An Over Current Protection Scheme for Hybrid Active Power filter

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Abstract **– A protection scheme for hybrid active power filters, which is combined shunt passive filter and small rated series active filter, is presented and analyzed in this paper. The proposed series active power filter operated as a high impedance "k(Ω)" to the fundamental component when over current occurs in the power distribution system, and three control strategies are proposed in this paper . The first is the method by detecting the fundamental source current through the p-q theory, the second is the method by detecting the fundamental component of load current in Synchronous Reference Frame (SRF) and the third is the method by detecting the input voltage. When the over current occurs in the power distribution system, the proposed scheme protects the series active power filter without additional protection circuits. The validity of proposed protection scheme is investigated through experimental result for the prototype hybrid active power filter system.**

Keyword – Fundamental component, hybrid active power filter, p-q theory, synchronous reference frame

I. INTRODUCTION

The series active power filter is connected before the load in series with the mains, using a matching transformer, to eliminate voltage harmonics, and to balance and regulate the terminal voltage of the load or line. It can be also used to isolate current harmonics from nonlinear loads.[1]

However, the main disadvantage of series active power filter is that requires a special protection scheme since the primary of series active power filter transformers are connected in series to the power distribution system, they operate as current transformers, so that their secondary windings cannot operate in open circuit. For this reason, if the over current is detected in the power distribution system, the inverter of series active power filter cannot be disconnected from the secondary of the transformer.[2] Therefore, it cannot be protected with normal circuit breakers or power fuses but the protection scheme must be able to limit the amplitude of the currents and voltages in the secondary circuit until over current of power distribution system is cleared or inverter is isolated. This paper deals with protection schemes of hybrid active power filter, which is combined shunt passive filter and small rated series active filter. This task is obtained by series active filter which is controlled a high impedance "k(Ω)" to the fundamentals of the source current, load current and is obtained by having the series active compensator outputting the reverse voltage to the source voltage.

The main advantages of proposed series active compensator protection scheme (compared to traditional protection scheme) are as follows.

(1) It does not necessary additional protection circuits.
(2) It is easy to implement.
(3) It does not consider energy dissipated at the varistor during the fault

II. GENERAL HYBRID ACTIVE POWER FILTER

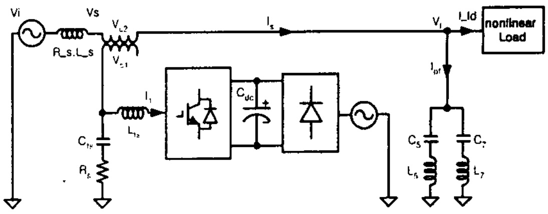


Fig. 1. Hybrid Active Power Filter

The general hybrid active power filter system consists of small rated series active compensator, 5% of the load kVA rating typically, and tuned L-C passive filters as shown in Fig. 1. The series active power filter has high impedance for high-frequency harmonics. As a result it is controlled to act as a "harmonic isolator" between the supply and load by constraining all the load current harmonics into the passive filters. And the hybrid active filter system aims at eliminating problems of using only conventional shunt passive or conventional shunt active filters.[3] Recently moreover series active power filter is able to compensate voltage unbalance by adequate control scheme.[4]

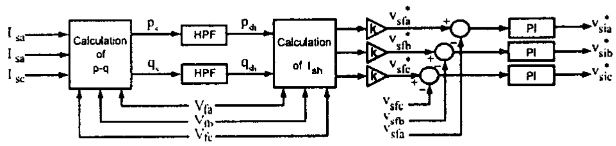


Fig. 2. Block diagram of the control scheme for conventional hybrid active power filter

Fig. 2 shows block diagram of the control scheme for conventional hybrid active power filter system. It is clear that ac output voltage reference of series active filter ($v_{sf}^*=k \cdot i_{sh}$) control it to present no impedance at the fundamental frequency and a "k(Ω)" resistance to the harmonics, where i_{sh} is the harmonic component of the source current i_s. The harmonic current (i_{sh}) is calculated by using the instantaneous real and imaginary powers p_s and q_s, which are powers that flow from the source into the load and the shunt passive filter. The harmonic components p_{sh} and q_{sh} of the source powers p_s and q_s are extracted by high pass filter, respectively. Then i_{sh} is calculated out from p_{sh} and q_{sh}. [5]

III. PROPOSED PROTECTION SCHEMES FOR HYBRID ACTIVE FILTERS

The block diagrams of the proposed hybrid active power filter protection schemes are shown in Fig. 3 They are also composed of three methods. The first is the method by detecting the fundamental source current through the p-q theory,[6][7] the second is the method by detecting the fundamental component of load current in Synchronous

Reference Frame (SRF) and the third is the method by detecting the input voltage. Exclusive of the shaded region in Fig. 3 (a), the control methods each figures are the same.

