A New Hybrid Active Power Filter (APF) Topology

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***Abstract*—In this paper, a new hybrid active power filter topology is presented. A higher-voltage, low-switching frequency insulated gate bipolar transistor (IGBT) inverter and a lower-voltage high-switching frequency metal oxide semiconductor field effect transistor (MOSFET) inverter are used in combination to achieve harmonic current compensation. The function of the IGBT inverter is to support utility fundamental voltage and to compensate for the fundamental reactive power. The MOSFET inverter fulfills the function of harmonic current compensation. To further reduce cost and to simplify control, the IGBT and MOSFET inverters share the same dc-link via a split capacitor bank. With this approach harmonics can be cancelled over a wide frequency range. Compared to the conventional APF topology, the proposed approach employs lower dc-link voltage and generates less noise. Simulation and experimental results show that the proposed active power filter topology is capable of compensating for the load harmonics.**

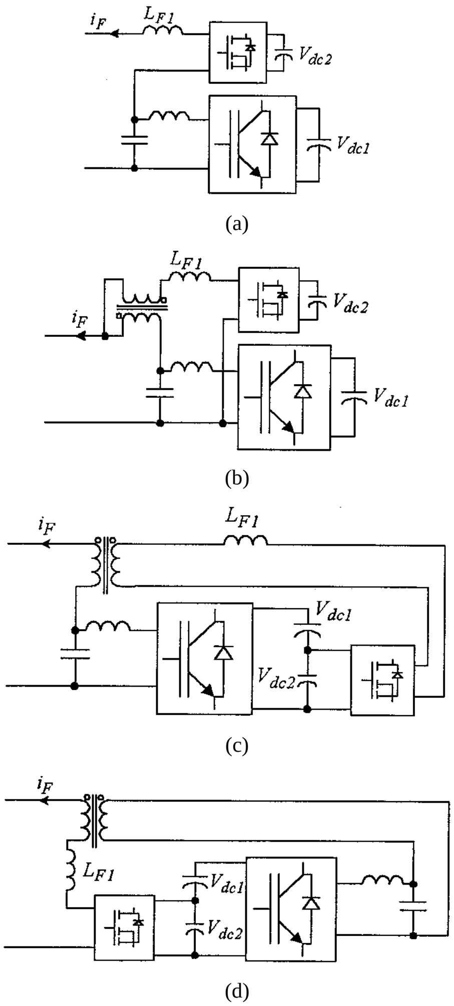
***Index Terms*—Hybrid active power filter, IGBT inverter, MOSFET inverter, DSP.**

I. INTRODUCTION

DUE to advancement in power electronics technology, active power filters (APF) continue to attract considerable attention. APF technology is the most efficient way to compensate for reactive power and cancel lower harmonics generated by nonlinear loads. Harmonic currents on the power system can distort the line voltage and lead to several adverse effects including equipment overheating, the malfunction of solid-state equipment and interference with communication systems [1]. Various active power filter topologies including hybrid-type as shown in Fig. 1(a) have been proposed [2], [3]. Some commercial APF units are currently available [4], [5]. References [2], [3] proposed a series connected hybrid active filter topology. In a three-phase version of this scheme, independent control of several series cascaded single-phase converter blocks is seen as a main disadvantage. Reference [3] discussed another variation of the series hybrid converter topology for adjustable speed drive systems.

In this paper, a new hybrid APF topology (Fig. 2) is proposed. The advantages of the approach are as follows.

1) A low switching frequency IGBT inverter is employed to support the input utility voltage and to compensate for reactive power.
2) A low voltage high switching frequency MOSFET inverter is employed for harmonic current compensation.



(a)

(b)

(c)

(d)

Fig. 1. Per-phase equivalent circuits of series and parallel connected hybrid-type active power filter topologies. (a) Series-type. (b) Parallel-type. (c) DC-link shared hybrid (high-frequency isolated transformer). (d) DC-link shared hybrid (low-frequency isolated transformer).

3) The IGBT and MOSFET inverters share the same dc-link via a split capacitor bank, thus simplifies control.
4) The required dc-link voltage of the IGBT inverter is lower, since its main function is to support fundamental voltage. Therefore, the proposed active power filter system operates at lower voltage compared to the conventional single stage APF.
5) By employing proper shielding in the isolation transformer at the output of the high-switching frequency inverter, overall noise can be reduced.
6) The proposed hybrid active power filter system is inherently more stable and can adapt to sudden load changes.
7) In large industrial systems, the function of the IGBT inverter can be replaced by a rotating synchronous machine.

