Comparison Among PPF, APF, HAPF and A Combined System of A Shunt HAPF and A Shunt Thyristor Controlled LC

Sut-Ian Ho[2], Chi-Seng Lam[1,2], Man-Chung Wong[1,2]
1 - *State Key Laboratory of Analog and Mixed-Signal VLSI, University of Macau, Macao, China*
2 - *Department of Electrical and Computer Engineering, Faculty of Science and Technology, University of Macau, Macao, China*
E-mail: cslam@umac.mo or C.S.Lam@ieee.org

***Abstract*—To compensate the reactive power and current harmonic issues of the distribution power system, different power filters were developed. In this paper, three conventional power filters and a proposed compensator will be discussed, designed and compared to solve the reactive power and current harmonic problems of a three-phase three-wire power system. These conventional filters are: passive power filter (PPF), active power filter (APF) and hybrid active power filter (HAPF). The proposed compensator (HAPF//TCLC) is a combined configuration of a shunt HAPF and a shunt thyristor controlled inductor capacitor (TCLC). These compensating devices of PPF, APF, HAPF and HAPF//TCLC are examined about the ability of dealing with excessive compensating reactive power due to the loading change. Moreover, PSCAD simulation results are given in order to verify that the proposed compensator has good compensating performances on dealing with both designed and excessive load reactive power under low inverter rating.**

Keywords—Passive Power Filter (PPF); Active Power Filter (APF); Hybrid Active Power Filter (HAPF); Shunt Hybrid Active Power Filter and Shunt Thyristor Controlled Inductor Capacitor Filter (HAPF//TCLC)

I. INTRODUCTION

With the development of science and technology in the society, the demand for power electronic equipment applications by customers is increasing. More and more electronic devices are connected to the power grid, hence they cause a lot of harmonics and reactive power fed back into the power network to deteriorate the power quality [1], [2]. It presents in lower power factor (*PF*) with generated reactive power and higher total harmonic distortion of current (*THDi*) caused by current harmonics with non-triplen and odd harmonic orders. Since with higher *THDi*, the problems like overheat and malfunction in equipments would happen more easily; and lower *PF* would lead to more system losses and lower system stability. Therefore, electrical customers are usually charged with extra cost for poor power factor. So to improve the power quality have become important issues; for the above reasons, different types of distributed power quality compensators continuously emerge, which are installed between the power grid and the loads as shown in Fig. 1, In Fig. 1, v_{sx} and v_{Lx} are the source and load voltage; i_{sx}, i_{Lx} and i_{cx} are the system, load and compensating currents; L_{sx} is the source impendence; L_L and R_L are the nonlinear load inductor and resistor which connected to a six-pulse diode rectifier; L_{Lx} and R_{Lx} are the inductive load inductors and resistors, and "*x*" denotes the phase *a*, *b* or *c*.

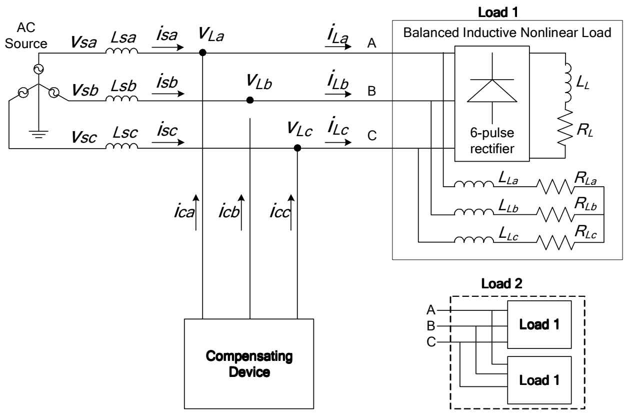

Fig. 1. The compensator is installed in a 3-phase 3-wire distributed power system with balanced inductive nonlinear loads.

Begin from the middle of 1940s after the first passive power filters (PPFs) was installed, PPFs have been rapidly and widely applied for compensating current harmonics and reactive power with the advantages of low cost, simple structure and high cost efficient [3]. However, PPFs are designed for specific system loads with low dynamic performance, and they are affected easily by the system load variations [4], [5]. Then until 1976, the concept of active power filter (APF) was proposed for system power quality compensation [3]. APFs have the advantage of get over the problems of PPFs; but their costs are more expensive than PPFs because of their high DC-link voltage, which reduce the extensive use of APFs [4], [5]. Afterwards, different hybrid active power filter (HAPF) topologies which consist of PPFs with series or parallel connected APFs in the distributed system were developed [4]-[8]. One of the HAPF topologies, an inductor and capacitor hybrid active power filter (LC-HAPF) was proposed in 2002 [6], which required lower DC-link voltage rating compared with APFs due to the compensating voltage drops on the capacitor of the passive part [7]. So such LC-HAPFs are cheaper than APFs, but more expensive than PPFs. Yet, the reactive power compensation range of LC-HAPFs is small than APFs [8]. So when the system load changes too much and causes the load reactive power excesses the designed compensation range of LC-HAPFs, the excessive part of the load reactive power cannot be compensated until