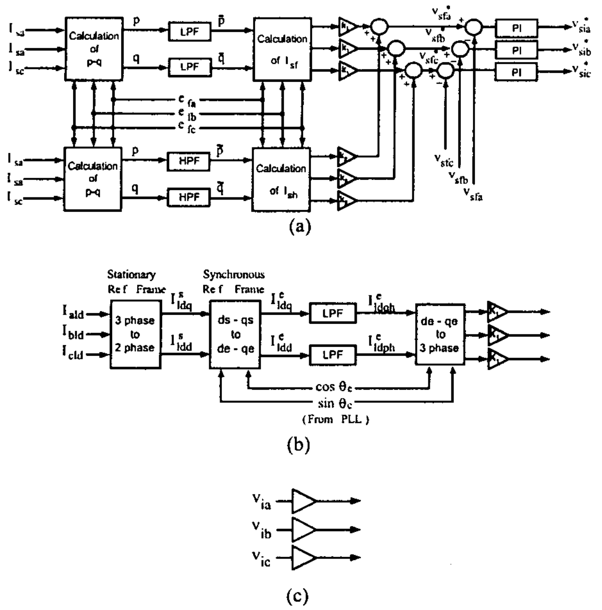


Fig. 3. The methods of producing reference value in proposed protection schemes for hybrid active power filter (a) Method I : detecting fundamental component of source current by applying the p-q theory (e_{fa}, e_{fb}, e_{fc} : fundamentals of v_{fa}, v_{fb}, v_{fc}), (b) Method II : Filtering a fundamental component of load current in Synchronous Reference Frame (SRF) and (c) Method III : Sensing of input voltage

The proposed protection schemes for the hybrid active power filter can be the causes of the parallel resonance between a source and a shunt passive filter, because when the schemes are implemented, the hybrid active power filter does not have the impedance of the harmonics but has the impedance of the fundamentals. Fig.3 shows that the impedance of the harmonics is zero (K=0) and 2 (K=2). When k is zero, the parallel resonance was happened but, when K is 2, the parallel resonance was not happened.

Therefore, the proposed hybrid active power filter possess a series active power filter which is controlled a high impedance "$k_1(\Omega)$" to the fundamental component and a high impedance "$k_2(\Omega)$" to the harmonic component when over current occurs in the power distribution system.

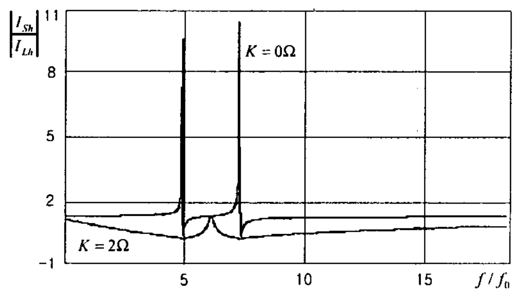
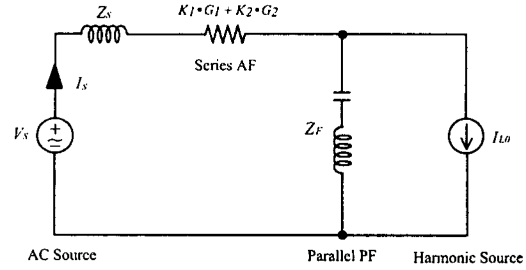


Fig. 4. Filter characteristic for load harmonic current in conventional Hybrid Active Filter.