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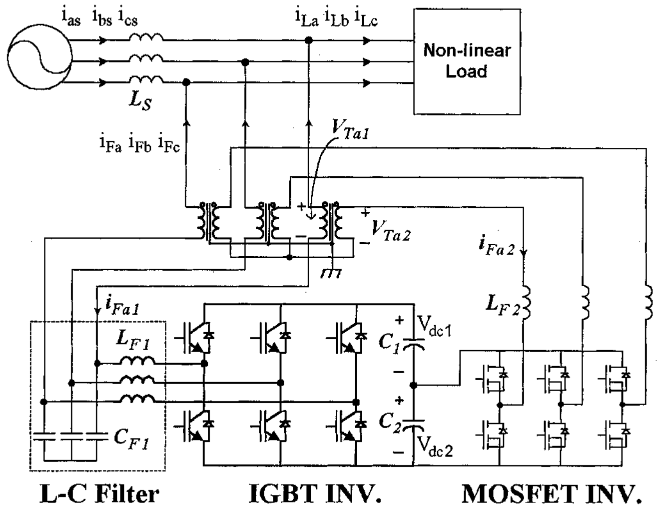


Fig. 2. Proposed hybrid active power filter topology.

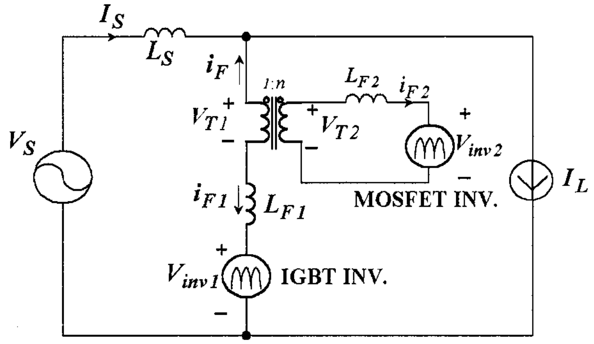


Fig. 3. Single-phase equivalent circuit of proposed topology.

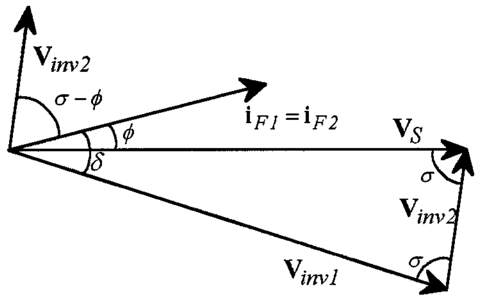


Fig. 4. Vector diagram for two independent dc voltage controls.

The function of the IGBT inverter is to support utility fundamental voltage and to compensate for fundamental reactive power. The MOSFET inverter fulfills the function of harmonic current compensation. To further reduce the cost and to simplify the control, the IGBT and MOSFET inverters share the same dc-link with a reduced voltage. Simulation and experimental results show that the proposed hybrid active power filter is capable of compensating for the load harmonic currents and the reactive power in a three-phase system.

II. PROPOSED TOPOLOGY

Fig. 1 shows possible APF topologies with series and parallel combinations. A series type topology shown in Fig. 1(a) has been proposed in [2], [3]. Since this topology requires the regulation of two dc-link voltages per phase, in a three-phase version six dc-link voltages need to be controlled. Fig. 1(b) shows a parallel type hybrid topology in which voltage rating of low frequency inverter is two times utility voltage to make zero voltage across the transformer even though the current is reduced. Common dc-link voltage shared topologies are shown in Fig. 1(c) and (d). Owing to zero fundamental voltage across the transformer, in this paper, a topology with high-frequency isolated transformer is adopted and is further explored.

Fig. 2 shows the proposed APF topology which employs an IGBT and a MOSFET inverter, a shared capacitor bank, and a three-phase isolation transformer. The function of the IGBT inverter with an output L-C filter is to support the utility voltage at the point of common coupling (PCC) and also to supply any reactive power. The MOSFET inverter is a low-voltage high-frequency type, which shares the same dc-link voltage with the IGBT inverter, and is coupled to a transformer as shown. Fig. 3 shows a per-phase equivalent circuit of the hybrid APF and load system for harmonics, where I_L, I_F, and I_S denote the load, APF harmonic current, and utility current, respectively, and V_T denotes the voltage of a transformer. The high dc-link voltage $V_{\rm dc1}+V_{\rm dc2}$ is regulated via the control of the fundamental current I_{F1} which is synchronized with the utility voltage just in case without reactive power compensation. On the other hand, the low dc-link voltage $V_{\rm dc2}$ control is achieved by adjusting the phase angle δ as shown in Fig. 4. Utility voltage and APF current can be written as

$$
\begin{aligned}
\mathbf{V}_s &= V_s\angle 0^\circ\\
\mathbf{I}_{F1} &= I_{F1}\angle\phi\\
\mathbf{V}_{\rm inv1} &= V_s\angle\phi-\delta\\
\mathbf{V}_{\rm inv2} &= V_s\angle\sigma
\end{aligned}
\tag{1}
$$