978-1-4799-8641-5/15/$31.00 ©2015 IEEE

either the coupling capacitor of the original compensator is re-designed and changed or increasing the DC-link voltage level. However, the first solution may be troublesome if the compensator has already been installed in the distributed system and the second solution may lose its low inverter rating characteristics.

In this paper, a novel combined system of a shunt hybrid active power filter and a shunt thyristor controlled inductor capacitor (HAPF//TCLC) are proposed and discussed. The TCLC filter of the proposed compensator is used to deal with the extra part of the compensating reactive power related to the existed HAPF design. The proposed HAPF//TCLC compensator would be compared with PPF, APF and LC-HAPF in terms of compensating performances. And the active inverter part voltage rating (V_{DC}) of APF, HAPF and HAPF//TCLC are also compared and investigated. Moreover, PSCAD is used as the simulation platform, and current quality compensation simulations are done under a 3-phase 3-wire distributed power system with balanced inductive nonlinear load change and excessive load reactive power (Q_{Lx}). In the following, Section II shows the review of PPF, APF and HAPF designs. Then the structure and control of HAPF//TCLC are studied in Section III. The simulation verification for HAPF//TCLC in comparisons to PPF, APF and HAPF is given in Section IV. Section V will draw the conclusion.

II. Conventional Power Filters (PPF, APF, HAPF)

In this selection, PPF, APF and HAPF are introduced and their parameter designs are also studied. A PPF basically has a capacitor (C_{xn}) and an inductor (L_{xn}) connected in series for an n^{th} order harmonic filter branch, as shown in Fig. 2. Each branch can provide a low impedance at the tuned n^{th} order harmonic frequency to filter out the related load harmonic current. C_{xn} and L_{xn} are designed by (1) and (2) in [9],

$$C_{xn} = \frac{Q_{cxn}}{V_L^2 \omega_1} \frac{1-n^2}{n^2} \qquad (1)$$

$$L_{xn} = \frac{1}{n^2 \omega_1^2 C_{xn}} \qquad (2)$$

where Q_{cxn} is the n^{th} branch compensating reactive power, ω_1 is the fundamental harmonic angular frequency. When $n = 1$, it means the component is fundamental, that is $Q_{cx1} = Q_{cxF}$, where the subscript "F" means fundamental.

An APF has an inductor (L_x) in each phase which is connected to a voltage source inverter (VSI), as shown in Fig. 3, and L_x can be designed by (3) [10],

$$L_x = \frac{V_{DC}}{4 f_{sw} I_{ripple}} \qquad (3)$$

where f_{sw} is the switching frequency of the VSI switching devices, and I_{ripple} is the ripple of the compensating current. APF requires a high V_{DC} to support the VSI for compensation, and it has a better dynamic compensation performance than PPF. The DC-link operating voltage (V_{DC}) is chosen to be larger than two times of the source peak voltage [10], or it can be calculated by the minimum DC-link voltage method [11]. Also, the VSI control method is based on the instantaneous p-q theory [12] and the hysteresis current control [13].

A HAPF has a coupling inductor (L_x) and capacitor (C_x) in series in each phase, which are then connected to the VSI like APF, so it can keep the dynamic compensation performances as APF [14], as shown in Fig. 4. Moreover, the HAPF requires much smaller V_{DC} rating than the APF, as the compensating voltage drops on the C_x. The parameters of HAPF (C_x and L_x) can be designed in the same way as the PPF in [9], and the required V_{DC} can be calculated by using the minimum DC-link voltage method as in [14], [15], [16]. The control method of HAPF is also based on the instantaneous p-q theory [12], the hysteresis current control [13] and the adaptive DC-link voltage control [14], [15].

