Over Current Protection Schemes for Active Filters with Series Compensators

Woo-Cheol Lee† and Taeck-Kie Lee*

Abstract - This paper presents and analyses protection schemes for a series active compensator, which consists of a Unified Power Quality Conditioner (UPQC) or a hybrid active power filter. The proposed series active compensator operates as a high impedance "k(Ω)" for the fundamental components of the power frequency during over current conditions in the distribution system. Two control strategies are proposed in this paper. The first strategy detects the fundamental source current using the p-q theory. The second strategy detects the fundamental component of the load current in the Synchronous Reference Frame (SRF). When over currents occur in the power distribution system momentarily, the proposed schemes protect the series active compensator without the need for additional protection circuits, and achieves excellent transient response. The validity of the proposed protection schemes is investigated through simulation and compared with experimental results using a hybrid active power filter systems.

Keywords: final manuscript, guidelines, instructions, prospective authors, template

1. Introduction

The series active compensator is inserted between the load and the mains in series using an impedance matching transformer to eliminate voltage harmonics while balancing and regulating the terminal voltage of the load. It can be also used to block harmonic currents from non-linear loads.[1]

However, the main disadvantage of a series active compensator is that it requires a special protection scheme since the primary of the transformer of the series active compensator is connected in series with the power distribution system. It acts as a current transformer, which does not allow operation with the secondary winding in the open state. Thus, if a over current is detected in the power distribution system, the inverter of the series active compensator cannot be disconnected from the secondary of the transformer.[2] Therefore, it cannot be protected with normal circuit breakers or power fuses and the protection scheme must be able to limit the amplitude of the currents and voltages in the secondary circuit until the over current of power distribution system is cleared or the inverter can be isolated. This paper deals with protection schemes of a series active compensator which consists of a UPQC or hybrid active power filter. This task is performed by a series active filter which controls the high impedance "k(Ω)" for the fundamentals components of the source and load current.

Compared to other traditional protection schemes against instantaneous over currents, the main advantages of the proposed protection scheme are as follows:

1) Eliminates the need for additional protection circuits.
2) Excellent transient response can be acquired.
3) Easy implementation.

Finally, the validity of the proposed protection algorithms is demonstrated in two ways: 1) Analysis of computer simulation results and 2) Prototype experiment.

2. General Series Active compensator

2.1 Unified Power Quality Conditioner

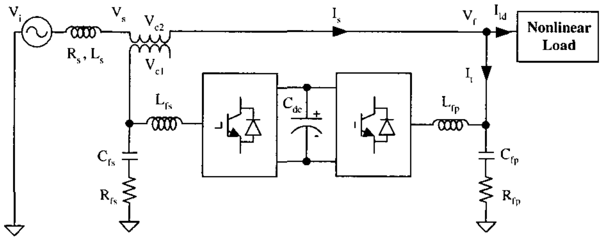

Fig. 1 Configuration of an Unified Power Quality Conditioner

Fig. 1 shows the basic system configuration of a general UPQC which consists of a combination of series and parallel active power filters. Two PWM converters, coupled with a common DC-link are used to carry out the functions of the series and parallel active filter. The series active filter is connected with three separate single phase

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Received January 9, 2004 ; Accepted August 25, 2004

transformers to perform the series connections.[3]

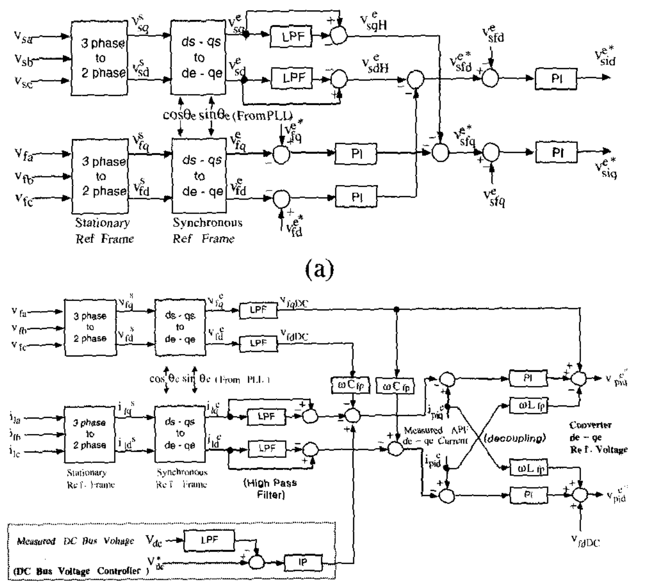


Fig. 2 Block diagram of a control scheme for a conventional UPQC system. (a) Series active filter of UPQC; (b) Parallel active filter of UPQC

Block diagrams of the control scheme for a conventional UPQC system are shown in Fig. 2. The series active filter shown in Fig. 2(a) consists of a voltage detector, a voltage controller for harmonic voltage compensation and is capable of regulating the voltage at the point of common coupling (PCC). The parallel active filter shown in Fig.2 (b) consists of current and voltage detectors, a DC-link voltage controller, and a current controller for current harmonics compensation, reactive power, negative-sequence compensation, and regulates the DC-link voltage.

2.2 Hybrid Active Power Filter

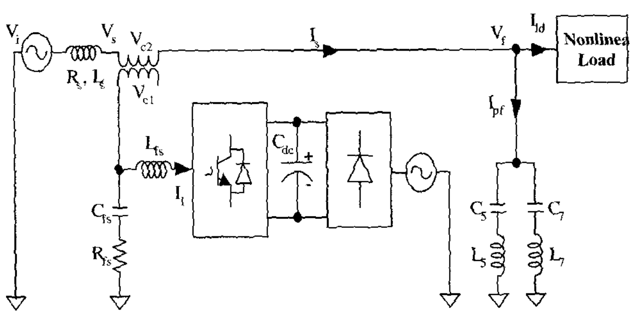


Fig. 3 Configuration of a Hybrid Active Power Filter

The general hybrid active power filter system consists of a series active compensator with a small rating, typically about 5% of the load kVA rating, and tuned L-C passive filters as shown in Fig. 3. 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. The hybrid active filter system eliminates harmonics by using conventional shunt passive and series active filters.[4] In addition, series active power filters compensate voltage imbalance with adequate control schemes.[5]

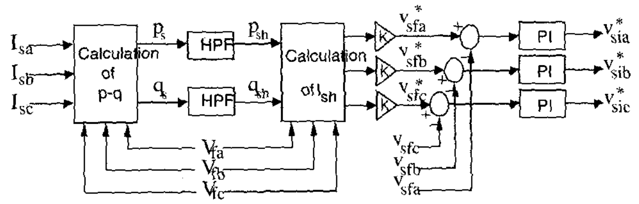


Fig. 4 Block diagram of the control scheme for a conventional hybrid active power filter.

