

Application Considerations and Compensation Characteristics of Shunt Active and Series Active Filters in Power Systems

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Abstract—This paper characterizes typical nonlinear loads into two types of harmonic sources—harmonic current source and harmonic voltage source, which produce highly distorted currents and voltages, respectively. The conventional approach of active harmonic compensation has been the parallel type or “shunt active filter.” It is shown in this paper that the shunt active filter is effective only to harmonic current sources but not to harmonic voltage sources. On the other hand, the active filter connected in series with the system or “series active filter” is very effective in suppression of the harmonic voltage sources. General compensation characteristics of shunt active filters and series active filters are given analytically. The features, required operation conditions, and application considerations of both filters are described analytically and demonstrated experimentally.

I. INTRODUCTION

Because the incidence of harmonic related problems in ac power systems is increasing, active power filters have attracted great attention and have been expected to be an effective remedy for alleviating the harmonic related problems. Generally, an active filter has been considered as a current source connected in parallel with the load (harmonic source). The approach is based on the principle of injecting harmonic current into the ac system, of the same amplitude and reverse phase to that of the load current harmonics. This type of active filters,

designated as shunt active filters here, are effective for those nonlinear loads which can be considered as current-source type of harmonic source (or abbreviated as harmonic current source), such as phase-controlled thyristor rectifiers with large dc inductance. Shunt active filters have been studied by many contributors since 1970s [1-9], and have been put into practical use [10-12]. However, no paper has discussed characteristics and application considerations of shunt active filters when they are applied to those nonlinear loads that are voltage-source type of harmonic source (abbreviated as harmonic voltage source), such as diode rectifiers with direct smoothing dc capacitors. This may be because traditional harmonic sources mainly were phase-controlled thyristor rectifiers and cycloconverters, which can be regarded as current-source loads.

On the other hand, since more and more diode rectifiers with smoothing dc capacitors are used in household appliances and ac drives, harmonics generated by these loads have become an issue. Naturally, one has tried to use the shunt active filters for harmonic compensation of these diode rectifiers. However, it has been found that the shunt active filters not only cannot cancel the harmonics completely but also cause problems such as enlarging the dc voltage ripples and ac peak current of the rectifier. A diode rectifier with smoothing capacitors behaves like a harmonic voltage source rather than a harmonic current source. Another fact is that there may be LC passive filters and power-factor correction capacitor banks connected on the load side (downstream) from the point where an active filter is connected. In this case, the equivalent circuit downstream from the connection point of active filter would not be a current source even if the main loads are a current source. When a conventional shunt active filter is applied to compensate such a diode rectifier or a power system that downstream contains passive filters and/or capacitor banks, the current injected by the active filter will flow into the diode rectifier or the load side that presents low impedance. As a result, harmonics of the source current cannot be completely canceled. Moreover, harmonic current flowing into the diode rectifier or the system downstream increases largely and overcurrent may occur due to the injected current.

A series active filter has been proposed to compensate for harmonics of diode rectifiers [16, 17]. Although the series active filter is not found in common practical use, Ref. [16] has shown that the series active filter is more suitable for harmonic compensation of diode rectifiers, i.e., harmonic voltage

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sources. This paper puts more emphasis on application considerations of both shunt and series active filters in power systems. Their features and required operation conditions are described analytically and demonstrated experimentally.

II. TWO TYPES OF HARMONIC SOURCES

A. Current-Source Type of Harmonic Sources (Harmonic Current Sources)

As a well-known fact, thyristor converters are a common and typical source of harmonic currents. The distortion of the current waveform, i.e., the generation of harmonics, results from the switching operation. Fig.1(a) shows a typical thyristor rectifier, where a sufficient dc inductance produces a constant dc current. Fig.2 shows the source voltage and rectifier current waveforms. Because the harmonic current contents and characteristic are less dependent upon the ac side, this type of harmonic source behaves like a current source. Therefore, they are called current-source type of harmonic source (or harmonic current source) and represented as a current source shown in Fig. 1(b).

B. Voltage-Source Type of Harmonic Sources (Harmonic Voltage Sources)

Nowadays, another type of common harmonic sources is diode rectifiers with smoothing dc capacitors as shown in Fig. 3(a). Fig. 4 shows the voltage and current waveforms. Although the current is highly distorted, its harmonic amplitude is greatly affected by the impedance of the ac side. Whereas the voltage of the rectifier (Fig. 4(b)) is characteristic and less dependent upon the ac impedance. Therefore, the diode rectifiers behave like a voltage source rather than a current source. Fig. 3(b) shows the equivalent circuit of the diode rectifier system, where the diode rectifier is represented as a voltage-source type of harmonic source (or harmonic voltage source). Accordingly, the harmonic current originates from the rectifier voltage, and its contents are determined by and dependent upon the rectifier voltage and the ac impedance.

III. CHARACTERISTIC ANALYSIS OF SHUNT ACTIVE FILTERS

A shunt active filter is to be placed in parallel with a load (or a harmonic source) to detect the harmonic current of the load and to inject a harmonic current with the same amplitude of that of the load into the ac system. In order not to lose generality, the harmonic current source is represented as Norton's equivalent circuit and harmonic voltage source as Thevenin's equivalent circuit, respectively, as shown in Figs. 5 and 6. A pure current-source type of harmonic source is a special case of the Norton's equivalent with $Z_L \rightarrow \infty$. A pure voltage-source type of harmonic source is a special case of Thevenin's equivalent with $Z_L \rightarrow 0$.