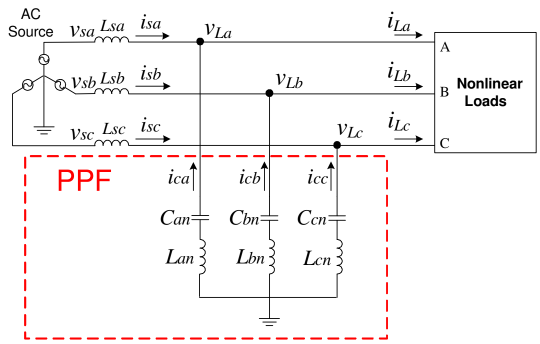

Fig. 2. The 3-phase 3-wire PPF compensator

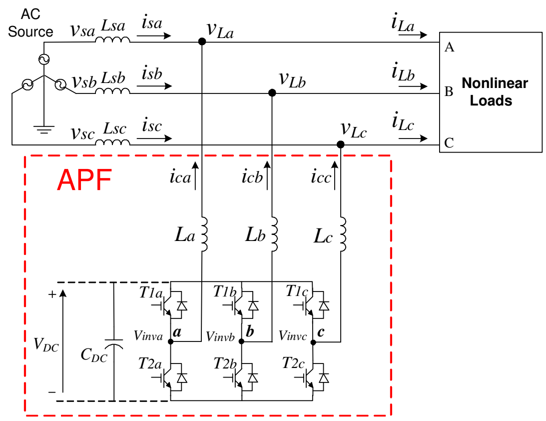

Fig. 3. The 3-phase 3-wire APF compensator

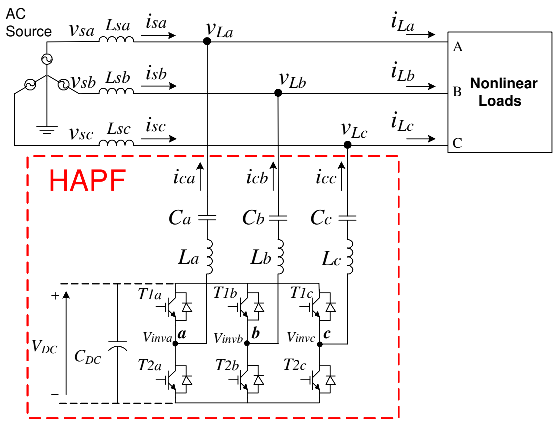

Fig. 4. The 3-phase 3-wire HAPF compensator

III. THE PROPOSED COMBINED SYSTEM OF A SHUNT HAPF AND A SHUNT THYRISTOR CONTROLLED LC

Since a pure HAPF has a lower V_{DC} rating than APF, thus a combined system of a shunt HAPF and a shunt thyristor controlled inductor capacitor (HAPF//TCLC) also has a low V_{DC} rating characteristic for the HAPF part as well. The circuit configuration and the control block diagram for the proposed HAPF//TCLC are shown in Figs. 5 and 6. The single-phase total compensating reactive power (Q_{cx}) of HAPF//TCLC is offered by both HAPF ($Q_{cx(HAPF)}$) and TCLC ($Q_{cx(TCLC)}$).

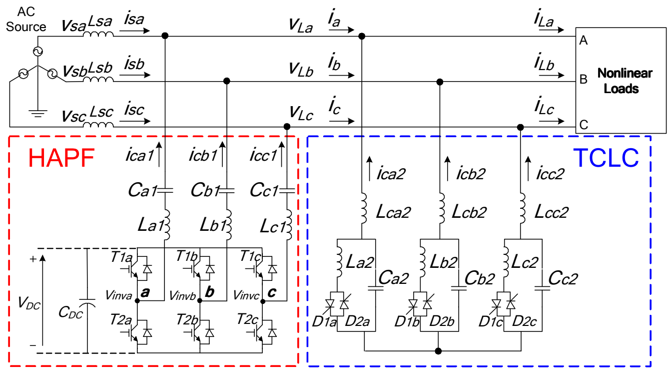

Fig. 5. The proposed 3-phase 3-wire HAPF//TCLC compensator

For the TCLC part in Fig. 5, the TCLC coupling inductor (L_{cx2}) is roughly designed by (4) [17] in this paper,

$$L_{cx2} = \frac{V_{Lcx2}}{\omega_{TCLC} I_{cx2}} \tag{4}$$

where ω_{TCLC} is the switching angular frequency of the bidirectional thyristor switches (D_{1x} and D_{2x}) and equals to the system angular frequency (ω); V_{Lcx2} is the voltage across L_{cx2} and I_{cx2} is the TCLC compensating current, where V_{Lcx2} and I_{cx2} are small values when TCLC does not provide compensating reactive power (i.e. $Q_{cx(TCLC)} = 0$). Moreover, the capacitor (C_{x2}) and the inductor (L_{x2}) of the TCLC part can be designed from (5) which referred to [18],