Fig. 4 shows the block diagram of the control scheme for a conventional hybrid active power filter system. It is clear that the ac output voltage reference of the series active filter ($v_{sf}^*=k \cdot i_{sh}$) is controlled to have no impedance at the fundamental frequency and a "k(Ω)" resistance for the harmonics, where i_{sh} is the harmonic component of the source current i_s. The harmonic current, i_{sh}, is calculated using the instantaneous real and imaginary powers. The harmonic components p_{sh} and q_{sh} of the source powers p_s and q_s are extracted from high pass filters, respectively. Then, i_{sh} is calculated from p_{sh} and q_{sh}.[6] Following equations represent these relations shown in Fig. 4.

$$\begin{bmatrix} p_s \\ q_s \end{bmatrix} = \begin{bmatrix} v_{fd} & v_{fq} \\ -v_{fq} & v_{fd} \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} P_{sh} \\ Q_{sh} \end{bmatrix} = G(s) \begin{bmatrix} P_s \\ Q_s \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} i_{shd} \\ i_{shq} \end{bmatrix} = \begin{bmatrix} v_{fd} & v_{fq} \\ -v_{fq} & v_{fd} \end{bmatrix}^{-1} \begin{bmatrix} P_{sh} \\ q_{sh} \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} v_{sfd} \\ v_{sfq} \end{bmatrix} = k \begin{bmatrix} i_{shd} \\ i_{shq} \end{bmatrix} \quad (4)$$

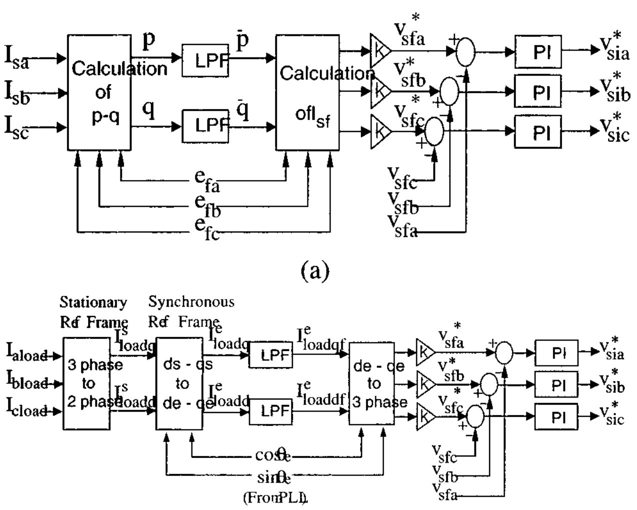
$$\begin{bmatrix} v_{fd} \\ v_{fq} \\ 0 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} v_{fa} \\ v_{fb} \\ v_{fc} \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} i_{sd} \\ i_{sq} \\ 0 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} \tag{6}$$

3. Proposed protection schemes

3.1 Unified Power Quality Conditioner

The proposed protection scheme has the same basic foundation as the universal compensation principle of the hybrid active power filter. In the hybrid active power filter system, the conventional series active power filter controls to have a high impedance for the harmonic components.[6]



(a)

(b)

Fig. 5 The methods of producing reference values in proposed protection schemes for UPQC.
(a) Method I : Detecting the fundamental component of source currents by applying the p-q theory (e_{fa}, e_{fb}, e_{fc} : fundamental components of v_{fa}, v_{fb}, v_{fc}); (b) Method II: Filtering the fundamental component of load currents in SRF.

However, when an over current occurs in the power distribution system, the proposed UPQC possesses a series active filter which shows a high impedance "k(Ω)" for the fundamental component while the parallel active power filter continuously compensates for the harmonics of the non-linear load. The DC-link voltage controller does not operate to reduce the source and inverter current. The block diagrams of the proposed UPQC protection schemes are shown in Fig. 5. There are two methods in the proposed protection schemes. The first is the method of detecting the fundamental source currents through using the p-q theory.[7][8] The second is detecting the fundamental component of load currents in SRF.

3.2 Characteristic analysis in method I

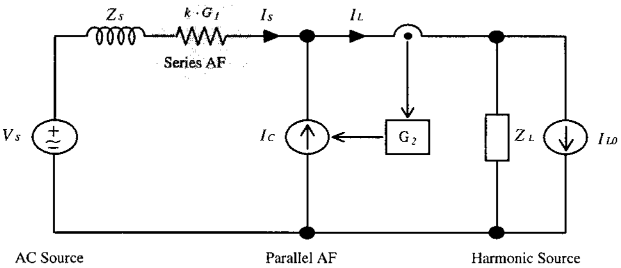


Fig. 6 The proposed protection scheme using source currents. (Zs: source impedance, Z_L: equivalent impedance on the load side, I_{LO}: equivalent harmonic current source)

G_1 is the equivalent transfer function of a series active power filter in the UPQC which includes the detection circuit of harmonics and fundamental components. In general, 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. G_2 is the equivalent transfer function for a parallel active power filter, and G_2 is almost zero at the fundamental frequency and, is almost 1 for harmonics that is, $|G_2|_h=1$, $|G_2|_f=0$. The k in Fig. 6 represents the gain in ohms.

The subscripts h and f represent the harmonic components and fundamental components, respectively. From Fig. 6 the following equations are obtained.

$$I_C = G_2 I_L \tag{7}$$

$$I_S = \frac{Z_L}{Z_S + G_1 \cdot K + \frac{Z_L}{1-G_2}} I_{LO} + \frac{V_S}{Z_S + G_1 \cdot K + \frac{Z_L}{1-G_2}} \tag{8}$$

Considering filtering characteristics for the load harmonic current I_{Loh}, if the source voltage V_s is sinusoidal then the source harmonic current I_{sh} can be represented by the following equation

$$I_{Sh} = \frac{Z_L(1-G_2)}{Z_s(1-G_2)+Z_L} \cdot I_{LOh} \cong 0 \tag{9}$$

It is obvious from (9) that the source current is not influenced by the harmonic currents of the load.

Focusing on the fundamental component, the transfer function is as follows.

$$I_{Sf} = \frac{Z_L}{Z_S + G_1 \cdot K + Z_L} I_{LOf} + \frac{V_{Sf}}{Z_S + G_1 \cdot K + Z_L} \tag{10}$$

It is obvious from (10) that the fundamental components of the source current can be limited by controlling the gain K.