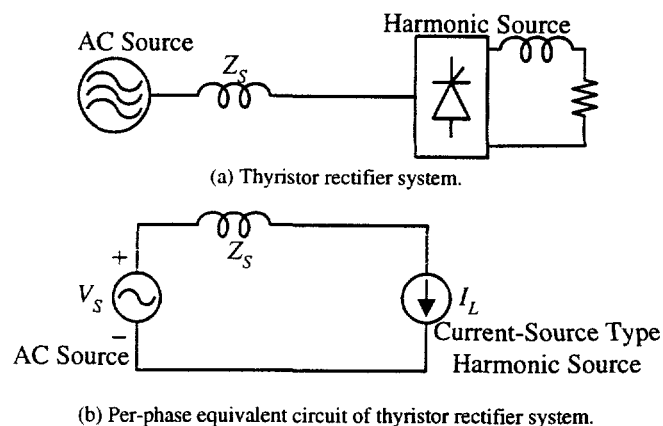


Fig. 1. Typical current-source type of harmonic source.

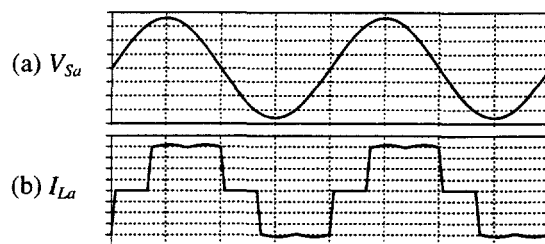


Fig. 2. Voltage and current waveforms of thyristor rectifier.

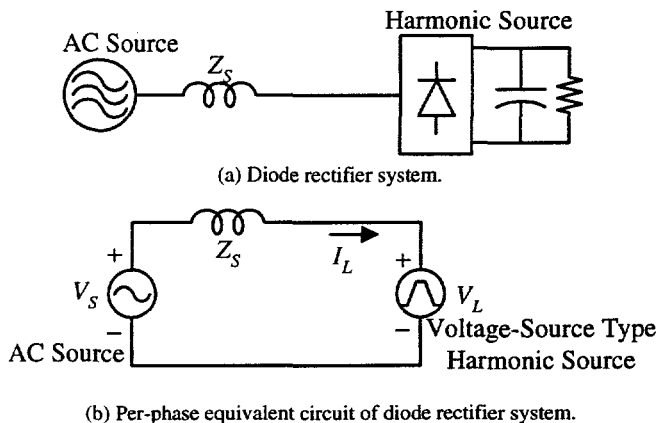


Fig. 3. Typical voltage-source type of harmonic source.

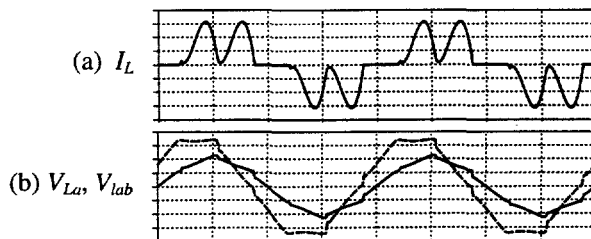


Fig. 4. Voltage and current waveforms of diode rectifier.

A. For Harmonic Current Sources

Fig. 5 shows the basic principle of a shunt active filter compensating for a harmonic current source, where the harmonic source is represented as Norton's equivalent, Z_S is the source (line) impedance, I_{LO} is the equivalent harmonic current source, Z_L is the equivalent impedance on the load side which may include passive filters and power-factor correction capacitors, and G is the equivalent transfer function of the active filter including the detection circuit of harmonics and the delay of the control circuit. In general, G has the function of notching the fundamental component, that is, $|G|_f=0$ at the fundamental, and $|G|_h=1$ for harmonics. In the following analysis, all equations are represented in per unit (pu). From Fig. 5, the following equations are obtained.

$$I_C = G I_L \quad (1)$$

$$I_S = \frac{Z_L}{Z_S + \frac{Z_L}{1-G}} \cdot I_{LO} + \frac{V_S}{Z_S + \frac{Z_L}{1-G}} \quad (2)$$

$$I_L = \frac{\frac{Z_L}{1-G}}{Z_S + \frac{Z_L}{1-G}} \cdot I_{LO} + \frac{1}{1-G} \cdot \frac{V_S}{Z_S + \frac{Z_L}{1-G}} \quad (3)$$

Focusing on harmonics, when the following equation

$$\left| \frac{Z_L}{1-G} \right|_h > |Z_S|_h, \quad (4)$$

is satisfied, (1), (2) and (3) can be rewritten as

$$I_C = I_{Lh} \quad (5)$$

$$I_{Sh} \approx (1-G)I_{LOh} + (1-G)\frac{V_{Sh}}{Z_L} \approx 0 \quad (6)$$

$$I_{Lh} = I_{LOh} + \frac{V_{Sh}}{Z_L}, \quad (7)$$

where, the subscripts, "h" and "f", represent the harmonic components and the fundamental components respectively. "1" represents the magnitude of a transfer function.

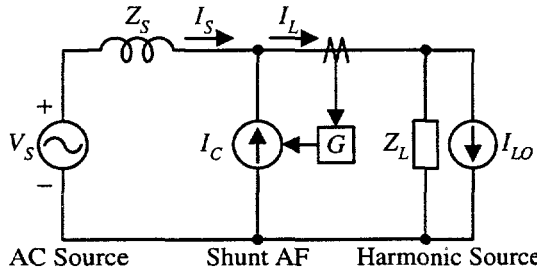


Fig. 5. Basic principle of shunt active filter for harmonic current source.

