_r = \frac{1}{\sqrt{L_c C_c}}, \ \xi = \frac{K_f}{2}\sqrt{\frac{C_c}{L_c}} \qquad (6)$$

, in which a damping ratio ξ is added to the system.

For the system voltage $V_{sys} = 155.5V$, switching frequency $f_{sw} = 5kHz$, dc-link voltage $V_{dc} = 30V$, inverter inject rated current $I_r = 8A$, $k = 0.4$. Via (1), Fig. 5 shows the relationship between ΔI_{ripple} (%) and minimum L_c required. Since the ΔI_{ripple} can be chosen between 15% and 25% of I_r, thus $L_c > 2mH$ as shown in Fig. 5. L_c is chosen to be $3mH$. If smaller current ripple is willing, larger L_c value can be chosen. C_c is chosen to be $81\mu F$ via (2).

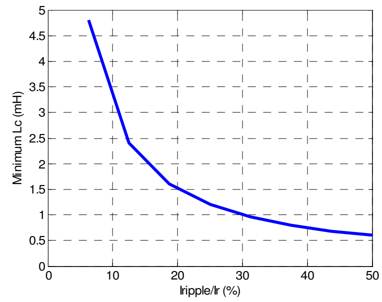


Figure 5. The relationship between ΔI_{ripple} (%) and minimum L_c required.

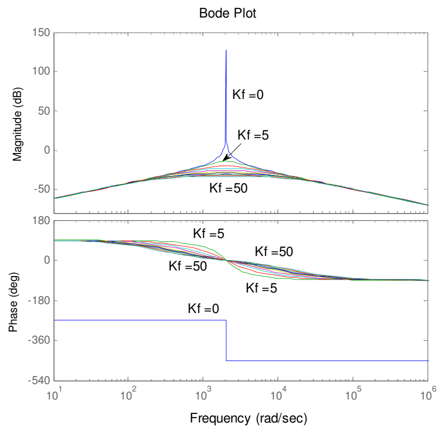


Figure 6. Bode plot of the transfer function $G_i^{'}(s)$ with no L_S.

Fig.6 shows a bode plot diagram of the transfer function $G_i^{'}(s)$. From Figs. 6, when K_f control is implemented, the original harmonic resonance at $\omega_r = 2028.6 rad/sec$ can be relaxed. And the two new poles are $s_{p1,2} = -166.7K_f \pm 2057613.2\sqrt{6.56nK_f^2 - 0.97\mu}$. For $\sqrt{6.56nK_f^2 - 0.97\mu} > 0$, $166.7K_f$ is always larger than $2057613.2\sqrt{6.56nK_f^2 - 0.97\mu}$ unless K_f equals ∞, thus $s_{p1,2}$ are located on the left of the jω axis. For $\sqrt{6.56nK_f^2 - 0.97\mu} < 0$, $s_{p1,2}$ are always located on the left of the jω axis. As a result, the system will be always stable after the implementation of K_f control. When K_f increases from 5 to 50, the gain margin (G.M.) and phase margin (P.M.) of $G_i'(s)$ are kept to be ∞, which verifies the proposed coupling current feedback control strategy for the capacitive-coupled APF.

When L_S is also being considered in the analysis, L_S value will affect the system harmonics resonance frequency. The larger the L_S value, the lower the harmonics resonance frequency ω_r and vice versa. With appropriate design of gain K_f, it can lessen the effects of the system harmonics resonance and also the system side inductance L_S.

IV. ANALYSIS OF SOURCE CURRENT VOLTAGE CONTROL

Fig. 7 shows the single-phase harmonic equivalent circuit, where i_{Ln} represents the n order harmonic load current. The APF is considered under voltage control mode, $v_{AF} = k_{Sn} \cdot i_{Sn}$. $Z_{Sn} = jn\omega L_s$ and Z_{PFn} represent the system side impedance and coupling impedance. i_{Sn} represents the source current harmonics contents. In ideal case, i_{Sn} should be zero and all the harmonic currents should be looped inside the APF and the load. When (7) is divided by i_{Ln}, it yields (8).

$$i_{Ln} = i_{Sn} + i_{PFn} \quad (7) \qquad K_{Sn} + K_{PFn} = 1 \quad (8)$$

K_{Sn} and K_{PFn} are the attenuation factor and loop factor, $K_{Sn} = i_{Sn} / i_{Ln}$, $K_{PFn} = i_{PFn} / i_{Ln}$.