The following ideal protection characteristics are obtained by assuming that k is infinitive:

$$I_{Sf} = 0 \tag{11}$$

3.3 Characteristic analysis in method II

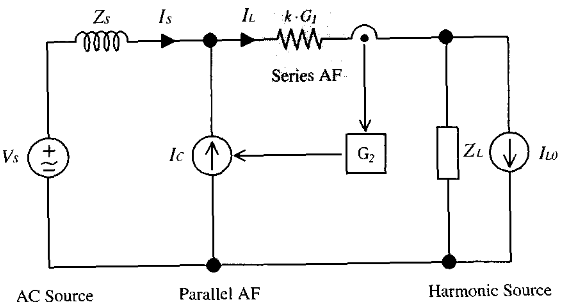


Fig. 7 The proposed protection Method II using load currents.

From Fig. 7 the following equations are obtained.

$$I_S = \frac{Z_L}{Z_S + \frac{G_1 \cdot K + Z_L}{1-G_2}} I_{LO} + \frac{V_S}{Z_S + \frac{G_1 \cdot K + Z_L}{1-G_2}} \tag{12}$$

Assuming that the source voltage V_S is sinusoidal, then

$$\frac{I_{Sh}}{I_{LOh}} = \frac{Z_L}{Z_S + \frac{G_1 \cdot K + Z_L}{1-G_2}} \tag{13}$$

Focusing on the harmonics, the transfer function is as follows

$$I_{Sh} = \frac{Z_L(1-G_2)}{Z_s(1-G_2)+Z_L} \cdot I_{LOh} \cong 0 \tag{14}$$

Focusing on the fundamental component, the transfer function is as follows

$$I_{Sf} = \frac{Z_L}{Z_S + G_1 \cdot K + Z_L} I_{LOf} + \frac{V_{Sf}}{Z_S + G_1 \cdot K + Z_L} \tag{15}$$

The results of (14) and (15) are the same as the results of (9) and (10), respectively. The detection of load currents is indispensable to the parallel active power filter in the conventional UPQC because of the harmonic load current compensation. Therefore, to implement the over current protection scheme in UPQC systems, Method II is more efficient than Method I.

3.4 Hybrid Active Power Filter

The block diagrams of the proposed hybrid active power filter protection schemes are shown in Fig. 8. There are two methods as in the case of the UPQC. The first method detects the fundamental source current using the p-q theory, the second detects the fundamental component of load currents in SRF. Except for the shaded region in Fig. 8, the control methods of each figure are the same.

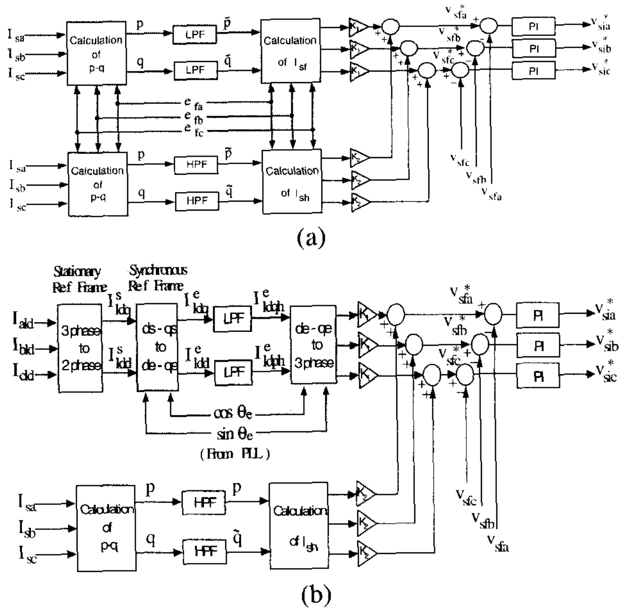


Fig. 8 Methods for producing reference values in proposed protection schemes for hybrid active power filter.
(a) Method I: Detecting fundamental components of source currents by applying the p-q theory (e_{fa}, e_{fb}, e_{fc} : fundamentals of v_{fa}, v_{fb}, v_{fc});
(b) Method II: Filtering fundamental components of load currents in SRF.

The proposed protection schemes for the hybrid active power filter may cause parallel resonance between the source and passive shunt filters when the schemes are implemented, because the hybrid active power filter does not have the impedance of the harmonics, but has the impedance of the fundamental. Fig.9 shows that the impedance of the harmonics is zero (k=0) and 2 (k=2). When k is zero, parallel resonance occurs, but when k is 2 parallel resonance does not occur.

Therefore, the proposed hybrid active power filter has to possess a series active power filter which controls the high impedance "$k_1(\Omega)$" to the fundamental component and a high impedance "$k_2(\Omega)$" to the harmonic component when over currents occur in power distribution systems. In this case, the output voltage of the series active power filter is increased by controlling harmonic and fundamental components.

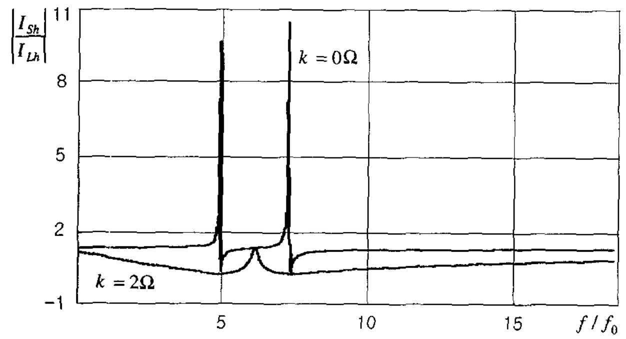


Fig. 9 Filter characteristics for load harmonic currents in a conventional Hybrid Active Filter.

3.5 Characteristic analysis in method I

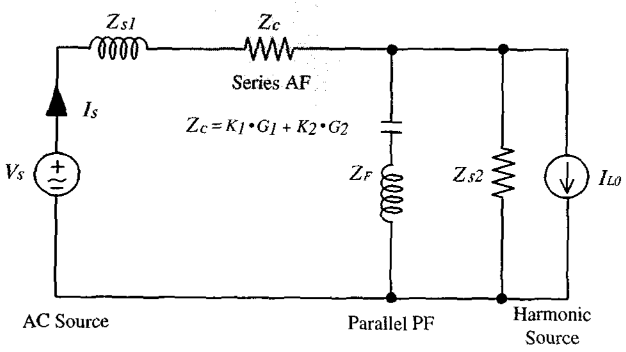


Fig. 10 The proposed protection Method I using the fundamental component of source currents.