where, ϕ is determined by reactive power compensation. The dc-link voltages of the IGBT and MOSFET inverters are the functions of $\cos\delta$ and $\cos(\sigma-\phi)$, respectively. The relationship of those angles is given by

$$\sigma = 90^\circ - \frac{\phi-\delta}{2}. \tag{2}$$

The function of the MOSFET inverter is to compensate for harmonics generated by the nonlinear load. Let us assume that the voltage of the IGBT inverter has the same of the utility voltage

$$V_{\rm inv1} = V_s \tag{3}$$

where, $V_{\rm inv1}$ is considered as the fundamental component. If the IGBT inverter is adequately controlled, the following voltage equation is given:

$$V_{T1} = V_{T2} \approx 0 \tag{4}$$

where, the voltages of the primary and secondary side of transformer are considered without harmonics. Therefore, the inverter dc capacitor voltage of the MOSFET inverter can be much smaller, so that harmonic current compensation can be achieved with a low inverter rating. Depending on the turns ratio of the transformer, compensated current is obtained as

$$i_F = -i_{F1} = -n\cdot i_{F2} \tag{5}$$

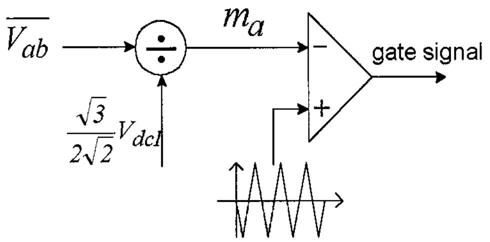
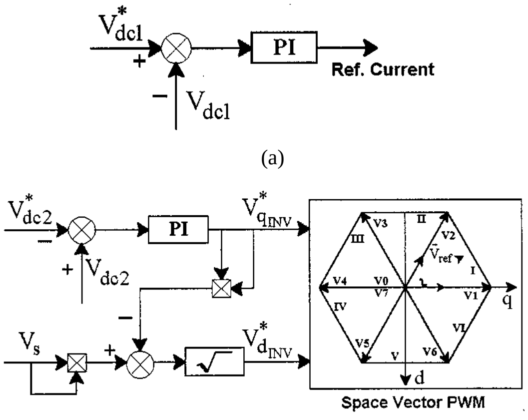


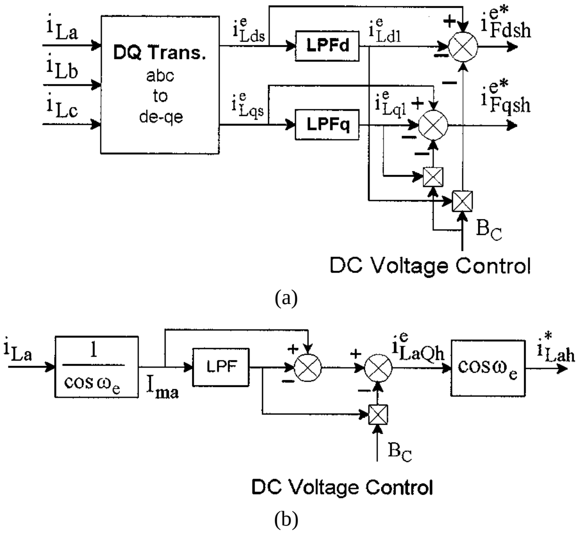
Fig. 5. Block diagram of IGBT inverter control system.



(a)

(b)

Fig. 6. DC voltage control. (a) IGBT inverter. (b) MOSFET inverter.



(a)

(b)

Fig. 7. Block diagrams for harmonic reference current generator. (a) Harmonic current reference generator on the synchronous reference frame. (b) Per-phase harmonic reference generator (PPHRG).

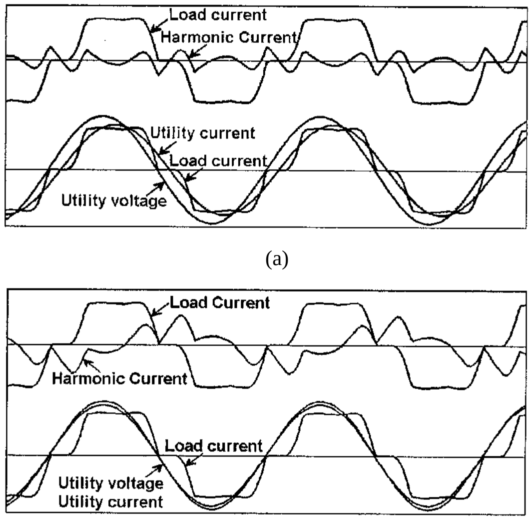
where, n is the turns ratio of the transformer. The fundamental component of the output voltage of the IGBT inverter is given by

$$V_{\mathrm{ab,rms}} = \frac{\sqrt{3}}{2\sqrt{2}} V_{\mathrm{dc1}} m_a \tag{6}$$

where, m_a is the modulation index. The fundamental voltage is dependent on the dc-link voltage and modulation index. Assuming that the utility voltage is fixed and dc-link voltage may be changed instantaneously, the modulation index can be given by

$$m_a = \frac{2\sqrt{2} V_{\mathrm{ab,rms}}}{\sqrt{3} V_{\mathrm{dc1}}} \tag{7}$$