Further simplify yields,

$$K_{Sn} = \frac{Z_{PFn}}{k_{Sn} + Z_{Sn} + Z_{PFn}} \quad (9) \qquad K_{PFn} = \frac{Z_{Sn} + k_{Sn}}{k_{Sn} + Z_{Sn} + Z_{PFn}} \quad (10)$$

In a perfect compensation, K_{Sn}=0 and K_{PFn}=1 should be achieved so that k_{Sn} should be very large. It can be equivalent to have a large resistor, k_{Sn}, connected in series with Z_{Sn}, as shown in Fig. 8. k_{Sn} can be treated as an harmonics attenuation factor, the larger the k_{Sn} value, the smaller the i_{Sn}. However, too large k_{Sn} value may cause system stability problem and also increase the power rating of the APF.

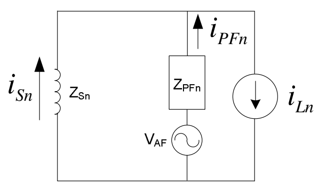


Figure 7. Single-phase harmonics equivalent circuit.

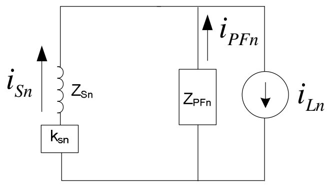


Figure 8. Detecting source current voltage mode equivalent circuit.

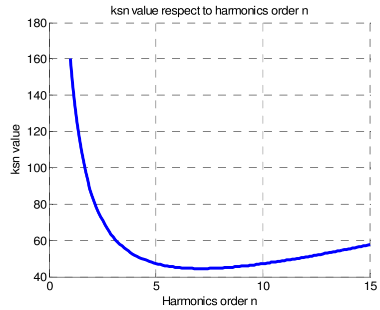


Figure 9. k_{Sn} value respects to different harmonics order n.

In order to simplify the determining process of k_{Sn} value, set $K_{Sn} = 0.2$. For $L_s = 2mH$, $L_c = 3mH$ and $C_c = 81\mu F$,

$$K_{Sn} = \frac{Z_{PFn}}{k_{Sn} + Z_{Sn} + Z_{PFn}} = 0.2 \quad (11) \qquad k_{Sn} = 4Z_{PFn} - Z_{Sn} \quad (12)$$

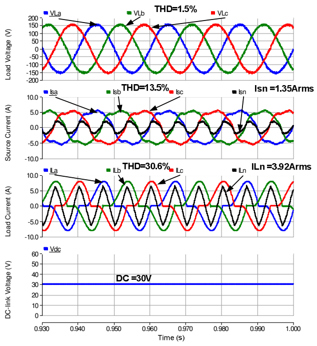
Fig. 9 shows different k_{Sn} value respects to different harmonics order n. For 2nd or higher harmonics order compensation, $k_{Sn} = 80$ will be enough.

V. SIMULATION RESULTS

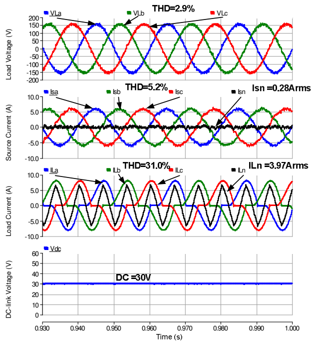
The simulation studies have been carried out using PSCAD/EMTDC. The reference voltage for the four-leg inverter of the APF is expressed as (13), and the trigger signals are determined by 3D direct PWM [3], [7].