In Fig. 10, G_1, G_2 are the equivalent transfer function of fundamental and harmonics components, respectively. G1 is almost 1 at the fundamental frequency, and is almost 0 for harmonics when over currents occur ($|G_1|_f= 1$, $|G_1|_h=0$). Function G_1 can limit the fundamental components with K_1. G2 is almost 0 at the fundamental frequency, and is almost 1 for harmonics when the over current occur ($|G_2|_f= 0$, $|G_2|_h= 1$). Function G_2 can limit the harmonic components with K_2 to avoid the parallel resonance. Therefore, the series active compensator can control as if it has a high impedance to the fundamental and harmonic components. The K_1, K_2 are the gain in ohms.

From Fig. 10 the following equations are obtained.

$$I_s = \frac{V_s(Z_{s2}+Z_F)+(I_{LO}\cdot Z_{s2}\cdot Z_F)}{Z_{s1}Z_{s2}+Z_{s1}Z_F+Z_{s2}Z_F+(Z_{s2}+Z_F)Z_c} \tag{16}$$

where, $Z_c=K_1G_1+K_2G_2$

For the harmonic component, the transfer function is as follows

$$I_{sh} = \frac{V_{sh}(Z_{s2}+Z_F)+(I_{LOh}\cdot Z_{s2}\cdot Z_F)}{Z_{s1}Z_{s2}+Z_{s1}Z_F+Z_{s2}Z_F+(Z_{s2}+Z_F)K_2} \tag{17}$$

The ideal characteristics are obtained by assuming that K_2 is infinitive:

$$I_{sh} \cong 0 \tag{18}$$

For the fundamental component, the transfer function is as follows

$$I_{sf} = \frac{V_{sf}(Z_{s2}+Z_F)+(I_{LOf}\cdot Z_{s2}\cdot Z_F)}{Z_{s1}Z_{s2}+Z_{s1}Z_F+Z_{s2}Z_F+(Z_{s2}+Z_F)K_1} \tag{19}$$

From (19) the fundamentals of source currents are limited by controlling the gain K_1.

The ideal protection characteristics are obtained by assuming that K_1 is infinitive.

$$I_{sf} \cong 0 \tag{20}$$

3.6 Characteristic analysis in method II

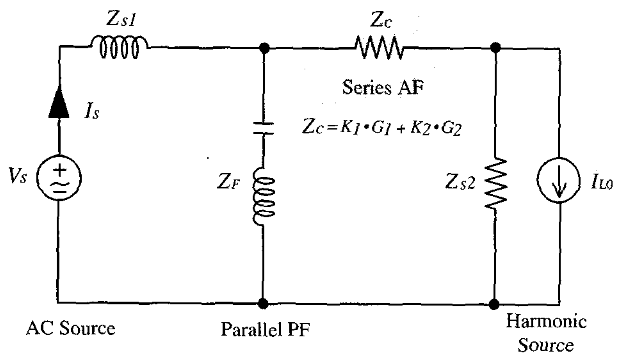


Fig. 11 Proposed protection Method II using the fundamental component of load currents.

From Fig. 11 the following equations are obtained.

$$I_s = \frac{V_s(Z_c+Z_{s2}+Z_F)+(I_{LO}\cdot Z_{s2}\cdot Z_F)}{Z_{s1}Z_{s2}+Z_{s1}Z_F+Z_{s2}Z_F+(Z_{s1}+Z_F)Z_c} \tag{21}$$

The transfer function of the harmonic component is as follows

$$I_{sh} = \frac{V_{sh}K_2+V_{sh}(Z_{s2}+Z_F)+(I_{LOh}\cdot Z_{s2}\cdot Z_F)}{Z_{s1}Z_{s2}+Z_{s1}Z_F+Z_{s2}Z_F+(Z_{s1}+Z_F)K_2} \tag{22}$$

The ideal characteristics are obtained by assuming that K_2 is infinitive:

$$I_{sh} \cong \frac{V_{sh}}{Z_{s1} + Z_F} \tag{23}$$

Harmonic currents do not exist any more, because the series active compensator compensates for the harmonic components of the source voltage.

The transfer function of the fundamental component is as follows

$$I_{sf} = \frac{V_{sf}K_1 + V_{sf}(Z_{s2} + Z_F) + (I_{LOf} \cdot Z_{s2} \cdot Z_F)}{Z_{s1}Z_{s2} + Z_{s1}Z_F + Z_{s2}Z_F + (Z_{s1} + Z_F)K_1} \tag{24}$$

The ideal characteristics are obtained by assuming that K_1 is infinitive:

$$I_{sf} \cong \frac{V_{sf}}{Z_{s1} + Z_F} \tag{25}$$

The impedance of the passive filter, Z_F, is infinitive to the fundamental components, so fundamental components of current can be limited.

However, in the proposed methods, the gains K_1, K_2 are used for limiting the fundamental and the harmonic component. Therefore, compared to the conventional HAPF, the output voltage of the series active compensator increases, and is related closely with the inverter capacity. Increment of the inverter capacity is explained by (26). Generally, the value of K_1 is selected to be larger than K_2.

$$V_C = K_1 \cdot I_f + K_2 \cdot I_h \tag{26}$$

However, Delta conversion UPS systems and DVR systems that have series active compensators can compensate for voltage and current imbalances. Compared to those systems, there is little difference in inverter capacity.[9][10] This will be explained later in more detail.

4. Power Flow of a hybrid active power filter

Fig. 12(a) shows the power flow of a hybrid active power filter system under normal load conditions, and Fig. 12(b) shows the power flow with the over current protection scheme in operation. 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 with 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 (27) and (28), respectively. Both instantaneous power $p_S(t)$ and $p_L(t)$ are composed of DC(p_{dc})and AC(p_{ac}) power components. Thus, (27), (28) can be rewritten as (29) and (30), respectively.

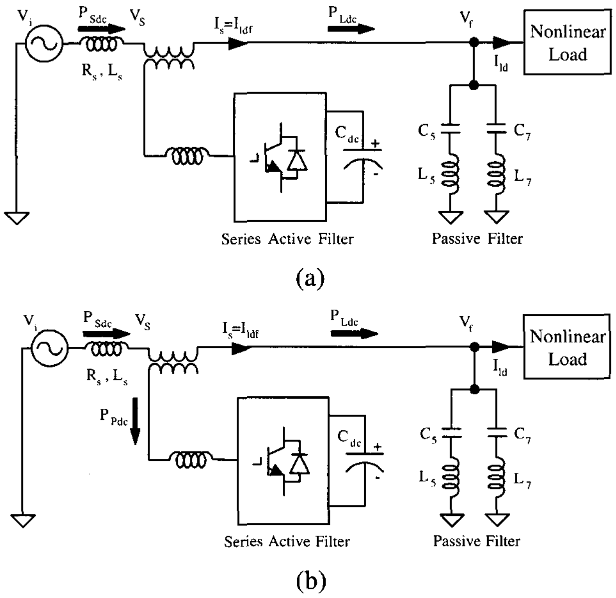


Fig. 12 Power Flow of the Hybrid active power filter. Normal load conditions; (b) Over current protection scheme in operation.