Equation (6) shows that the source current becomes sinusoidal when (4) is satisfied. Therefore, (4) is the required op-

erating condition for the shunt active filter to cancel the harmonic current. From (4), it is seen that only G can be pre-designed and determined by the active filter while Z_S and Z_L are determined by the system, i.e., parameters of the ac source and the load side. Therefore, compensation characteristics of the active filter are determined not only by the active filter itself but also by the ac source and load impedance just like the conventional passive filters. On the other hand, we have $|Z_L| \gg |Z_S|$ for a pure current-source type of harmonic source such as a thyristor rectifier with a large dc inductance. So (2) and (4) can be reduced to the following equations, respectively.

$$\frac{I_S}{I_{LO}} = (1-G) \quad (8)$$

$$|1-G|_h \ll 1. \quad (9)$$

Equation (8) shows that compensation characteristics of the active filter are not influenced by the source impedance, Z_S . So far this property has been allegedly claimed as the fact that the active filter is superior to the passive filter. However, this superior property holds true only under the condition of $|Z_L| \gg |Z_S|$. Equation (9) can be easily satisfied by the active filter. G is determined by the active filter, and mainly dominated by the detection circuit of harmonics, delay time of the control circuit, and current response of the inverter of the active filter. In general, $|1-G|_h=0.1-0.3$, so the compensation rate of harmonics, which is defined as $(1-|I_S/I_{LO}|) \cdot 100\%$, ranges over 90% ~ 70%.

However, the load impedance, Z_L , will become very low for harmonics when a shunt passive filter or power-factor improvement capacitor bank is connected on the side of the thyristor rectifier. Consequently, compensation characteristics of the active filter are influenced by the source impedance, Z_S , because the condition, $|Z_L| \gg |Z_S|$, is no longer satisfied [13]. Moreover, it is clear from (7) that the current flowing into the passive filter connected on the load side is equal to $I_{Lh} - I_{LOh} = V_{Sh}/Z_L$. This current may be devastatingly large when the ac source is stiff and has appreciable voltage distortion, V_{Sh} . This means that ambient harmonics upstream will flow into the passive filter. The load harmonic current, I_{LOh} , will be entirely compensated by the active filter but not by the passive filter. Therefore, special considerations are needed when a shunt passive filter and a shunt active filter are placed in the same power system. If one tries to use a combined system of shunt active filter and shunt passive filter to compensate load harmonics, the compensation responsibility of both the active filter and passive filter should be clear. For example, using an active filter to compensate for the 5th- and 7th- order harmonics and a passive filter for higher order harmonics is a good responsibility sharing of harmonic compensation, since an active filter is better for lower order harmonic compensation and a passive filter is better for higher order harmonic compensation. In this case, only the 5th- and 7th-order harmonics of the load current should be extracted as the reference of the active

filter so that the active filter would not inject higher order harmonic current into the line.

B. For Harmonic Voltage Sources

Fig. 6 shows the basic principle of shunt active filter compensating for a harmonic voltage source, where the load is represented as Thevenin's equivalent, i.e., a voltage source V_L with an impedance Z_L . From Fig. 6, we have the following equations.

$$I_C = GI_L, \quad (10)$$

$$I_S = \frac{V_S - V_L}{Z_S + \frac{Z_L}{1-G}}, \quad (11)$$

$$I_L = \frac{1}{1-G} \cdot \frac{V_S - V_L}{Z_S + \frac{Z_L}{1-G}} = \frac{V_S - V_L}{(1-G)Z_S + Z_L}. \quad (12)$$

Therefore, when the following equation

$$\left| Z_S + \frac{Z_L}{1-G} \right| \gg 1pu, \quad (13)$$

is satisfied, the source current will become sinusoidal. That is,

$$I_C = I_{Lh}, \quad (14)$$

$$I_{Sh} \approx 0, \quad (15)$$

$$I_{Lh} = \frac{V_{Sh} - V_{Lh}}{Z_L}. \quad (16)$$

Equation (13) is the required operation condition that should be satisfied when a shunt active filter compensates for harmonic voltage source. However, it is difficult for a shunt active filter to satisfy (13), because a harmonic voltage source usually presents a very low internal impedance, Z_L . For example, considering a diode rectifier with a large smoothing electrolytic dc capacitor, we have $|Z_L| \approx 0$ as long as no series reactor is placed on the ac side of the rectifier. So (13) cannot be satisfied only with the source impedance, Z_S , which is usually under 10 percent ($0.1 pu$). Provided that $|Z_S| = 3\% = 0.03pu$, $|1-G|_h = 0.1$ for the 5th-order harmonic, a series reactor of $0.06 pu$ (i.e., 6 percent) has to be placed on the ac side of the diode rectifier to let $|Z_S + Z_L/(1-G)| = 3pu$. Moreover, it is evident from (12), (14) and (16) that (i) the shunt active filter makes the source impedance equivalent to zero as seen from the load side, thus lowering ac impedance to the load, (ii) harmonic current injected by the shunt active filter will flow into the load, (iii) distortion of the source voltage, V_{Sh} , also causes a large harmonic current to flow into the load. These effects will largely increase the load harmonic current and the required Volt-Ampere (VA) rating of the shunt active filter, especially when Z_L is small. These problems will be shown in Section VI in more detail by simulation and experiment.

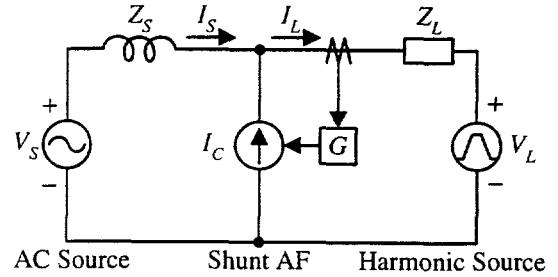


Fig. 6. Basic principle of shunt active filter for harmonic voltage source.