A. Characteristic analysis of Method I and Method II



Zs: the source impedance, I_{LO}: the equivalent harmonic current source, Z_F: the equivalent impedance of the passive filter

Fig. 5. The proposed protection Method I, II using the fundamentals of current

The G_1, G_2 are the equivalent transfer functions of series active power filter in the proposed hybrid active power filter including the detection circuit of harmonics and fundamental component. When over current occurred, G_1 has the function of notching the harmonic component, that is, $|G_1|_f=1$ at the fundamental frequency and $|G_1|_h=0$ for harmonics. However G_2 is almost zero at the fundamentals and, is almost 1 for harmonics, that is, $|G_2|_h=1$, $|G_2|_f=0$. K_1 and K_2 are gains with the dimension of ohms. Therefore series active power filter has high impedance both fundamental frequency and harmonics. Form Fig. 5 the following source current equation is obtained.

$$I_s = \frac{Z_F \cdot I_{Lo} + V_s}{Z_S + Z_F + K_1 \cdot G_1 + K_2 \cdot G_2} \tag{1}$$

Focusing on fundamental component

$$I_{sf} = \frac{Z_F \cdot I_{Lf}}{Z_S + Z_F + K_1} + \frac{V_{sf}}{Z_S + Z_F + K_1} \tag{2}$$

$$I_{sf} \cong 0 \text{ if } K_1 >> Z_S, Z_F \tag{3}$$

That is, the source current fundamentals are limited using the control gain K_1.

Focusing on the harmonic components

$$I_{sh} = \frac{Z_F \cdot I_{Lh}}{Z_S + Z_F + K_2} + \frac{V_{sh}}{Z_S + Z_F + K_2} \tag{4}$$

$$I_{sh} \cong 0 \text{ if } K_2 >> Z_S, Z_F \tag{5}$$

Equation (4) shows that source current harmonics are isolated using the control gain K_2. However in this case, output voltage of series active power filter is increased because it is controlled by harmonics and fundamentals. It is shown in equation (6).

$$V_C = K_1 \cdot I_{sf} + K_2 \cdot I_{sh} = (Z_F \cdot I_{Lf} + V_{sf}) + (Z_F \cdot I_{Lh} + V_{sh}) \tag{6}$$

$$\text{if } K_1 >> Z_S, Z_F \text{ and } K_2 >> Z_S, Z_F$$

Hence the required rating of the series active power filter is larger than that of a conventional series active power filter in hybrid active filter.

B. Characteristic analysis in method III

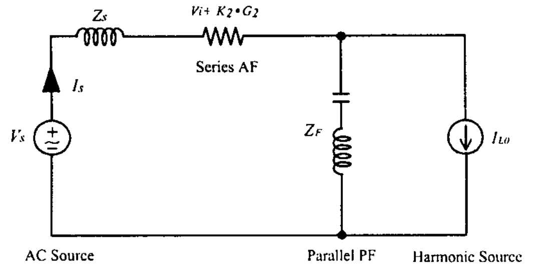


Fig. 6. The proposed protection Method III using the input voltage

The Method III deals with protection of hybrid active power filter which is obtained by having the series active power filter outputting both the reverse voltage to the source voltage and the high impedance to harmonics.

IV. POWER FLOW OF HYBRID ACTIVE POWER FILTER

Fig. 7 shows power flow of the hybrid active power filter system under normal load condition and applied the proposed fault protection schemes. The former is shown Fig. 7 (a) and the later is shown Fig. 7 (b). In Fig. 1, the balanced, regulated and harmonic free output voltage (v_{fa}, v_{fb}, v_{fc}) and the compensated source current (i_{sa}, i_{sb}, i_{sc}) are always in phase whit the non-compensated input voltages (v_{sa}, v_{sb}, v_{sc}). The three-phase instantaneous input power $p_S(t)$ and instantaneous load power $p_L(t)$ are given by equations (7) and (8), respectively. Both instantaneous power $p_S(t)$ and $p_L(t)$, are composed of dc (p_{dc})and ac (p_{ac})power component. Thus, equations (7), (8) can be rewritten as follows, respectively.

$$p_s(t) = v_{sa}i_{sa} + v_{sb}i_{sb} + v_{sc}i_{sc} = p_{sdc} + p_{sac} \quad (7)$$

$$p_L(t) = v_{fa}i_{ald} + v_{fb}i_{bld} + v_{fc}i_{cld} = p_{Ldc} + p_{Lac} \quad (8)$$

The harmonic power P_{Lac} is compensated by the parallel passive filter, and P_{Sac} by the series active filter. Thereby considering that the harmonic of the load current were compensated by the parallel passive filter, the fundamental components of the load current are equal to the fundamental components of the input currents, that is, $i_{saf} = i_{aldf}$, $i_{sbf} = i_{bldf}$ and $i_{scf} = i_{cldf}$. Thus, the three-phase instantaneous powers of the series active filter are given by (9) and (10), respectively.