$$Q_{cx(TCLC)} = \frac{V_{Lx}^2}{\dfrac{\pi X_{Lx2} X_{Cx2}}{X_{Cx2}(2\pi - 2\alpha_x + \sin 2\alpha_x) - \pi X_{Lx2}} + X_{Lcx2}} \tag{5}$$

where X_{Lx2}, X_{Cx2} and X_{Lcx2} are the reactance values of the L_{x2}, C_{x2} and L_{cx2}. When the firing angle (α_x) is $180°$, the maximum capacitive $Q_{cx(TCLC)}$ is given and C_{x2} can be calculated; and when $\alpha_x = 90°$ with the given maximum inductive $Q_{cx(TCLC)}$, L_{x2} can be obtained. Moreover, the TCLC part can be controlled by generating the thyristor controlled signal according to the firing angle (α_x) from (5) and the amount of $Q_{cx(TCLC)}$. On the other hand, the design of the HAPF part in Fig. 5 is the same as the pure HAPF, so the HAPF parameters and V_{DC} can be referred to the HAPF in Section II.

But the HAPF part control is a bit different with the pure HAPF, because the 3-phase dc component of the HAPF compensating reactive power ($Q_{cF(HAPF)}$) is set to be a fixed amount as the compensating reactive power reference ($Q_{cF(HAPF)}*$) which is equal to the original designed fundamental compensating reactive power of the pure HAPF for the unchanged load case. And the 3-phase ac component of the HAPF compensating reactive power (Q_{cH}) equals to the reverse-directional harmonic components that generated by the load and the TCLC part. When the load inductive reactive power (Q_{Lx}) falls outside the designed compensation range of the HAPF part of the HAPF//TCLC by additional inductive nonlinear loads (i.e. $|Q_{Lx}|<|Q_{cxF(HAPF)}|$ or $|Q_{Lx}|>|Q_{cxF(HAPF)}|$), the HAPF part would keep on providing a fixed amount of the dc compensating reactive power ($Q_{cF(HAPF)}*$) to the power system and the TCLC part can deal with the compensating reactive power difference by subtracting the fixed HAPF compensating reactive power reference ($Q_{cF(HAPF)}*$) from the dc compensating reactive power (Q_{cxF}) of the TCLC part (i.e. $Q_{cx(TCLC)} = Q_{cxF} - Q_{cxF(HAPF)}*$) as shown in Fig. 6. Moreover, when the load reactive power is the same as the HAPF designed range (i.e. $|Q_{Lx}| = |Q_{cxF(HAPF)}*|$), the TCLC part would provide approximately zero or very less compensating reactive power (i.e. $Q_{cxF(HAPF)}* = Q_{cxF}$, and $Q_{cx(TCLC)} = 0$).