IV. CHARACTERISTIC ANALYSIS OF SERIES ACTIVE FILTERS

A series active filter discussed in this paper is to be placed in series between the ac source and the load (or harmonic source) to force the source current to become sinusoidal. The approach is based on a principle of harmonic isolation by controlling output voltage of the series active filter. In other words, the series active filter is to present high impedance to harmonic current, therefore blocking harmonic current flow from the load to the ac source and from the ac source to the load side. As in the preceding section, characteristics of series active filters are developed for harmonic current sources and harmonic voltage sources.

A. For Harmonic Current Sources

Fig. 7 shows the basic principle of a series active filter compensating for a harmonic current source, where V_C represents output voltage of the series active filter and the load (or harmonic source) is represented as Norton's equivalent. If the series active filter is controlled as

$$V_C = KGI_S, \quad (17)$$

then we get the source current as follows,

$$I_S = \frac{Z_L \cdot I_L}{Z_S + Z_L + KG} + \frac{V_S}{Z_S + Z_L + KG}, \quad (18)$$

where, G is the equivalent transfer function of a detection circuit of harmonic current, including delay time of the control circuit. G is supposed to equal zero at the fundamental and approximately equal to 1 for harmonics, that is, $|G|_f = 0$ and $|G|_h = 1$. K is a gain with the dimension of ohms in pu . Distortion voltage of the ac source, V_{Sh} , usually is much smaller than harmonic current of the harmonic source. So when

$$K \gg |Z_L|_h \text{ and } K \gg |Z_S + Z_L|_h \quad (19)$$

is satisfied, we have

$$V_C \approx Z_L I_{Lh} + V_{Sh}, \quad (20)$$

$$I_S \approx 0, \quad (21)$$

that is, the source current becomes sinusoidal. Here, (19) is the required operating condition for the series active filter to com-

compensate for a harmonic current source. Equation (19) requires that the gain, K , should be large and the impedance of the load side, $|Z_L|_h$, be small for harmonics, in order to suppress the source harmonic current. However, for a conventional phase-controlled thyristor rectifier, Z_L is almost infinite, so (19) cannot be satisfied. And it is clear from (20) that the required output voltage of the series active filter, V_C , also becomes infinite. As a result, the series active filter cannot compensate for a current-source type of harmonic source theoretically. If a shunt passive filter is placed with the thyristor rectifier, however, Z_L will become very small, (19) can be easily satisfied, and the required output voltage, V_C , becomes very small as well. This case is the combined system of series active filter and shunt passive filter, which has been discussed in [14]. In addition, it should be noted that the series active filter has a very important feature, that is, it provides harmonic isolation between the source and load. Equations (20) and (21) mean that neither the source harmonics, V_{sh} , will appear on the load side, nor the load harmonics, I_{Lo} , will flow into the ac source.

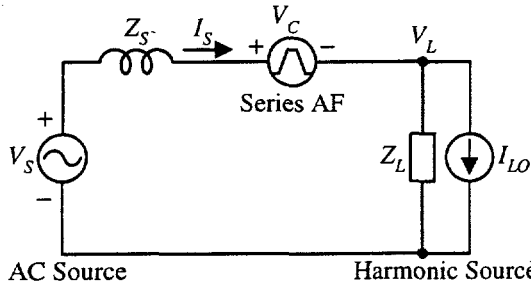


Fig. 7. Basic principle of series active filter for a harmonic current source.

B. For Harmonic Voltage Sources

Fig. 8 shows the basic principle of series active filter compensating for a harmonic voltage source. If the series active filter is controlled as

$$V_C = KGI_s, \quad (22)$$

the source current becomes

$$I_s = \frac{V_s - V_L}{Z_s + Z_L + KG}. \quad (23)$$

Therefore, when (24) is satisfied, we have (25) and (26) as:

$$K \gg 1pu, \quad (24)$$

$$I_s \approx 0, \quad (25)$$

$$V_C \approx V_{sh} - V_{Lh}. \quad (26)$$

Equation (24) is the required operating condition for the series active filter to compensate for a harmonic voltage source. To realize a large gain, K , the hysteresis-comparator control method shown in Fig. 9 can be adapted. In this case, we have almost $K = \infty$. Also, the ramp-comparison control method

shown in Fig. 10 can be utilized, where the reference of output voltage, V_C^* , is given by

$$V_C^* = G(KI_s - V_L). \quad (27)$$

Hence, assuming $V_C = V_C^*$ the source current becomes

$$I_s = \frac{V_s - (1-G)V_L}{Z_s + Z_L + KG}. \quad (28)$$

When V_{sh} is small and

$$|1-G|_h \ll 1. \quad (29)$$

is satisfied, the source current becomes sinusoidal even with $K=1pu$ and $|Z_s+Z_L| \ll K$, that is,

$$I_{sh} = -(1-G)V_{Lh} \approx 0. \quad (30)$$

Equation (29) is the required operating condition for the series active filter to compensate for a harmonic voltage-source load, which depends only on the series active filter itself. It is also clear from (30) that the compensation characteristics of the series active filter are independent from the source impedance Z_s and the load impedance Z_L . Hence the series active filter can suppress harmonics of the source current effectively. These conclusions of the series active filter compensating for a harmonic voltage-source load are completely equivalent to those of the shunt active filter compensating for a harmonic current-source load. Experimental verification is shown in Section VI.