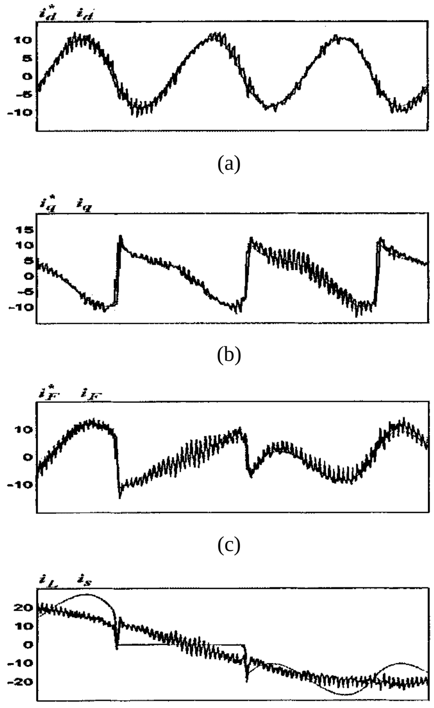
and its comparison with the triangular carrier signal as shown in Fig. 5 is used to control the output terminal voltage of the inverter.



(a)

(b)

Fig. 8. Comparision of two harmonic reference current generators: (a) without reactive power compensation and (b) with reactive power compensation.



(a)

(b)

(c)

(d)

Fig. 9. Control response. (a) D-axis reference and real currents. (b) Q-Axis reference and real currents. (c) Phase reference and real currents. (d) Load and utility currents.

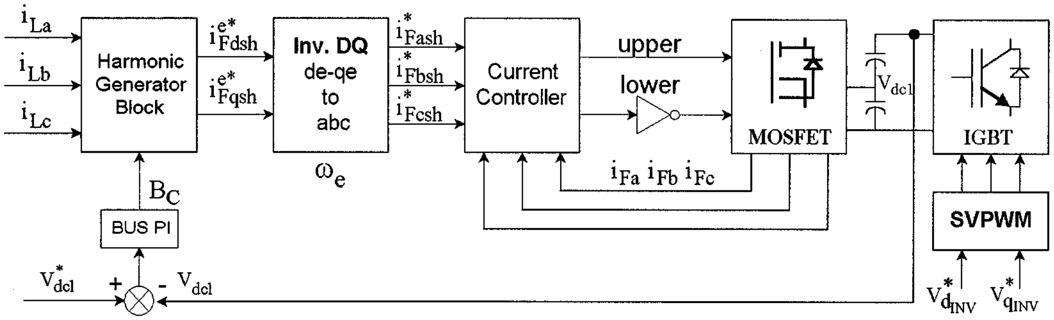
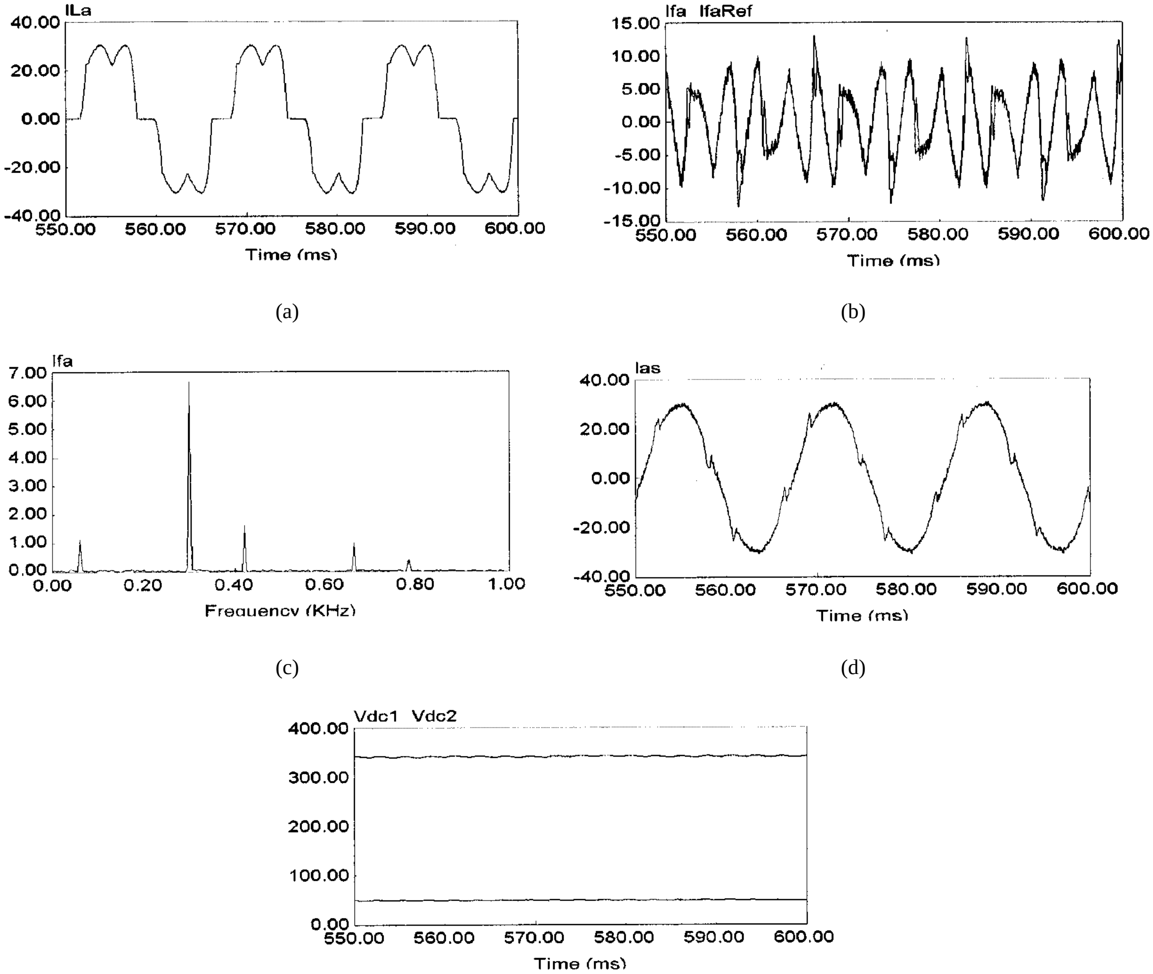