$$p_s(t) = v_{sa}i_{saf} + v_{sb}i_{sbf} + v_{ca}i_{scf} \quad (9)$$

$$p_L(t) = v_{fa}i_{aldf} + v_{fb}i_{bldf} + v_{fa}i_{cldf} \quad (10)$$

If the output voltages (v_{fa}, v_{fb}, v_{fc}) of the series active filter are harmonic free, and if the input currents (i_{sa}, i_{sb}, i_{sc}) are without harmonic components after current compensation, the instantaneous power $P_L(t)$ and $P_s(t)$ have only dc component, as given by (11). Fig 7 (a) shows the average power flow of the series active filter output (P_{sdc}) and the load (P_{Ldc}), in which the hybrid active filter system performs only normal load condition.

$$p_s(t) = p_{sdc} = p_{Ldc} \quad (11)$$

If series active filter protects that the over current detected in the power distribution system, the active power P_{sdc} can be different from P_{Ldc} and equation (11) is not true. Fig. 7 (b) shows the over current occurs in the power distribution system that is, P_{sdc} is greater then P_{Ldc} or P_{sdc} of normal load condition. Equation (12) shows that P_{Ldc} is limited by using P_{pdc}.

$$p_{sdc} = p_{Ldc} + p_{pdc} \quad (12)$$

In this case instantaneous power p_{pdc}, for over current protection, is accumulated to dc link capacitor (C_{dc}). Therefore proposed over current protection schemes have growth of dc-link voltage and considering of dc-link over voltage is very important element in hybrid active filter.

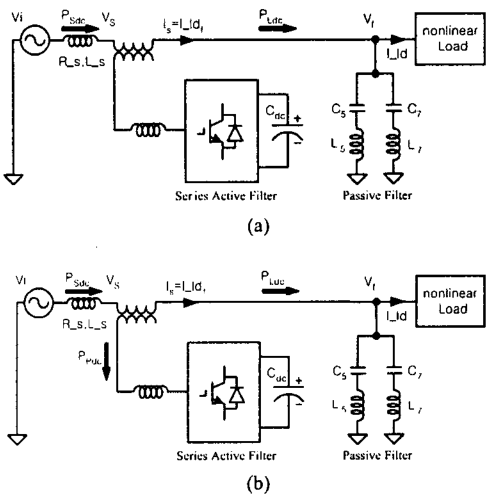


Fig. 7. Power Flow of the Hybrid active power filter (a) Under normal load condition and (b) Applied fault protection schemes.

V. EXPERIMENTAL RESULT

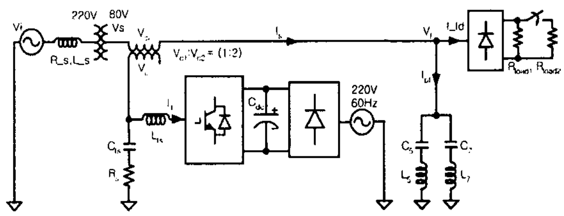


Fig. 8. Experiment system configuration

Fig. 8 shows the configuration of the experimental system. The series active power filter which consists of three-phase voltage source PWM inverter placed in series with the ac source through three transformers (turns ratio=1:2) and the diode rectifier, for constant dc-link voltage, used a separated ac source. The shunt passive LC filters are connected in parallel with a load, which are used to compensate for the load harmonics (fifth, seventh). The load condition of experimental system is assumed that over load (R_{load1} and R_{load2}) is about 3 times of normal load (R_{load1}) condition.

Table I System parameters

Parameters	Value
Input Voltage (V_{sa}, V_{sb}, V_{sc})	80V, 60Hz
Line Impedance (R_s, L_s)	•
dc-link Capacitor	13000μF
dc-link Voltage	320V
C_{fs}, L_{fs}, R_s	100μF, 1.3mH, 2Ω
R_{load1}, R_{load2}	16Ω , 9Ω
C_5, L_5	200μF, 1.24mH
C_7, L_7	125μF, 1.18mH

Table I shows system parameters. For the purpose of avoiding the serious problems, input voltage was stepped down to 80 voltage. When the system and control algorithms are stabilized, the input voltage gets back to 220 voltage instead of 80 voltage.

Fig. 9 shows experimental waveforms in a typical Hybrid Active Power Filter. (a) is waveforms before the operation of series active power filter and (b) is waveforms after the operation of series active power filter.