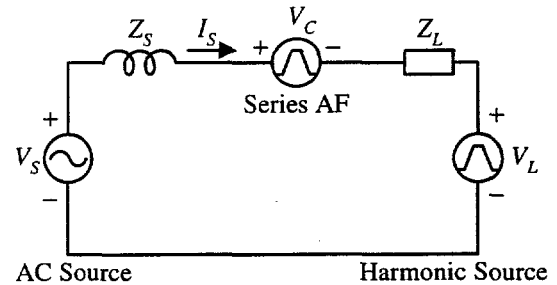


Fig. 8. Basic principle of series active filter for a harmonic voltage source.

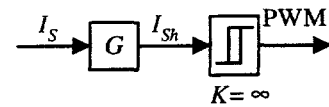


Fig. 9. Hysteresis control method for series active filter.

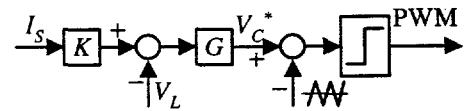


Fig. 10. Ramp-comparison control method for series active filter.

V. COMPARISON OF SHUNT ACTIVE FILTERS AND SERIES ACTIVE FILTERS

In the previous sections, compensation characteristics of shunt active filters and series active filters were analyzed theoretically. The corresponding required operation conditions of both shunt active filter and series active filter for harmonic current sources and harmonic voltage sources were derived, respectively. In circuit configurations, duality relationships exist between the shunt active filter and the series active filter, that is, Fig. 5 is the dual of Fig. 8, and Fig. 6 is the dual of Fig. 7. Therefore, the properties of the corresponding adaptive loads (harmonic sources) are the dual of each other.

Table 1 summarizes comparisons of shunt active filters and series active filters, where their respective features and application considerations are concluded.

VI. EXPERIMENTAL RESULTS OF COMPENSATION FOR HARMONIC VOLTAGE SOURCES

For a harmonic current-source load shown in Fig. 5, compensation characteristics of the shunt active filters have been discussed in many papers. This configuration has been considered as a typical case to study active filters. In addition, the combined system of series active filter and shunt passive filter, which is a case of Fig. 7, has been presented in [14, 15]. However, compensation characteristics for harmonic voltage sources have not been studied so far. Therefore, for a typical harmonic voltage-source load, a diode rectifier with smoothing

dc capacitor, characteristics of both shunt active filter and series active filter are discussed in this section by simulation and experiment.

A. Shunt Active Filters

Fig. 11 shows the practical system configuration discussed here by simulation and experiment, where the circuit constants are indicated in detail. L_r , C_r and R_r form a small passive filter to reduce the pulse width modulation (PWM) switching ripples generated from the inverter. The equivalent transfer function of the shunt active filter, G , is given by

$$G(s) = kG_n e^{-\tau s} \frac{\omega_0}{s + \omega_0}, \quad (31)$$

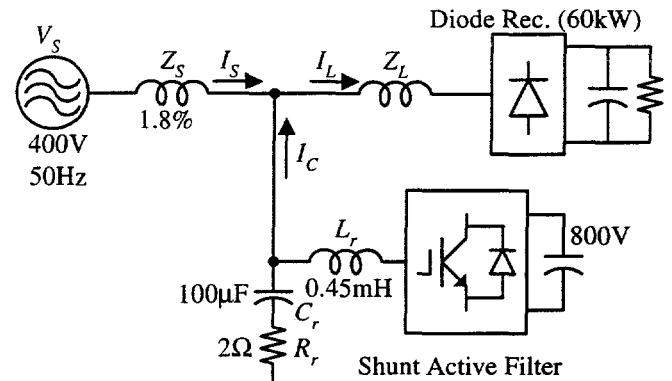
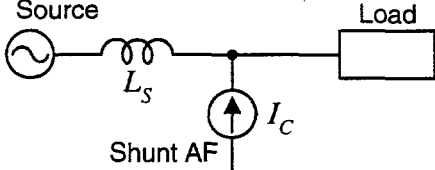
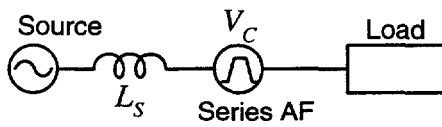


Fig. 11. System configuration of shunt active filter.

Table 1. Comparison of shunt active filters and series active filters

System Configuration		
Basic Operating Principle	Operates as a current source	Operates as a voltage source
Adaptive Loads	Inductive or current-source loads or harmonic current sources, e.g., phase-controlled thyristor rectifiers	Capacitive or voltage-source loads or harmonic voltage sources, e.g., diode rectifiers with direct smoothing capacitors
Required Operation Conditions	Z_L should be high and the active filter should meet $ 1 - G _h \ll 1$	Z_L should be low and the active filter should meet $ 1 - G _h \ll 1$
Compensation Characteristics	Excellent and independent of the source impedance, Z_S , for current-source loads, but depend on Z_S when the load impedance, Z_L , is low	Excellent and independent of the source impedance, Z_S , and the load impedance, Z_L , for voltage-source loads, but depend on Z_L when the loads are a current-source type
Application Considerations	Injected current flows into the load side and may cause overcurrent when applied to a capacitive or voltage-source load	A low impedance shunt branch (shunt passive filter or power-factor improvement capacitor bank) is needed when applied to an inductive or current-source load

where, k is the equivalent gain ($k=1\pm0.01$, the error results from the precision of current sensors and current control), G_n is the equivalent transfer function of the harmonic detection circuit where the pq theory (in the experimental system, first-order high-pass filter with cutoff frequency, $f_c=30\text{Hz}$, is used) or the synchronous reference frame can be used (see [15] and [8] for details), τ is the delay time of the control circuit (a DSP digital control is used in the practical system, $\tau=30\mu\text{sec}$), and $\omega_p/(s+\omega_p)$ is the transfer function of the isolation amplifier used in the control circuit. From (11), the compensation characteristics can be obtained as

$$\left| \frac{I_s}{V_L} \right|_{V_s=0} = \left| \frac{1}{Z_s + \frac{Z_L}{1-G}} \right| \quad (32)$$

Fig. 12 shows the theoretical values plotted in the solid lines. It is clear that the smaller the load impedance, the worse are the compensation characteristics. Fig. 13 shows the simulation waveforms with $Z_L=0.24\%$ (the series ac reactor shown in Fig. 11). Several of harmonics remained in the source current after the shunt active filter was started. In addition, harmonic current of the load, especially the peak value, increases largely due to the injected harmonic current from the active filter, which may cause overcurrent. When the series reactance Z_L is reduced to zero, the shunt active filter will form a positive feedback, as one can image, because the injected current will completely flow into the load side and then will be picked up by the active filter itself as its current reference.