$$v_{AFj} = k_{Snj} \times i_{Snj} \quad j=a,b,c, \quad (13)$$

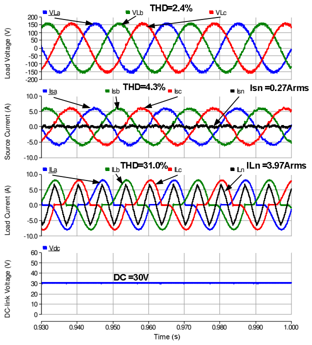
in which i_{Snj} is determined by instantaneous reactive power theory [8]–[9]. Moreover, $f_{sw} = 5kHz$ and $K_f = 40$. From Fig. 10 (a), when $k_{Sn} = 5$, the three-phase load and neutral currents have been compensated to THD=13.5% and 1.35Arms from 30.6% and 3.92Arms before compensation. Even though it satisfies the IEC 61 000-3-2 standard of THD_i <16% [10], the compensated results are not satisfactory because k_{Sn} is much smaller than 80. When $k_{Sn} = 150$, the three-phase load and neutral currents as shown in Fig. 10 (b) have been further compensated to THD=5.2% and 0.28Arms. However, the switching noise or ripple is larger. From Fig. 10 (c), when k_{Sn} is lowered to 80, the three-phase load and neutral currents have been compensated to THD=4.3% and 0.27Arms, which has the best compensating performance among three cases. The THD_v of load voltage for three cases fall within the IEEE standard 519:1992 (THD_v <5%) [11]. And the dc voltage required is 30V, which is greatly reduced compared with the minimum $V_{dc} \geq \sqrt{6}V_s = 270V$ in the conventional inductive-coupled two-level four-leg inverter [12]. This also illustrates the distinct characteristics of the capacitive-coupled APF. Fig. 11 shows that the reactive power can also be compensated for three k_{Sn} cases. It can be seen that the source current and voltage become almost in-phase after compensation. Compared with Fig. 11 (a), the power factor has been improved from 0.84 to 0.99.



(a) $k_{Sn} = 5$

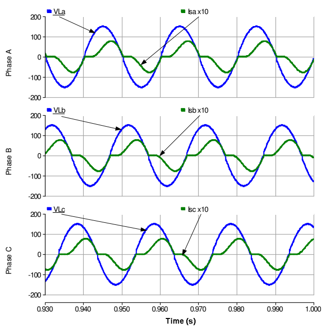


(b) $k_{Sn} = 150$

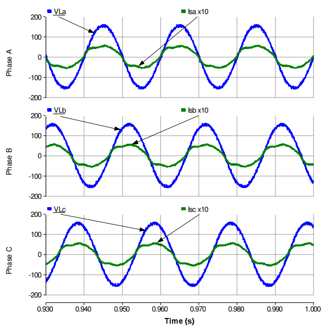


(c) $k_{Sn} = 80$

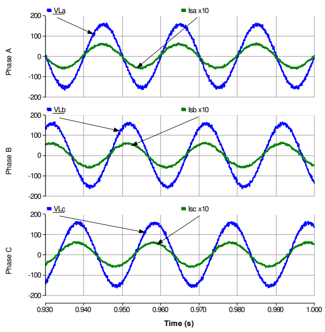
Figure 10. Before and after compensation with (a) $k_{Sn} = 5$, (b) $k_{Sn} = 150$, (c) $k_{Sn} = 80$.



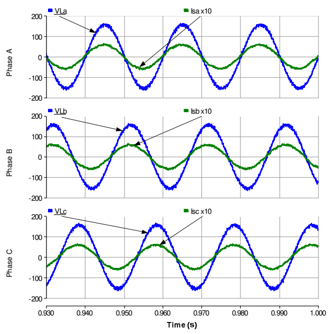
(a)



(b)



(c)



(d)

Figure 11. (a) Power factor before compensation, after compensation with (b) $k_{Sn} = 5$, (c) $k_{Sn} = 150$, (d) $k_{Sn} = 80$.

VI. Conclusion

In this paper, a low rating capacitive-coupled transformerless APF for reactive power, current harmonics and neutral current compensation in three-phase four-wire power system is presented. It can greatly reduce the VA rating of the APF without significantly deteriorate the compensation capability. Moreover, it can reduce the switching loss and EMI problems. A novel control strategy is proposed to strengthen the system damping and stability. Finally, simulation results verify the viability and effectiveness of the APF and its control strategy. And the capacitive-coupled APF is distinguished by low capacity, economical cost, stable performance, good filtering effect and easy realization.

Acknowledgment

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