Fig. 10. Closed loop control block diagram of the proposed hybrid active power filter system.



(a) (b)

(c) (d)

(e)

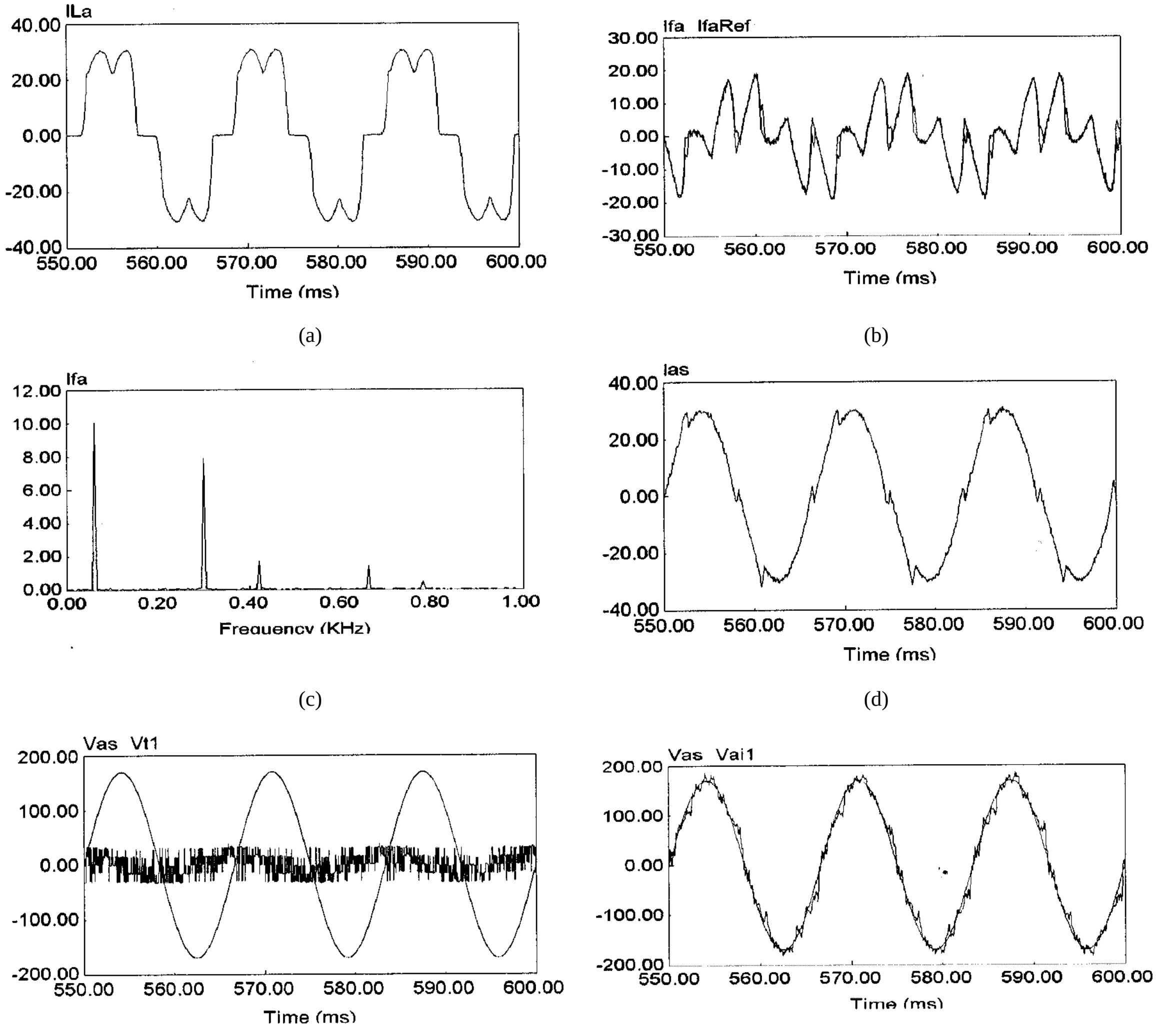
Fig. 11. Simulation results without reactive power compensation. (a) Load current. (b) APF reference (IfaRef) and real (Ifa) currents. (c) Harmonic analysis of APF current (RMS: 5A). (d) Utility current (THD: 7.3%). (e) DC voltages.