With the same conditions, experiments were performed. The experimental waveforms are shown in Fig. 14, which exactly agree with the simulation waveforms shown in Fig. 13. The FFT results of the experimental waveforms are plotted as "x" in Fig. 12, which agree with the calculated results very well. In Fig. 14, the dc voltage of the shunt active filter was 800V, the rms VA rating and the peak VA rating* of the active filter were 76% and 123% of that of the load, respectively. Therefore, it is not economical and practical for a shunt active filter to compensate for a harmonic voltage-source load, especially when the load-side impedance is low, because the required VA rating of the shunt active filter may be even larger than that of the load. In the case of applying a shunt active filter to a harmonic voltage source, it is necessary that a series reactor should be placed on the load side to enhance the load impedance. Fig. 15 shows experimental waveforms with larger series inductance, $Z_L=7.3\%$. In this case, the source current, I_s , becomes sinusoidal, and the rms and peak VA ratings of the shunt active filter were 33% and 49% of that of the diode rectifier, respectively. Therefore, to compensate for a harmonic voltage source a minimum 6% of series inductance should be placed on the load side to meet the required operation conditions as mentioned in Section III.B.

*The peak VA rating is defined as the product of peak voltage value and peak current value, divided by 2, that is, the peak VA rating $= (V_p/\sqrt{2}) \cdot (I_p/\sqrt{2})$.

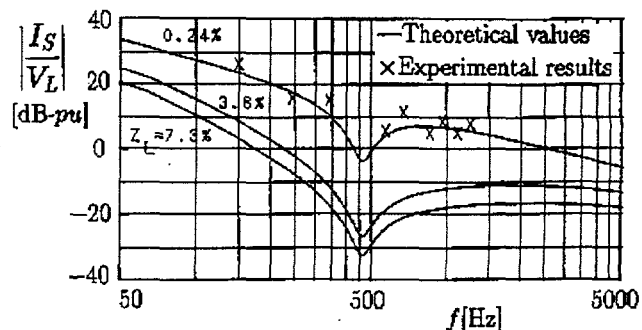


Fig. 12. Compensation characteristics of shunt active filter for a harmonic voltage source with different load impedances.

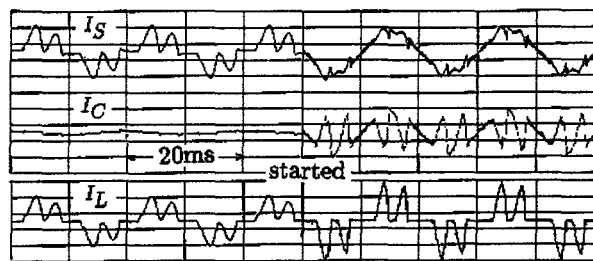


Fig. 13. Simulated waveforms of shunt active filter for a harmonic voltage source (diode rectifier) with $Z_L=0.24\%$.

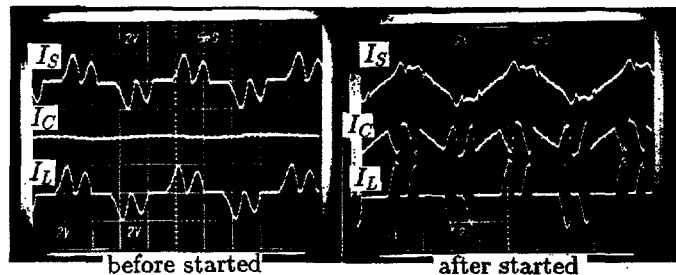


Fig. 14. Experimental waveforms of shunt active filter for a harmonic voltage source (diode rectifier) with $Z_L=0.24\%$, I_s , I_C , and I_L : 200A/div, time: 5ms/div.

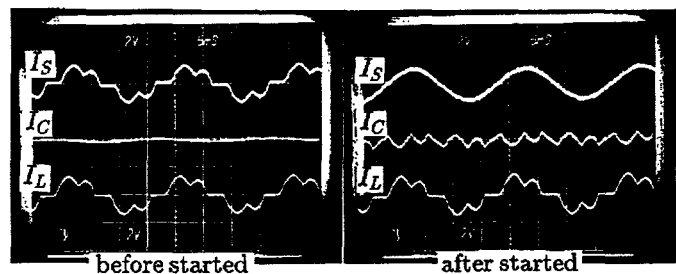


Fig. 15. Experimental waveforms of shunt active filter for a harmonic voltage source (diode rectifier) with $Z_L=7.30\%$, I_s , I_C , and I_L : 200A/div, time: 5ms/div.