$$P_s(t) = v_{sa}i_{sa} + v_{sb}i_{sb} + v_{sc}i_{sc} \tag{27}$$

$$P_L(t) = v_{fa}i_{ald} + v_{fb}i_{bld} + v_{fc}i_{cld} \tag{28}$$

$$P_s(t) = p_{sdc} + p_{sac} \tag{29}$$

$$P_L(t) = p_{Ldc} + p_{Lac} \tag{30}$$

The harmonic power P_{Lac}, P_{Sac} are compensated with parallel passive filters and series active filters. Therefore, 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 power of the series active filter is shown in (31) and (32), respectively.

$$p_s(t) = v_{sa}i_{saf} + v_{sb}i_{sbf} + v_{ca}i_{scf} \tag{31}$$

$$P_L(t) = v_{fa}i_{aldf} + v_{fb}i_{bldf} + v_{fc}i_{cldf} \tag{32}$$

If the output voltages (v_{fa}, v_{fb}, v_{fc}) compensated with 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 powers $P_L(t)$ and $P_s(t)$ have only DC components, as shown in (33). Therefore, under normal load conditions, source and load power are identical.

$$p_s(t) = p_{sdc} = p_{Ldc} \tag{33}$$

If the series active filter protects the over current detected in the power distribution system, the active power P_{sdc} is different from P_{Ldc}. Fig. 12(b) shows over currents occurring in the power distribution system, that is, P_{sdc} is greater than P_{Ldc}. P_{Ldc} can be limited by using P_{pdc} from (34).

$$p_{sdc} = p_{Ldc} + p_{pdc} \tag{34}$$

Instantaneous power p_{pdc} is used to charge the DC-link, as a result DC-link voltage increases. Therefore, the amplitude and duration of over current depend on over-voltage level of DC-Link. This power can be used to charge the battery in the DC-link. If the duration of over current is a little long, discharging circuits are needed in the DC-link. However, in the short period of over current, excellent transient response is acquired without additional circuits. The validity of the proposed protection schemes is investigated through simulation and experimental results in the hybrid active power filter systems.

5. Simulation and experimental results

5.1 Unified Power Quality Conditioner

Table 1 shows simulation parameters for UPQC.

Table 1 Simulation Parameters

Parameters	Value
Input Voltage (V_{sa}, V_{sb}, V_{sc})	220V, 60Hz
Line Impedance (R_s, L_s)	0.2Ω, 0.025mH
DC-link Capacitor	13000 μF
DC-link Voltage	400V
C_{fs}, L_{fs}, R_{fs}	280 μF, 0.5mH, 0.5Ω
C_{fp}, L_{fp}, R_{fp}	17 μF, 1.5mH, 1Ω

The proposed protection scheme was studied using simulation tools and ACSL (Advanced Continuous Simulation Language). Fig. 13-15 show simulation results of UPQC in Fig. 1.

Fig. 13 shows the waveforms of voltage and current without any protection schemes. Fig. 14 and 15 show the waveforms of voltage and current when the over current protection schemes named Method I, II were applied, respectively. The over current happened at 0.2 second. If the over current appears in the power distribution system, a large current will be generated in the secondary of the transformer as shown in Fig. 13. However, when the over current occurred, Fig. 14, 15 showed that these proposed methods could reduce the source current substantially. Basic theory of Method I, II is the same as having a high impedance to the fundamental component of a source and load current. Therefore, simulation results are similar. When the protection scheme was applied, series converter absorbs the over current, and charges the DC-link. Charged DC-link discharges through parallel converter. Therefore, even though over current occurs four times larger than normal load, load current is limited effectively, and these methods have excellent transient response. However, there are some interruptions at load current about half cycle as shown in Fig. 14 and 15.

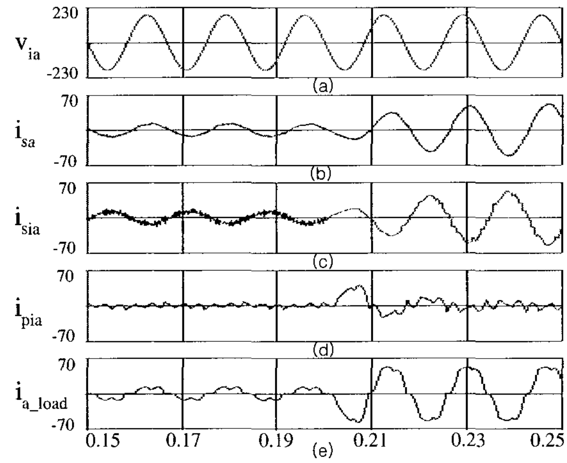


Fig. 13 Simulation waveforms without any protection scheme (a) Source voltage; (b) Source current; (c) Current of series active compensator; (d) Current of parallel active compensator; (e) Load current

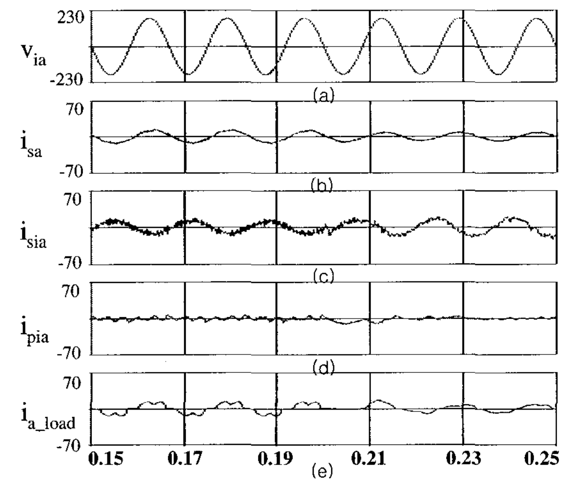


Fig. 14 Simulation waveforms in Method I (a) Source voltage, (b) Source current, (c) Current of series active compensator, Current of parallel active compensator, (e) Load current