III. DC VOLTAGE CONTROL AND HARMONIC REFERENCE CURRENT GENERATOR

To design the control system and harmonic reference current generator, the dq transformation method is used owing to its advantages to achieve harmonic cancellation and thus obtain high performance of the controller. The stationary circuits are transformed to rotationary circuits and rotationary circuits to stationary circuits. To adopt a useful equivalent matrix formulation, the following three-element matrix vectors are expressed by using dq transformation matrix $\mathbf{T}(\theta)$ and inverse dq transformation matrix $\mathbf{T}^{-1}(\theta)$

$$\mathbf{f}_{dqs} = \mathbf{T}(\theta)\mathbf{f}_{abcs}, \tag{8}$$

$$\mathbf{f}_{abcs} = \mathbf{T}^{-1}(\theta)\mathbf{f}_{dqs}, \tag{9}$$



(a) (b)

(c) (d)

(e) (f)

Fig. 12. Simulation results with reactive power compensation. (a) Load current. (b) APF reference (IfaRef) and real (Ifa) currents (RMS: 9.2A). (c) Harmonic analysis of APF current. (d) Utility current (THD: 7.4%). (e) Utility voltage and IGBT inverter terminal voltage (Vail). (f) Utility and transformer (Vtl) voltages.

where, the $\mathbf{f}$ variable denotes the current or voltage quantities and the transformation matrix is given as

$$\mathbf{T}(\theta)=\frac{2}{3}\begin{bmatrix}\sin\theta & \sin\left(\theta-\frac{2}{3}\pi\right) & \sin\left(\theta+\frac{2}{3}\pi\right)\\ \cos\theta & \cos\left(\theta-\frac{2}{3}\pi\right) & \cos\left(\theta+\frac{2}{3}\pi\right)\\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}\end{bmatrix}. \tag{10}$$

Assuming a balanced voltage of the IGBT inverter, voltage equation can be expressed as

$$\begin{aligned}V_{a_{\mathrm{INV}}}&=\sqrt{2}V_s\sin(\omega t-\delta)\\ V_{b_{\mathrm{INV}}}&=\sqrt{2}V_s\sin\left(\omega t-\delta-\frac{2\pi}{3}\right).\\ V_{c_{\mathrm{INV}}}&=\sqrt{2}V_s\sin\left(\omega t-\delta+\frac{2\pi}{3}\right).\end{aligned} \tag{11}$$

Taking the dq transformation, an IGBT inverter reference voltage vector is obtained in a synchronous reference frame as follows:

$$\begin{aligned}\mathbf{V}_{\mathrm{inv1}}&=\begin{bmatrix}V_{d_{\mathrm{INV}}}\\ V_{q_{\mathrm{INV}}}\end{bmatrix}=\mathbf{T}(\theta)\mathbf{V}_{abcs_{\mathrm{INV}}}\\ &=\sqrt{2}V_s\begin{bmatrix}\cos\delta\\ -\sin\delta\end{bmatrix}\end{aligned} \tag{12}$$

where, δ is the phase angle, considering only the power flowing into the IGBT inverter. Therefore, δ can be calculated as

$$\begin{aligned}\delta&=-\sin^{-1}\left(\frac{V_{q_{\mathrm{INV}}}}{\sqrt{2}V_s}\right)\\ &=\cos^{-1}\left(\frac{V_{d_{\mathrm{INV}}}}{\sqrt{2}V_s}\right),\quad -90^\circ<\delta<90^\circ.\end{aligned} \tag{13}$$