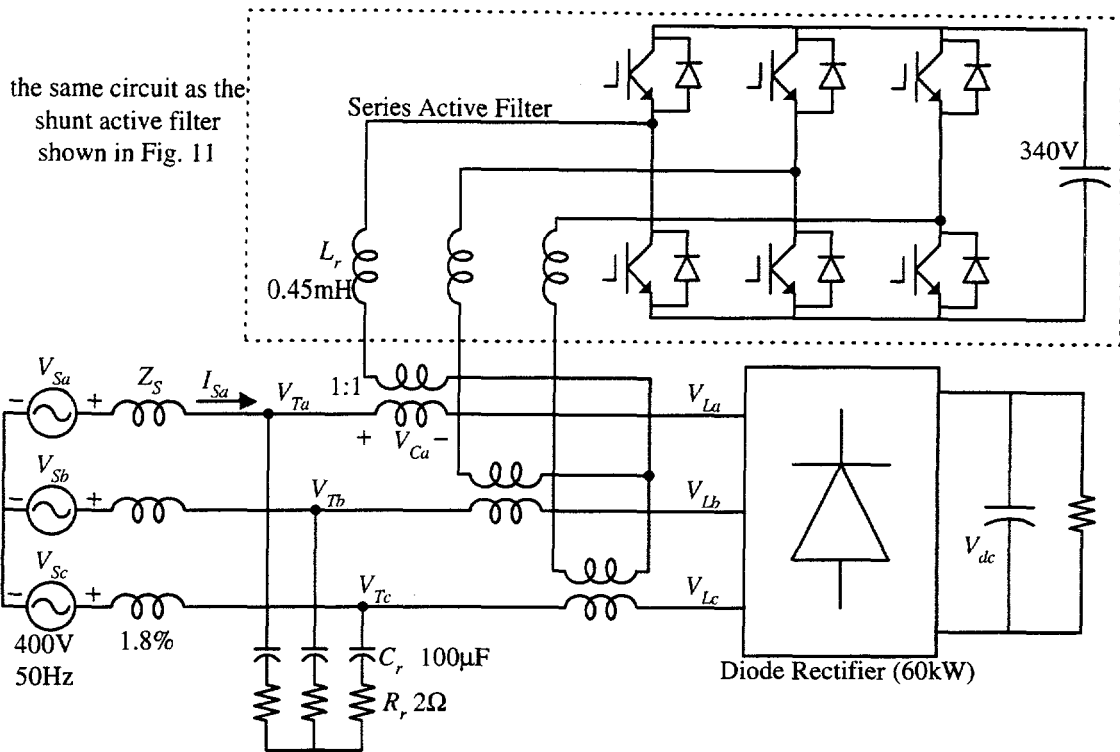


Fig. 16. System configuration of series active filter for harmonic compensation of a diode rectifier.

B. Series Active Filters

From the above-mentioned theoretical and experimental results, it is evident that the injected harmonic current from a shunt active filter flows into the load side rather than into the source side for a harmonic voltage-source load, thus being unable to cancel the harmonic current of the source and enlarging harmonic current of the load. To solve the above problems, a large series reactor should be placed on the load side. However, a large series reactor is bulky, increases costs, and causes a fundamental voltage drop, hence undesirable. Since it has been shown in the previous analysis that series active filters are better suited for harmonic compensation of a harmonic voltage source, a series active filter is applied to harmonic compensation of the diode rectifier in this section. The validity is corroborated by experiment.

Fig. 16 shows the system configuration of a series active filter used to compensate for the diode rectifier. The series active filter is placed between the ac source and the load through a three-phase transformer, the main circuit of which is the same circuit used in the shunt active filter shown in Fig. 11, composed of three-phase bridge PWM inverter. L_r , C_r , and R_r form a switching ripple trap just like the switching ripple filter used in the shunt active filter. The hysteresis control method shown in Fig. 9 is used, the average switching frequency is 4 kHz, and the dc voltage of the series active filter is 340V, which is much lower than that of the shunt active filter of Fig. 11.

Figs. 17, 18 and 19 show experimental and simulated waveforms under the same conditions. Note that no series reactor is placed on the rectifier side, that is, $Z_L=0$. After the series active filter was started, the source current became sinusoidal. The output voltage of the series active filter, V_C , was 65V. Without the aforementioned problems of the shunt active filter, the series active filter has excellent compensation characteristics. The rms VA rating of the series active filter was 25% of that of the load. Also, it is clear that since the current (in this case, the source current is equal to the load current) becomes sinusoidal, the peak value of the load current and the ripples of the dc voltage of the rectifier, are minimized. In addition, the series active filter and the diode rectifier can share the same dc capacitor (source) by selecting an appropriate turns ratio for the isolation transformer [17]. In this way, the dc voltage control will become very easy.

VII. CONCLUSIONS

In this paper, common nonlinear loads have been characterized into two types of harmonic sources, current-source type of harmonic source and voltage-source type of harmonic source. Compensation characteristics of both shunt active filters and series active filters have been discussed theoretically and experimentally for these two types of harmonic sources. The corresponding required operation conditions, features, application considerations, and adaptive harmonic sources of both filters have been presented. It has been clearly addressed

that the traditional active filter, the shunt (or parallel) active filter, is not panacea to harmonic compensation and one cannot use it blindly. The shunt active filter will increase harmonic current and may cause overcurrent of the load when the load is a harmonic voltage source. Instead, it has been verified that the series active filter is more suited for compensation of a harmonic voltage source such as a diode rectifier with smoothing dc capacitor. This paper also implies that when a shunt active filter is installed in a power system network such as at a point of common coupling, the network impedance and main harmonic sources downstream from the installation point should be investigated in order to get good performance and to minimize influence to the loads downstream. In some cases, a combined system of shunt active filter and series active filter may be necessary by utilizing the harmonic isolation function of the series active filters.