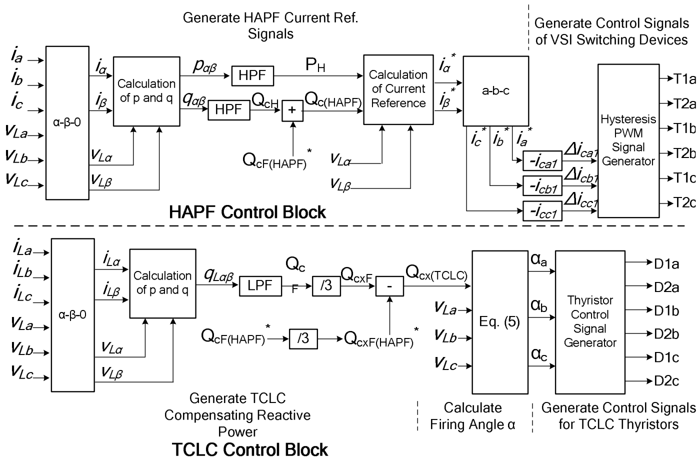

Fig. 6. Control block diagram of the proposed 3-phase 3-wire HAPF//TCLC

IV. SIMULATION VERIFICATION

In this section, the PSCAD simulation results of a 3-phase 3-wire distributed power system with balanced inductive nonlinear loads under compensation by PPF, APF, HAPF and the proposed HAPF//TCLC will be given. During the simulation, the system loads would change suddenly from *Load 1* to *Load 2*, which affects the load reactive power (Q_{Lx}), as in Fig. 1 and Table I. Table I shows the parameters of the system and loads. Since *Load 2* is set to have half impedance of *Load 1* by connecting two *Load 1* in shunt to the power system, so Q_{Lx2} after the load change would be twice of Q_{Lx1} before the load change ($Q_{Lx2} = 2 \times Q_{Lx1}$) and the total harmonic distortion of source current (THD_{isx}) is similar. The current waveforms of the system before and after PPF, APF, HAPF and HAPF//TCLC compensation with the load change at 1.9s are shown in Fig. 7, as well as the power quality data with and without the load change after compensation by different power filters are summarized in Table VI. To simplify the simulations, a fixed DC-link voltage is supplied to the voltage source inverter of APF, HAPF and HAPF//TCLC in simulations. This paper targets on getting the total harmonic distortion of the source current (THD_{isx}) less than *15%* after compensation. As according to the IEEE 519-2014 Standards [19], when the ratio of the short circuit current over the load current (I_{SC} / I_L) is within *100* and *1000*, the total demand distortion of the source current (TDD_{isx}) would be equaled to *15%*; and THD_{isx} = TDD_{isx} = *15%* when assume that the rate current equals to the fundamental load current for the worst case.

TABLE I. THE SYSTEM AND LOAD PARAMETERS

Parameters		Physical Values
System	*Vsx, f, Lsx*	220V, 50Hz, 0.5mH
Load 1	L_L, R_L, L_{Lx}, R_{Lx}	30mH, 20Ω, 40mH, 5Ω

TABLE II. THE PPF PARAMETERS

Parameters	Physical Values		
Harmonic Order	*5th*	*7th*	*11th*
L_{xn}, C_{xn}	*2.8mH, 107μF*	*2.7mH, 78μF*	*1.7mH, 50.3μF*

TABLE III. THE APF PARAMETERS

Parameters	Physical Values
L_x	*5mH*
V_{DC}	*630V*

TABLE IV. THE HAPF PARAMETERS

Parameters	Physical Values
L_x, C_x	*1mH, 240μF*
V_{DC}	*30V*

TABLE V. THE HAPF//TCLC PARAMETERS

Parameters		Physical Values
HAPF	L_{x1}, C_{x1}	*1mH, 240μF*
	V_{DC}	*30V*
TCLC	L_{cx2}, L_{x2}, C_{x2}	*5mH, 30mH, 230μF*

Before compensation, as shown in Fig. 7(a) and Table VI, when the *Load 1* is connected, the total harmonic distortion of the system current (THD_{isx}) = *17.30%* and power factor (*PF*) = *0.8200*. When the *Load 2* is connected, the THD_{isx} = *16.04%* and *PF = 0.8104*.

In the PPF simulation, the PPF has three tuned LC branches with the filter parameters shown in Table II, which eliminates the *5th*, *7th* and *11th* current harmonics. When *Load 1* is applied, it obtains THD_{isx} = *4.42%* and *PF* = *0.9986*. However, when the load change to *Load 2*, it obtains THD_{isx} = *3.62%* due to the filter characteristic; and there is about only half of Q_{Lx2} compensated (*53%*) due to the PPF is designed to offering the compensating reactive power which is same as the load reactive power of *Load 1* (i.e. $Q_{cx} = Q_{Lx1}$), thus it reduces the *PF to 0.9533* after the Load 2 is connected.

In the APF simulation, the filter parameter of APF is shown in Table III, and the minimum DC-link voltage (V_{DC}) of *630V* is applied to the inverter. It results THD_{isx} = *6.20%* and *PF=0.9968* for *Load 1*; and THD_{isx} = *9.07%* and *PF = 0.9941* for *Load 2* due to the high V_{DC}, as well as *87%* of *Load 2* reactive power is compensated.