Active power filter current must be synchronized with the utility voltage V_s without reactive power compensation in order to get unity power factor on utility side. Also, the MOSFET inverter voltage is equal to the transformer voltage, neglecting the inductance L_{F2}. Therefore, the high dc-link voltage depends on the fundamental current of the IGBT inverter with phase angle δ. Low dc voltage is finally controlled by changing the phase angle δ which is nearly zero at steady state. In the control block diagram, voltage references for IGBT inverter are obtained by

$$V^*_{d_{\mathrm{INV}}}=\sqrt{V_s^2-V^{*2}_{q_{\mathrm{INV}}}}. \tag{14}$$

Fig. 6 shows the control block diagram for two separate dc voltage controls. High dc-link voltage error is applied to the fundamental reference current, and PWM input can be obtained by controlling the low dc voltage. Either sinusoidal PWM or space vector PWM technique can be easily adopted for this application. Block diagrams for harmonic reference current generator are shown in Fig. 7. Depending on the way to compensate for reactive power, two harmonic reference current generators can be used [6]. In order to subtract the fundamental component, the low pass filter is designed to cancel higher frequency components on the synchronous reference frame with the fundamental angular frequency of the utility, ω_e. Harmonic reference currents are obtained as

$$\begin{bmatrix} i^{e*}_{Fdsh} \\ i^{e*}_{Fqsh} \end{bmatrix} = \begin{bmatrix} i^{e}_{Lds} \\ i^{e}_{Lqs} \end{bmatrix} - (1 + B_C) \begin{bmatrix} i_{Ld1} \\ i_{Lq1} \end{bmatrix} \tag{15}$$

where, i_{Ld1} and i_{Lq1} are the fundamental load currents, and B_C is the output of the dc-link voltage controller of the IGBT inverter and indicates active or reactive power components to control the dc-link voltage of the IGBT inverter. Thus, dc-link voltage control of the IGBT inverter is achieved by fundamental currents which have dc component on the synchronous dq reference frame. To obtain unity power factor as shown in Fig. 7(b), the instantaneous magnitude of a-phase current can be written as

$$I_{ma} = \frac{I_{La}}{\cos \omega_e} \tag{16}$$

where, I_{ma} represents dc side current component. Higher harmonics are cancelled with low pass filter as well. To generate a reference current per phase, a reference current of phase-a can be simplified

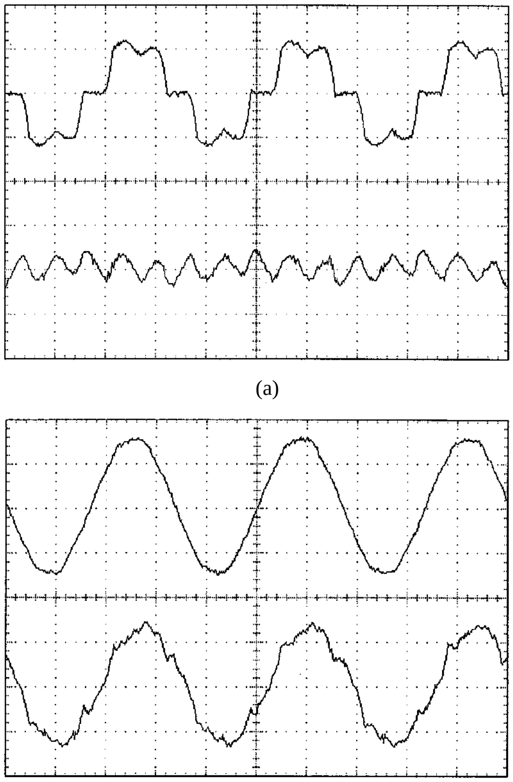
$$I^*_{Lah} = I^e_{LaQh} \cos \theta \tag{17}$$

where, I^*_{Lah} is a harmonic reference current of phase-a. Unity power factor is obtained by per-phase harmonic reference generator, PPHRG. In Fig. 8, two harmonic generators are compared under balanced load condition. Fig. 8(a) includes harmonic current compensation without reactive power compensation using a harmonic current reference generator as shown in Fig. 7(a). Using another generator in Fig. 7(b), both of compensation can be achieved as shown in Fig. 8(b). Control responses are shown with the harmonic reference currents in the synchronous dq frame in Fig. 9(a) and (b). Fig. 9(c) shows the response for phase-a reference current. Final compensated utility current is shown in Fig. 9(d). Total control block diagram is shown in Fig. 10. The proposed hybrid active power filter system comprises of a harmonic reference current generator, separate voltage controllers, hysteresis current controller, space vector PWM algorithm, and the two inverters.