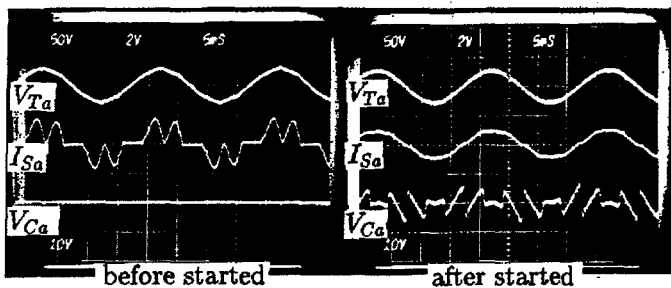


Fig. 17. Experimental results of series active filter, V_{Ta} : 635V/div, I_{Sa} : 200A/div, V_{Ca} : 254V/div, time: 5ms/div.

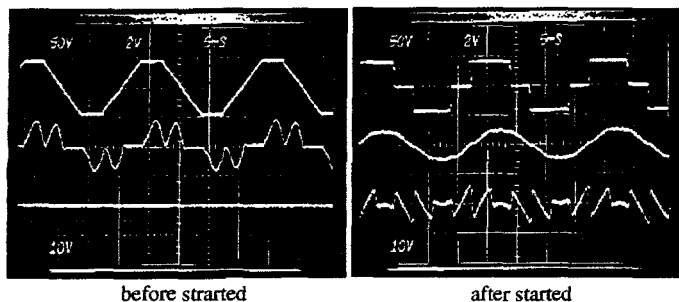


Fig. 18. Experimental results of series active filter, upper trace= V_{Lab} : 635V/div, middle trace= I_{Sa} : 200A/div, lower trace= V_{Ca} : 254V/div, time: 5ms/div.

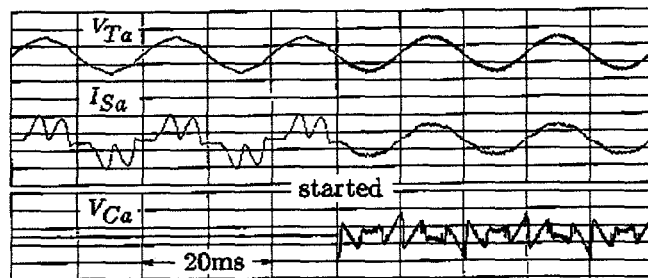


Fig. 19. Simulated results of series active filter.

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REFERENCES

- [1] H. Sasaki and T. Machida, "A New Method To Eliminate AC Harmonic Currents By Magnetic Compensation—Considerations On Basic Design," *IEEE Trans. PAS*, Vol.90, no. 5:pp.2009, 1971.
- [2] L. Gyugyi and E. C. Strycula, "Active AC Power Filters," *IEEE/IAS Annual Meeting*, pp.529, 1976.
- [3] N. Mohan, H.A. Peterson, W.F Long, G. R. Dreifaerst, and J.J. Vithayathil, "Active Filters For AC Harmonic Suppression," *IEEE PES Winter Meeting*, A77 026-8, 1977.
- [4] H. Akagi, A. Nabae, and S. Atoh, "Control Strategy of Active Power Filters Using Voltage-Source PWM Converters," *IEEE Trans. Ind. Appl.*, vol.22, no.3:pp.460, 1986.
- [5] K. Komatsugi and T. Imura, "Harmonic Current Compensator Composed of Static Power Converter," *IEEE/PESC*, pp.283, 1986.
- [6] K. Hayafune, T. Ueshiba, E. Masada, and Y. Ogiwara, "Microcomputer Controlled Active Power Filter," *IEEE/IECON*, pp.1221, 1984.
- [7] S. Bhattacharya, A. Veltman, D. M. Divan and R.D. Lorenz, "Flux Based Active Filter Controller," *IEEE/IAS Annual Meeting*, pp. 2483–2491, 1995.
- [8] Subhashish Bhattacharya and Deepak. M. Divan, "Synchronous Frame Based Controller Implementation for a Hybrid Series Active Filter System," *IEEE/IAS Annual Meeting*, 1995. pp. 2531–2540.
- [9] S.M. Williams and R.G. Hoft, "Implementation of Current Source Inverter for Power Line Conditioning," *IEEE/IAS Annual Meeting*, pp.1071–1080, 1990.
- [10] M. Takeda, K. Ikeda, Y. Tominaga, and K. Oku, "Harmonic Current Compensation with Active Filters," *IEEE/IAS Annual Meeting*, pp.808, 1987.
- [11] M. Kohata, et al, "Practical Active Power Filters Using SI Thyristors," *Proc. of ISPE*, 1989.
- [12] N. Watanabe, "Applications of Active Power Filters to UPS Systems," *Proc. of ISPE*, 1989.
- [13] F.Z. Peng, et al, "Some Considerations on Active Power Filters Using PWM Converters," *IEE of Japan, PE-86-154*, 1986. (in Japanese)
- [14] F.Z. Peng, H. Akagi, and A. Nabae, "A New Approach to Harmonic Compensation in Power Systems," *IEEE/IAS Annual Meeting*, pp.874, 1988.
- [15] F.Z. Peng, H. Akagi, and A. Nabae, "Compensation Characteristics of the Combined System of Shunt Passive and Series Active Filters," *IEEE/IAS Annual Meeting*, pp.959–966, 1989.
- [16] F.Z. Peng et al, "Compensation Characteristics of Shunt Active and Series Active Filters," *Chinese-Japanese Power Electronics Conference*, pp.381–387, Beijing China, 1992.
- [17] H. Akagi, "New Trends in Active Filters," *EPE Conference, Sevilla*, pp.0.017–0.026, 1995.