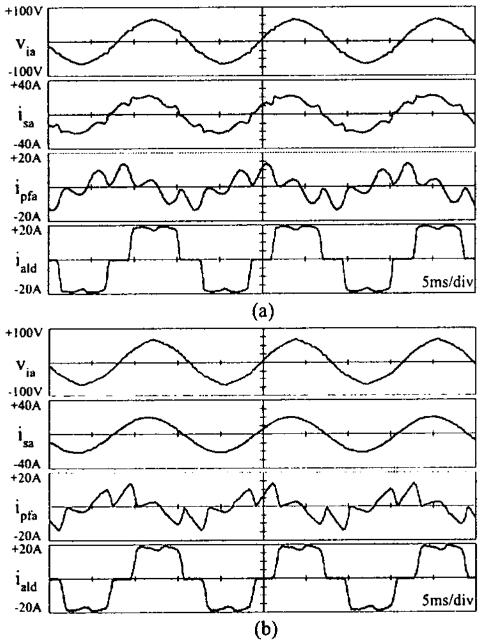


Fig. 9. Experimental waveforms in a typical hybrid active power filter. (a) Before the operation of series active power filter, (b) After the operation of series active power filter

(v_{ia} : Input voltage, i_{sa} : Source current, i_{pfa} : Current of passive filter i_{ald} : Load current)

Fig. 10 (a) shows the waveforms of voltage, current without any protection method in experimental system. Fig. 10 (b) ~ 10 (c) show the waveforms of voltage, current with Method I , II respectively. An over current was modeled as about 3 times as much as the normal load current. If a over current appears in the power distribution system, a large current will be generated in the secondary of the transformer as shown in Fig. 10 (a), but when the over current was occurred, Fig. 10 (b) ~ 10 (c) showed that these proposed methods could reduce the source current a lot.

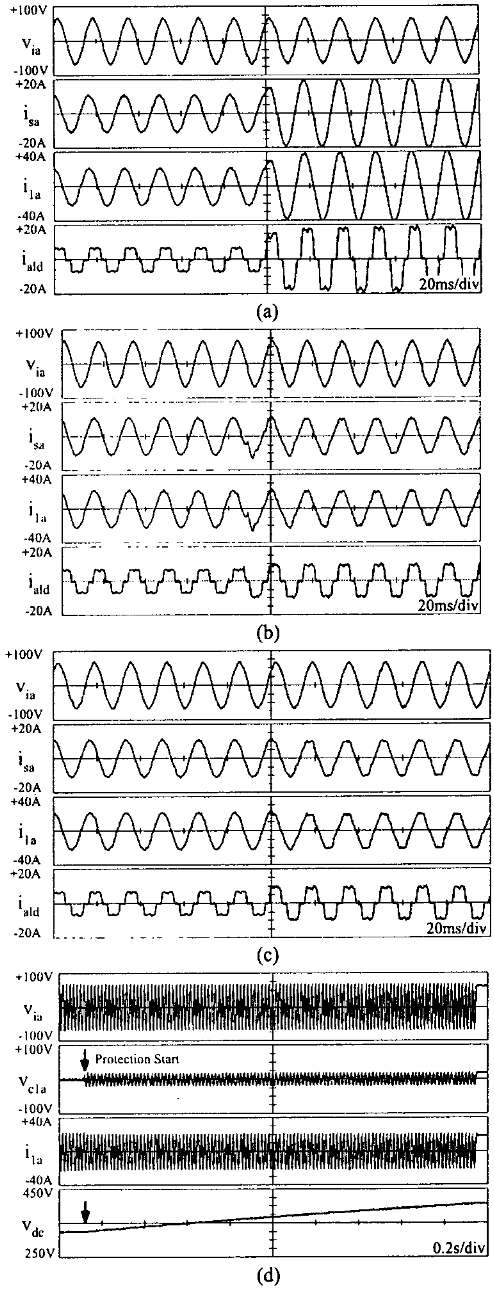


Fig. 10. Experimental waveforms when over current were happened. (a) Without any protection scheme, (b) Protection scheme Method I was applied, (c) Protection scheme Method II was applied, (d) Growth of dc-link voltage because of over current protection scheme (v_{ia} : Input voltage, i_{sa} : Source current, i_{la} : Converter output current, v_{cia} : Converter output voltage, i_{ald} : Load current, v_{dc} : dc-link voltage)