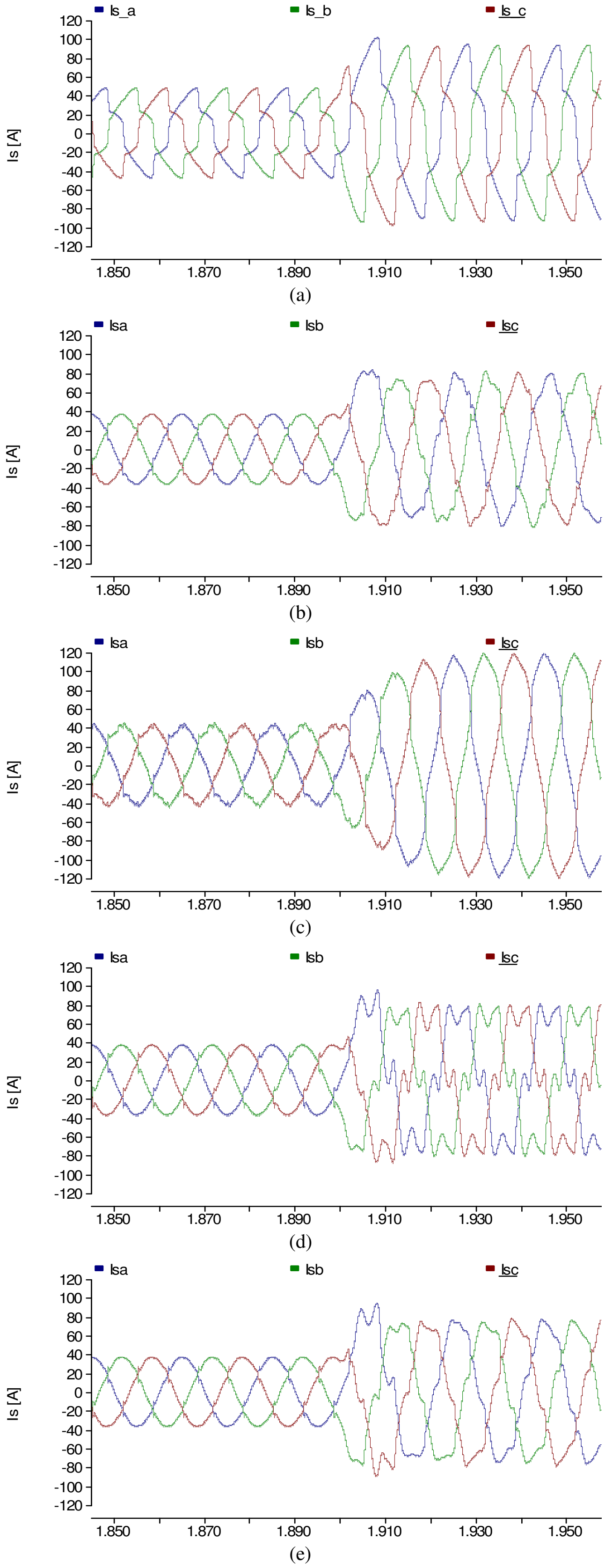

Fig. 7. Source current waveforms under balanced inductive nonlinear load change (a) before compensation, (b) after PPF compensation, (c) after APF compensation, (d) after HAPF compensation, e) after HAPF//TCLC compensation.

In the HAPF simulation, the HPAF is designed based on filtering the 7^{th} current harmonics with the filter parameters as Table IV, since it have lower impedance values and lower V_{DC} requirement when tunes at the 7^{th} harmonics than the 5^{th} harmonics. The minimum DC-link voltage uses $V_{DC} = 30V$. Before the load change, the system with Load 1 under the HAPF compensation obtains $THD_{isx} = 4.50\%$ and $PF = 0.9996$ with compensating current $I_{cx(HAPF)} = 17.66A$. When *Load 2* is applied, the *PF* reduce to *0.9213* and THD_{isx} rise to *25.96%* as the HAPF cannot fully compensate the Q_{Lx2} and there is only about *54%* of Q_{Lx2} is compensated. Since the HAPF is designed for compensating *Load 1*, so the excessive load reactive power caused by *Load 2* related to *Load 1* cannot be compensated by the HAPF.

In the HAPF//TCLC simulation, the compensator parameters of Table V are used. The HAPF part provides a fixed amount of dc compensating reactive power $Q_{cxF(HAPF)}$ as the set reference $Q_{cxF(HAPF)}*$ which is as the magnitude of the *Load 1* reactive power (i.e. $Q_{cx(HAPF)} = Q_{cx(HAPF)}* = 3677var$ in the paper). The HAPF part is also designed to filter the 7^{th} current harmonics due the low impedance of the compensator and hence gives a low V_{DC} implementation characteristic like the pure HAPF. In this simulation, $V_{DC} = 30V$ is also used as the pure HAPF for the HAPF//TCLC comparison. For *Load 1*, the HAPF//TCLC works as the pure HAPF, as the HAPF part can fully compensate the *Load 1* with $I_{cx(HAPF)} = 17.79A$ which is close to the pure HAPF and the TCLC part gives very less compensating current for little uncompensated port from the HAPF part, and obtains $THD_{isx} = 3.77\%$. When the load changes to *Load 2*, the system is compensated to $THD_{isx} = 4.34\%$ and $PF = 0.9992$ for *Load 2* due to the TCLC part compensates the excessive load reactive power which is out of the range of the HAPF part with $I_{cx(TCLC)} = 16.32A$, while the HAPF part still provide full compensating reactive power with $I_{cx(HAPF)} = 19.73A$.