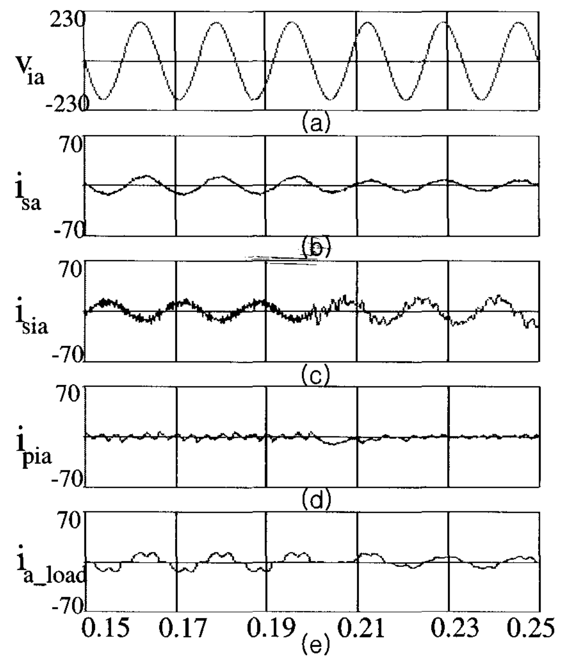


Fig. 15 Simulation waveforms in Method II (a) Source voltage, (b) Source current, (c) Current of series active compensator, (d) Current of parallel active compensator, (e) Load current

There are several advantages each method. Method I detects source current like a hybrid active power filter, and it controls to have a high impedance not only harmonics but also fundamentals. Therefore, it can be applied to the hybrid active power filter directly. Method II detects load current, the detection of load currents is indispensable to the parallel active power filter in the conventional UPQC because of the harmonic load current compensation. Therefore, to implement the over current protection scheme in UPQC systems, Method II is more efficient than Method I.

This Method can be applied to power conversion systems using a series converter.

5.2 Hybrid Active Power Filter

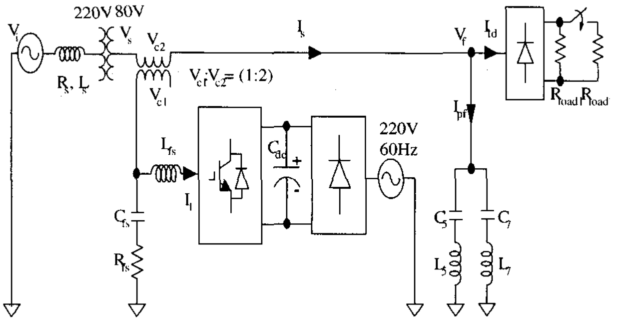
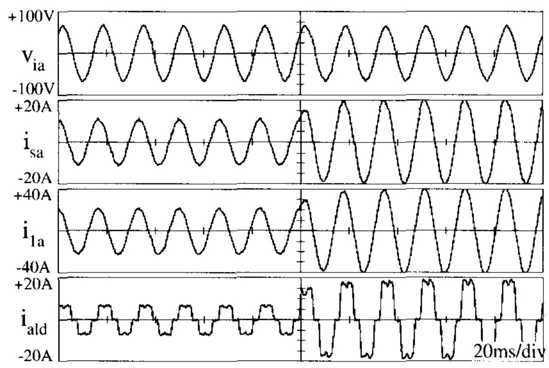


Fig. 16 Experimental setup of the Hybrid Active Power Filter.

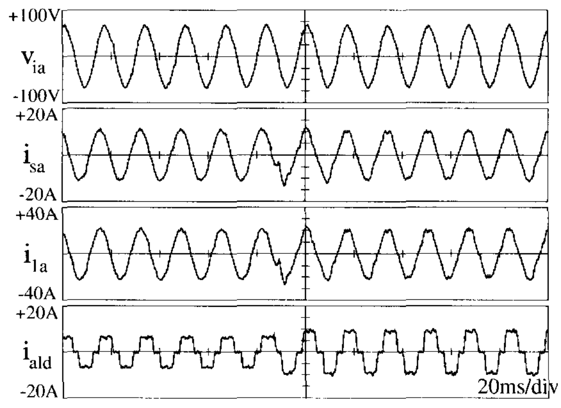
Fig. 16 shows the experimental setup of the Hybrid Active Power Filter. The series active power filter is inserted in series between the load and the mains using a transformer. A diode rectifier was used to charge the DC-link. Shunt passive LC filters used to compensate for load harmonics(fifth, seventh) are connected in parallel with the load. The over load condition of the experimental system was modelled as three times larger than the normal load.
For the purpose of avoiding serious problems, a step-down transformer was used to reduce the input voltage from 220V to 80V. When the system and control algorithms are stabilized, the input voltage was restored to its original level of 220(V). Table 2 shows the system parameters.

Table 2 Systems parameters.

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



(a)



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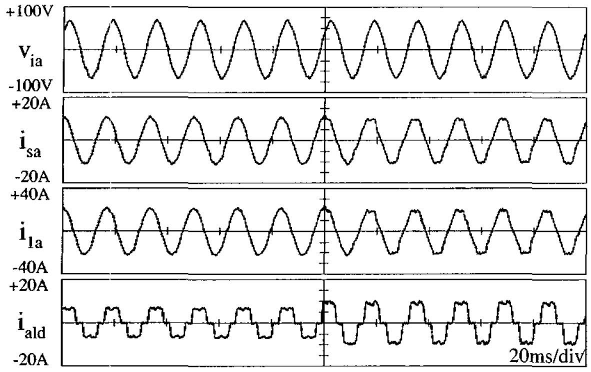
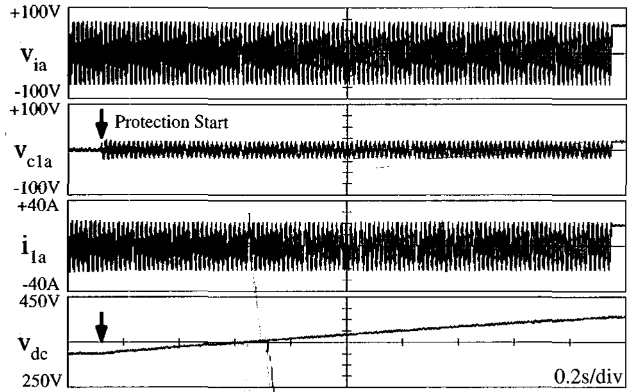


(c)



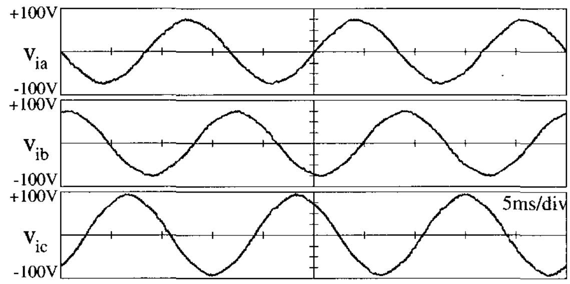
(d)