In the case of the proposed over current protection scheme, the rating of the series compensator is a little larger than that of a typical hybrid active power filter. However, in many papers the series compensator compensates for the unbalanced source voltage, and in this case the increase of the converter rating is indispensable. Also, in this case, the rating of the converter is not a serious problem anymore, because the converter has to supply the negative sequence of current to the source. Fig. 11 and 12 showed that there were no differences in the rating between the compensating of the unbalanced source voltage and the proposed protection schemes. However, the rating of the converter depends on how much the unbalanced source voltage is compensated for and how much limitation of the over current is allowed. Fig. 11 shows input voltage waveforms (a), compensated voltage waveforms (b), converter output waveforms (c) on the assumption that the source voltage of C-phase steps up to 25%. Fig. 12 shows converter output voltage and current waveforms when unbalanced source voltage was compensated (a) and the over current protection scheme was applied (b). In the Fig. 12, if we compare the converter voltage (V_{cia}) and current (i_{1a}) between Fig. 12(a) and Fig. 12(b), there were few differences between them in the point of the rating.

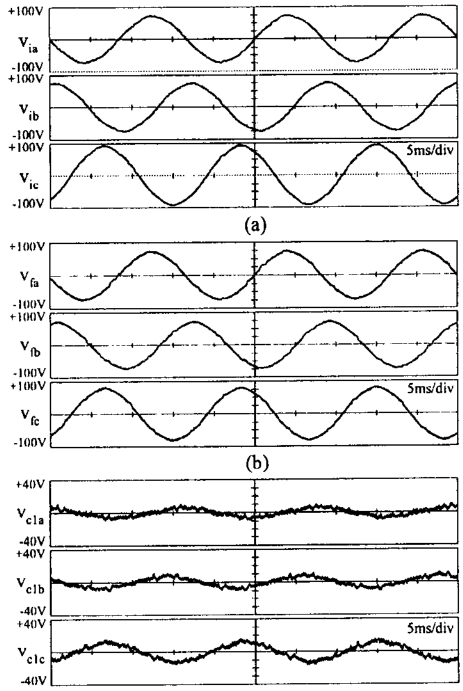
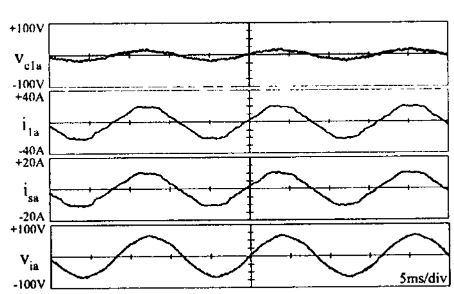
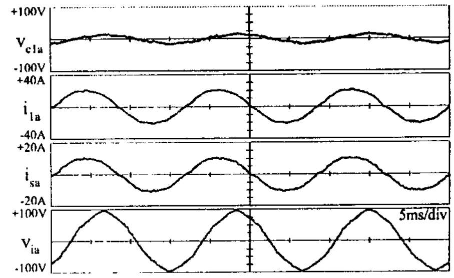


Fig. 11. Experimental waveforms in the case that Hybrid Active Power Filter compensates for the imbalance of source voltage (a) Unbalanced three-phase input voltage, (b) Compensated three-phase PCC (Point of Common Coupling) voltage, (c) Converter output voltage in Hybrid Active Power Filter (v_{ia}, v_{ib}, v_{ic} : Input voltage, v_{fa}, v_{fb}, v_{fc} : Point of common coupling voltage, v_{cla}, v_{clb}, v_{lcc} : Converter output voltage)



(a)



(b)

Fig. 12. Experimental waveforms of converter output voltage and current for one phase. (a) When over current protection scheme was applied (about 3 times), (b) When the imbalance of source voltage was compensated (25% imbalance) (v_{cla} : Converter output voltage, i_{la} : Converter output current, i_{sa} : Source current, v_{ia} : Input voltage)

VI. CONCLUSION

A protection scheme for Hybrid active power filter has been presented and analyzed in this paper. The proposed scheme protects that when the over current occurs in the power distribution system. The ability of over current protection of hybrid active power filter is obtained by series active power filter which is a high impedance "k" to the fundamentals of the source current, load current and is obtained by having the series active power filter outputting the reverse voltage to the source voltage. In the case hybrid active filter has a high impedance both fundamentals and harmonics. As a result, series active power filter can protect when short-circuit faults occur in the power distribution system. The technical validity of the proposed schemes were testified through experimental result for the prototype hybrid active power filter system.

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