For the compensation *Load 1*, these four compensating devices show good compensating performances with *PF* close to one and THD_{isx} less than *6%*, which meets the IEEE 519-2014 Standards of less than *15%*; the HAPF//TCLC with $V_{DC} = 30V$, which is same as the minimum DC-link voltage of the pure HAPF, gives the lowest THD_{isx} among the four compensators. For the *Load 2* compensation simulation, Q_{Lx2} is fully compensated by HAPF//TCLC (*100%*) and mostly compensated by APF (87%), so it shows that the APF and the proposed compensator have higher compensation ability for compensating excessive Q_{Lx}, which is outside the designed compensating range of the PPF (*53%*), and HAPF (*54%*). Furthermore, even through the HAPF//TCLC and the APF give low $THD_{isx} < 15\%$ to meet the IEEE 519-2014 Standards and similar results on the load reactive power compensation and $PF \approx 1$, the proposed HAPF//TCLC uses a small voltage rating for the inverter as only about *4.8%* of the APF inverter voltage. For the proposed HAPF//TCLC, when the load changes and leads to the load reactive power over the HAPF compensation range, the extra shunt connected TCLC filter can compensate the excessive of load reactive power. On the other hand, it can also think that for an existing TCLC filter, a HAPF compensator would be a good choice to be added to the system for current harmonic compensation because of its low DC-link voltage requirement.

V. CONCLUSION

In this paper, the PPF, APF, HAPF and the proposed HAPF//TCLC are discussed, stimulated and compared in terms of their compensating performances and voltage rating of the inverter parts. In the simulation, the proposed HAPF//TCLC configuration has the best compensating performance for both the designed range and outside range of load reactive power compensation of the HAPF part with low DC-link voltage related to APF, while PPF and HAPF cannot deal with the case of excessive load reactive power.

ACKNOWLEDGMENT

This work is supported by the Macao Science and Technology Development Fund (FDCT) (FDCT 109/2013 /A3) and the Research Committee of University of Macau (MYRG2015-00030-AMSV, SRG2014-00007-AMSV and MRG012/WMC/2015/FST)

REFERENCES

[1] Duarte, L.H.S., Alves, M.F.: 'The degradation of power capacitors under the influence of harmonics'. Proc. IEEE 10th Int. Conf. on Harmonics and Quality of Power, vol. 1, pp. 334–339, 2002.

[2] Subjek, J.S., Mcquilkin, J.S.: 'Harmonics-causes, effects, measurements and analysis', *IEEE Trans. Ind. Electron.*, vol. 26, no. 6, pp. 1034–1042,

TABLE VI. SIMULATION RESULTS OF PPF, APF, HAPF AND HAPF // TCLC BEFORE AND AFTER LOAD CHANGE FDURING LOAD 1 AND LOAD 2

	Load 1 Applied (Before Load Change)					**Load 2 Applied (After Load Change)**				
Parameter	**Before Comp.**	**PPF**	**APF**	**HAPF**	**HAPF // TCLC**	**Before Comp.**	**PPF**	**APF**	**HAPF**	**HAPF // TCLC**
V_{sx} [V]	217.41	220.05	220.36	219.77	220.03	214.79	217.36	218.90	217.67	219.72
I_{sx} [A]	31.07	26.02	29.53	26.18	26.07	61.58	53.74	82.04	54.23	51.97
P_{sx} [W]	5,544	5,717	6,486	5,750	5,727	10,719	11,134	17,852	10,875	11,409
Q_{sx} [var]	3,677	-95	79	-97	83	7,416	3,490	1,001	3,439	-2
PF	0.8200	0.9986	0.9968	0.9996	0.9986	0.8104	0.9533	0.9941	0.9213	0.9992
THD_{isx} [%]	17.30	4.42	5.21	4.50	3.77	16.04	3.62	9.07	25.96	4.34
I_{cx} [A]	---	17.46	17.33	17.66	17.79 (HAPF) 1.26 (TCLC)	---	19.19	42.68	21.12	19.73 (HAPF) 16.32 (TCLC)
V_{DC} [V]	---	---	630	30	30	---	---	630	30	30

1990.