Fig. 17 Experimental waveforms during over current conditions. (a) Without any protection schemes; (b) Protection scheme Method I was applied; (c) Protection scheme Method II was applied; (d) Increase in DC-link voltage due to the over current protection scheme. (v_{ia} : Input voltage, i_{sa} : Source current, i_{1a} : Converter output current, v_{cia} : Converter output voltage, i_{ald} : Load current, v_{dc} : DC-link voltage)

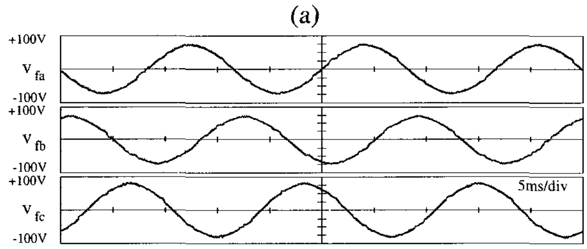
Fig. 17(a) shows the waveforms of the voltage and currents without any protection schemes. Fig. 17(b) and (c) show the waveforms of voltage and currents when the over current protection schemes named Method I, II were applied, respectively. If an over current appears in the power distribution system, a large current will be generated in the secondary of the transformer as shown in Fig. 17(a). However, when the over current occurred, Fig. 17(b), (c) showed that these proposed methods could reduce the source current substantially. Fig. 17(d) shows an increase in DC-link voltage due to the over current protection scheme. The level and duration of the over current depends on the level of DC-link voltage and capacity of the capacitor. As shown in Fig. 17(d), the system can protect against over currents for 2 seconds. This is due to the capacity of the capacitor is larger than a conventional one. As the capacitance decreases, the duration of over current decreases.

However, compared to the conventional protection method, the proposed protection methods have some advantages for instantaneous over currents. First, additional protection circuits are not needed. Second, excellent transient response can be achieved. Third, implementation is easy. However, if the duration of over current is long, additional discharging circuits may be necessary.

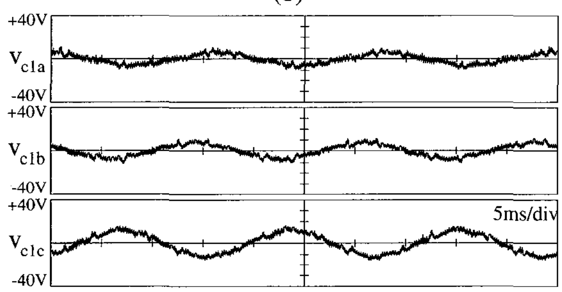
In the case of the proposed over current protection scheme, the rating of the series compensator is a little larger than that of a typical hybrid active power filter. However, many previous researches show that the series compensator compensates for an unbalanced source voltage, and in this case an increase in the converter rating is indispensable. Therefore, the rating of the converter is not a serious problem any more since the converter has to supply a negative sequence of current and voltage to the source.



(a)



(b)



(c)

Fig. 18 Experimental waveforms when the Hybrid Active Power Filter compensates for the imbalance of the source voltage. (a) Unbalanced three-phase input voltage; (b) Compensated three-phase Point of Common coupling (PCC) voltage; (c) Converter output voltage in a Hybrid Active Power Filter. (v_{ia}, v_{ib}, v_{ic} : Input voltage, v_{fa}, v_{fb}, v_{fc} : Point of common coupling voltage, v_{c1a}, v_{c1b}, v_{1cc} : Converter output voltage)

Fig. 18 and 19 show that there are no differences in the rating between the compensation 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 and how much over current is allowed. Fig. 18 shows the input voltage waveforms (a), compensated voltage waveforms (b) and converter output waveforms (c) with the assumption that the source voltage of C-phase steps up to 30%.

Fig. 19 shows the converter output voltage and current waveforms when the over current protection scheme was applied and unbalanced source voltage was compensated. When comparing the converter voltage (V_{cia}) and the current (i_{la}) of Fig. 19(a) with that of Fig. 19(b), it can be seen that there is little difference between them at the point of rating.

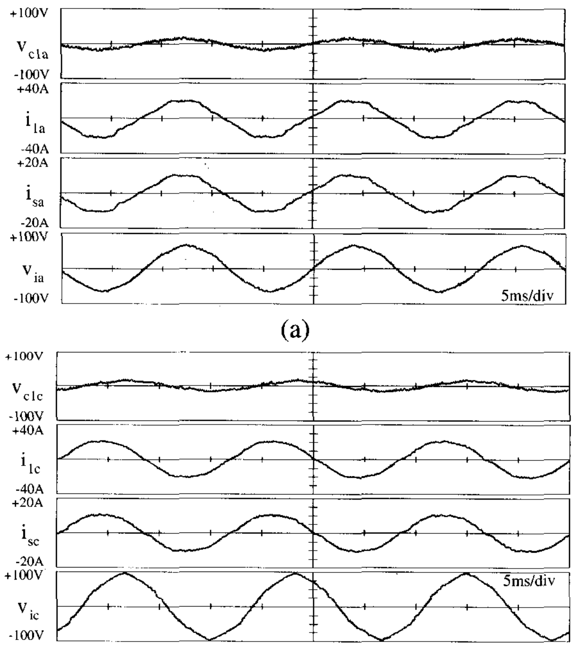


Fig. 19 Experimental waveforms for converter output voltage and current for one phase. (a) When an over current protection scheme was applied (about 3 times); (b) When the imbalance of source voltage was compensated (25% imbalance). (v_{cla} : Converter output voltage, i_{la} : Converter output current, i_{sa} : Source current, v_{ia} : Input voltage)

Fig. 20, 21 and 22 shows simulation results of the converter output current, source current, and converter output voltage in synchronous reference frame when over currents occur.

Fig. 20 shows the moment when the over current occurs. The d-axis current of the converter is increased from about –6A to +4A, and the q-axis current of the converter is increased from about +6A to +9A. The total current of converter was almost the same, and total current of source was also the same as shown in Fig. 21. However, the total voltage of converter was increased from 0 to 30V as shown in Fig. 22. Therefore, we know that when the proposed protection scheme is applied, the current rating of the converter is not increased but the voltage rating of the converter is increased. Step down transformers were used for safety. If the step down transformer was not used, the converter output voltage will increase to about 80V. Even if the proposed protection scheme is not used, if we just want to implement the HAPF, we have to use the IGBT with 600 volts in rating to resist the DC-link voltage of 300 – 400 voltage. Therefore, the voltage rating is not a big problem. The current and voltage rating call for a design of a series active compensator which can be designed equally like a conventional HAPF.