IV. SIMULATION AND EXPERIMENTAL RESULTS

TABLE I
PARAMETERS OF HYBRID ACTIVE POWER FILTER

Line to line voltage	208 [V]
IGBT inverter switching frequency	3 [kHz]
MOSFET inv. average switching frequency	50[kHz]
Transformer turn ratio	1 : 1
DC capacitor C_1	290[V], 2000 [uF]
DC capacitor C_2	50[V], 5500 [uF]
L-C filter cut-off frequency	1.5 [kHz]
L-C filter inductor L_{F1}	500 [uH]
MOSFET inverter inductor L_{F2}	100 [uH]
L-C filter capacitor C_{F1}	20 [uF]
High dc voltage V_{dc1}	400 [V]
Low dc voltage V_{dc2}	50 [V]


(a)

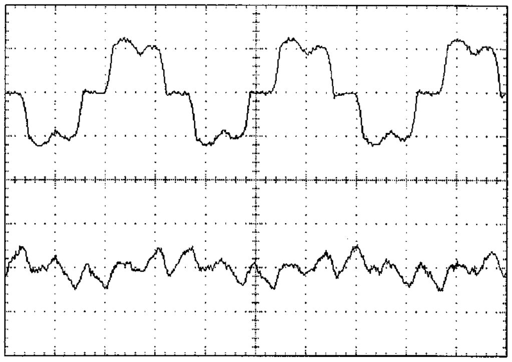
(b)

Fig. 13. Experimental results without reactive power compensation (voltage: 100 V/div, current: 10 A/div). (a) Load current and APF current. (b) Utility voltage and current.

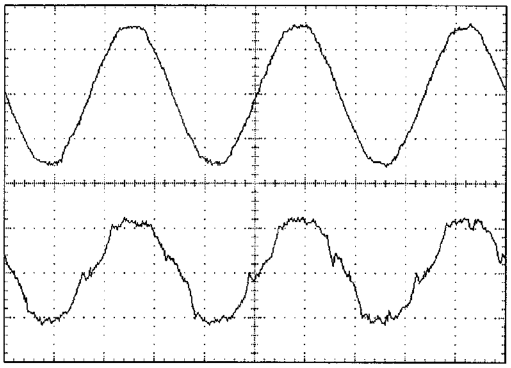
Simulation results are shown in Fig. 11 and 12. The digital simulation for a hybrid active power filter system was performed using PSIM simulation tool which can be linked with a C language program. Non-linear load harmonics are generated by a three-phase diode rectifier. Table I lists the main parameters used in the circuit. The dc-link voltage of IGBT inverter is obtained from (6)

$$\begin{aligned} V_{\mathrm{dc1}} &= \frac{2\sqrt{2}}{\sqrt{3}} V_{\mathrm{ab,rms}} \quad (m_a = 1) \\ &\approx 339.4\ \mathrm{V} \end{aligned} \tag{18}$$

by taking the maximum modulation index m_a. To achieve a cost free low-voltage low-frequency inverter, IGBT inverter switching frequency is selected as 3 kHz, the low dc voltage reference of the MOSFET inverter as 50 V, and the dc-link capacitance is reduced. The power ratings of IGBT and MOSFET



(a)



(b)

Fig. 14. Experimental results without reactive power compensation (voltage: 100 V/div, current: 10 A/div). (a) Load current and APF current. (b) Utility voltage and current.

inverters are 1.8 kVA and 264 VA without reactive power compensation and 3.3 kVA and 485 VA with reactive power compensation, respectively. Figs. 13 and 14 show experimental results with and without reactive power compensation. The proposed hybrid active power filter system is implemented on TI DSP, TMS320F243, which has a fixed-point arithmetic [7].

V. CONCLUSION

In this paper, a new hybrid active power filter topology has been presented. The high-voltage low-frequency IGBT inverter can support the utility fundamental voltage and compensate for fundamental reactive power. The low-voltage high-frequency MOSFET inverter fulfills the function of harmonic current compensation. By sharing the same dc-link voltage for the two inverters, the topology can be simplified. Finally simulation and experimental results validate the system performance.

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Dr. Enjeti received the IEEE-IAS Second and Third Best Paper Award in 1993, 1996, 1998, and 1999, respectively, the Second Best IEEE-IAS Transaction Paper published in mid-year 1994 to mid-year 1995 Awards, the IEEE-IAS Magazine Prize Article Award in 1996, and the select title “Class of 2001 Texas A&M University Faculty Fellow” Award for demonstrated achievement of excellence in research, scholarship and leadership in the field. He is a member of the IEEE IAS Executive board and the Chair of the Standing Committee on “Electronic Communications.” He is a registered professional engineer in the state of Texas.