[3] S. T. Senini and P. J.Wolfs, “Systematic identification and reviewof hybrid active filter topologies,” in *Proc. IEEE 33rd Annu. Power Electron. Spec. Conf.*, vol. 1, pp. 394–399, 2002.

[4] P. Salmer´on and S. P. Litr´an, “A control strategy for hybrid power filter to compensate four-wires three-phase systems,” *IEEE Trans. Power Electron.*, vol. 25, no. 7, pp. 1923–1931, Jul. 2010.

[5] H. Fujita and H. Akagi, “Apractical approach to harmonic compensation in power systems: Series connection of passive and active filters,” IEEE Trans. Ind. Appl., vol. 27, no. 6, pp. 1020–1025, Nov./Dec. 1991.

[6] S. Srianthumrong andH.Akagi, “Amedium-voltage transformerless ac/dc Power conversion system consisting of a diode rectifier and a shunt hybrid filter,” *IEEE Trans. Ind. Appl.*, vol. 39, no. 3, pp. 874–882, May/Jun. 2003.

[7] W. Tangtheerajaroonwong, T. Hatada, K. Wada, and H. Akagi, “Design and performance of a transformerless shunt hybrid filter integrated into a three-phase diode rectifier,” *IEEE Trans. Power Electron.*, vol. 22, no. 5, pp. 1882–1889, Sep. 2007.

[8] Chi-Seng Lam, Man-Chung Wong, *Design and control of hybrid active power filters*, Heidelberg: Springer, 2014.

[9] Ryszard Klempka, “Designing a group of single-branch filters taking into account their mutual influence”, *Archives of Electrical Engineering*, vol. 63, pp. 81-91, Jan. 2014.

[10] Ning-Yi Dai, Man-Chung Wong, "Design considerations of coupling inductance for active power filters," *Industrial Electronics and Applications (ICIEA), 2011 6th IEEE Conference*, pp. 1370-1375, Jun. 2011.

[11] Chi-Seng Lam, Xiao-Xi Cui, Man-Chung Wong, Ying-Duo Han, “Minimum DC-Link Voltage Design of Three-Phase Four-Wire Active Power Filters,” in *Control and Modeling for Power Electronics (COMPEL), 2012 IEEE 13th Workshop*, pp. 1-5, Jun. 2012.

[12] H. Akagi, S. Ogasawara, Kim Hyosung, “The theory of instantaneous power in three-phase four-wire systems: a comprehensive approach,” *in Conf. Rec. IEEE-34th IAS Annu. Meeting*, vol. 1, pp. 431–439, 1999.

[13] Chi-Seng Lam, Man-Chung Wong, Ying-Duo Han, “Hysteresis current control of hybrid active power filters”, *IET Power Electronics*, vol. 5, no. 7, pp. 1175 – 1187, Aug. 2012.

[14] Chi-Seng Lam, Man-Chung Wong, Wai-Hei Choi, Xiao-Xi Cui, Hong-Ming Mei, Jian-Zheng Liu, “Design and performance of an adaptive low dc voltage controlled LC-hybrid active power filter with a neutral inductor in three-phase four-wire power systems”, *IEEE Transactions on Industrial Electronics*,vol. 61, no, 6, pp. 2635 – 2647, Jun. 2014.

[15] Chi-Seng Lam, Wai-Hei Choi, Man-Chung Wong, Ying-Duo Han, “Adaptive dc-link voltage controlled hybrid active power filters for reactive power compensation”, *IEEE Transactions on Power Electronics*, vol. 27, no, 4, pp. 1758 – 1772, Apr. 2012.

[16] Chi-Seng Lam, Xiao-Xi Cui, Wai-Hei Choi, Man-Chung Wong, Ying-Duo Han, “Minimum inverter capacity design for three-phase four-wire LC-hybrid active power filters”, *IET Power Electronics*, vol. 5, no. 7, pp. 956 – 968,Aug. 2012.

[17] Helder J. Azevedo, José M. Ferreira, António P. Martins, Adriano S. Carvalho, "Direct Current Control of an Active Power Filter for Harmonic Elimination, Power Factor Correction and Load Unbalancing Compensation," *EPE, Power Electronics In Generation, Transmission And Distribution Of Electrical Energy*, Toulouse, 2003.

[18] E. Acha, C. R. Fuerte-Esquivel, et.al, “Power Electronic Control in Electrical Systems”, *Newnes*, 2002.

[19] IEEE Standard, 519-2014 - IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems, Jun. 2014.