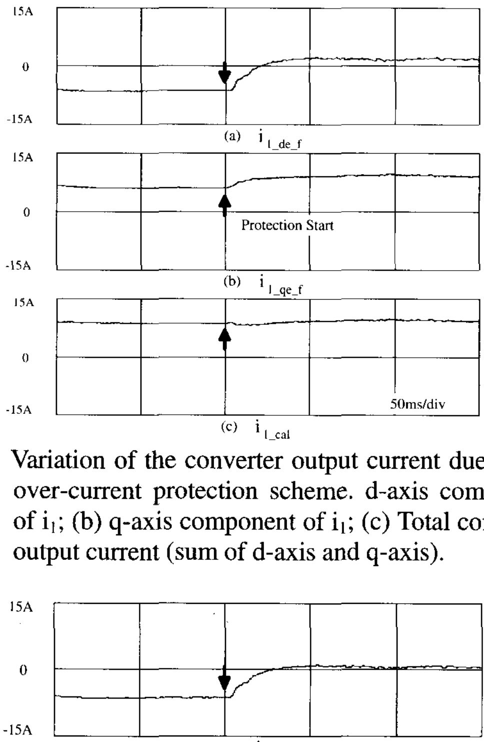


Fig. 20 Variation of the converter output current due to the over-current protection scheme. d-axis component of i_l; (b) q-axis component of i_l; (c) Total converter output current (sum of d-axis and q-axis).

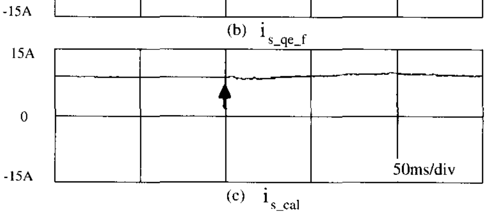


Fig. 21 Variation of the source current due to the over-current protection scheme. (a) d-axis component of i_s; (b) q-axis component of i_s; (c) Total source current (sum of d-axis and q-axis).

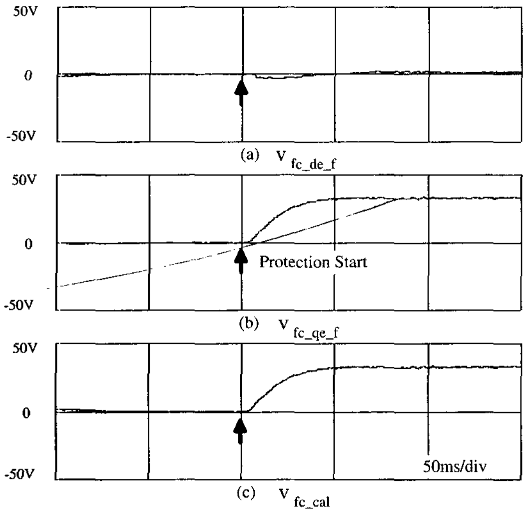


Fig. 22 Variation of the converter output voltage because of the over current protection scheme. (a) d-axis component of V_{fc}; (b) q-axis component of V_{fc}; (c) Total converter output voltage (sum of d-axis and q-axis).

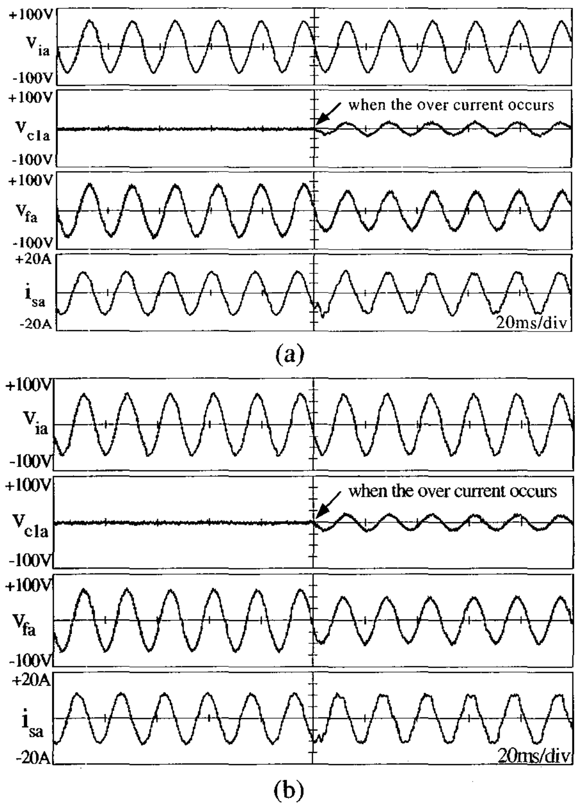


Fig. 23 Experimental waveforms for converter and inverter output voltage and current for one phase. (a) When an over current protection scheme, Method I, was applied (about 3 times); (b) When an over current protection scheme, Method II, was applied. (v_{ia} : Input voltage, v_{c1a} : Converter output voltage, V_{fa} : Inverter output voltage, i_{sa} : Source current,)

Fig. 23 shows waveforms of converter and output voltage when the over current protection schemes named Method I, II were applied respectively. Series converters output to limit the over current according to the protection algorithm as shown in Fig. 23. As a result, output voltage decreases, but source current sustains almost constantly. Voltage amplitude of series converter is decided by the gain k to limit the fundamentals. Fig.23(a) shows similar results of Fig. 23(b).

Although promising results were obtained, further research needs to be done related to input voltage of 220 volts and more severe over current conditions, and experiment of UPQC will be done.

6. Conclusion

Protection schemes for a series active compensator, which consists of a Unified Power Quality Conditioner (UPQC) or a hybrid active power filter, were presented and analyzed. The proposed series active compensator operates as a high impedance "k(Ω)" for the fundamental components when over currents occur in the power distribution system. Two control strategies are proposed in this paper. The first method detects the fundamental source currents using the p-q theory. The second method detects the fundamental component of load currents in the Synchronous Reference Frame (SRF).

Compared to conventional protection methods, the proposed protection methods have some advantages for instantaneous over currents. First, additional protection circuits are not required. Second, excellent transient response can be achieved. Third, Implementation is easy. However, if the duration of over current is long, additional discharging circuits may be required.

The validity of the proposed protection schemes was investigated through simulation and experimental results using the hybrid active power filter systems. During short periods of over currents in the power distribution system, the proposed schemes protect the series active compensator without the need for additional protection circuits. The validity of proposed protection scheme was investigated through simulation and experimental results using the hybrid active power filter systems.

Although promising results were obtained, further research needs to be done related to input voltage of 220 volts and more severe over current conditions.

Acknowledgements

This work was supported by a research grant from Hankyong National University in the year of 2002.

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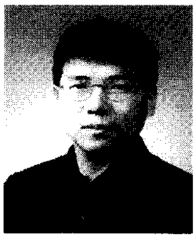

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