Design strategy for the combined system of shunt passive and series active filters

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Abstract— The authors have already proposed the combined system of a shunt passive filter and a small-rated series active filter. The purpose of the series active filter is to solve such a problem as series and parallel resonance which is inherent in a shunt passive filter used alone.

This paper presents design strategy of the combined power filter for a three-phase twelve-pulse thyristor rectifier. The shunt passive filter, which can minimize the output voltage of the series active filter, is designed and tested in a prototype model. A specially designed shunt passive filter makes it possible to reduce the required rating of the series active filter to 60%, compared with a conventional shunt passive filter.

INTRODUCTION

The authors have already proposed a combined system of a shunt passive filter and a small-rated series active filter[1][2]. The shunt passive filter compensates for harmonics produced by the load, while the series active filter improves compensation characteristics of the shunt passive filter. This results not only in elimination of parallel and series resonance between the source and the shunt passive filter, but also in a great reduction of the required rating of the series active filter.

This paper presents design strategy of the combined power filter for a three-phase twelve-pulse thyristor rectifier. Design of the shunt passive filter is discussed, paying attention to the required rating of the series active filter. As a result, the shunt passive filter designed to minimize the peak voltage of the series active filter makes it possible to reduce the required rating of the series active filter to 60%, compared with a conventional shunt passive filter. The characteristics of the combined system using the designed shunt passive filter are discussed by digital simulations, and verified by experiments in a small-rated laboratory model.

COMBINED FILTER SYSTEM

System Configuration

Fig.1 shows a combined power filter[1], which is designed and used for experiment in this paper. A shunt passive filter of rating 10kVA consists of a 11th- and 13th-tuned LC filter and a high pass filter. It is installed in parallel with a three-phase twelve-pulse thyristor rectifier of rating 20kVA. A series active filter of rating 0.18kVA consists of three single-phase voltage-source PWM inverters using twelve MOS-FET's, which are connected in series with the source by three current transformers having a turn ratio of 1 to 20.

The shunt passive filter suppresses harmonic currents produced by the thyristor rectifier, just like a conventional one does. On the other hand, the series active filter does not act as a harmonic compensator, but acts as a harmonic isolator, which forces no harmonic current to flow in the source. As a result, the combined filter can eliminate series and parallel resonance inherent in a shunt passive filter used alone. In addition, the rating of the series active filter is much smaller than that of a conventional shunt active filter.

Compensation Principle

A control circuit is also shown in Fig.1. The source harmonic current $\mathbf{i}_{Sh}$ are detected and calculated by applying the p-q theory[3]. The detected harmonics are amplified by gain K, and given to the series active filter as voltage reference

$$\mathbf{v}_C^* = \mathbf{K} \cdot \mathbf{i}_{Sh}. \tag{1}$$

As a result, the series active filter acts as pure resister $\mathbf{K}$ for the source harmonic current.

Fig.2 shows a single-phase equivalent circuit of the combined filter system in Fig.1, where the series active filter is a controllable voltage source $\mathbf{V}_C$, and the thyristor rectifier is a current source $\mathbf{I}_L$. The source harmonic current $\mathbf{I}_{Sh}$, the terminal harmonic voltage $\mathbf{V}_{Th}$, and the output voltage of the series active filter $\mathbf{V}_C$ are given as follows.

$$\mathbf{I}_{Sh} = \frac{\mathbf{Z}_F}{\mathbf{K}+\mathbf{Z}_S+\mathbf{Z}_F}\mathbf{I}_{Lh} + \frac{\mathbf{V}_{Sh}}{\mathbf{K}+\mathbf{Z}_S+\mathbf{Z}_F} \tag{2}$$

$$\mathbf{V}_{Th} = -\frac{(\mathbf{K}+\mathbf{Z}_S)\mathbf{Z}_F}{\mathbf{K}+\mathbf{Z}_S+\mathbf{Z}_F}\mathbf{I}_{Lh} + \frac{\mathbf{Z}_S}{\mathbf{K}+\mathbf{Z}_S+\mathbf{Z}_F}\mathbf{V}_{Sh} \tag{3}$$

$$\mathbf{V}_C = \frac{\mathbf{K}\mathbf{Z}_F}{\mathbf{K}+\mathbf{Z}_S+\mathbf{Z}_F}\mathbf{I}_{Lh} + \frac{\mathbf{K}}{\mathbf{K}+\mathbf{Z}_\mathbf{S}+\mathbf{Z}_\mathbf{F}}\mathbf{V}_{Sh} \tag{4}$$

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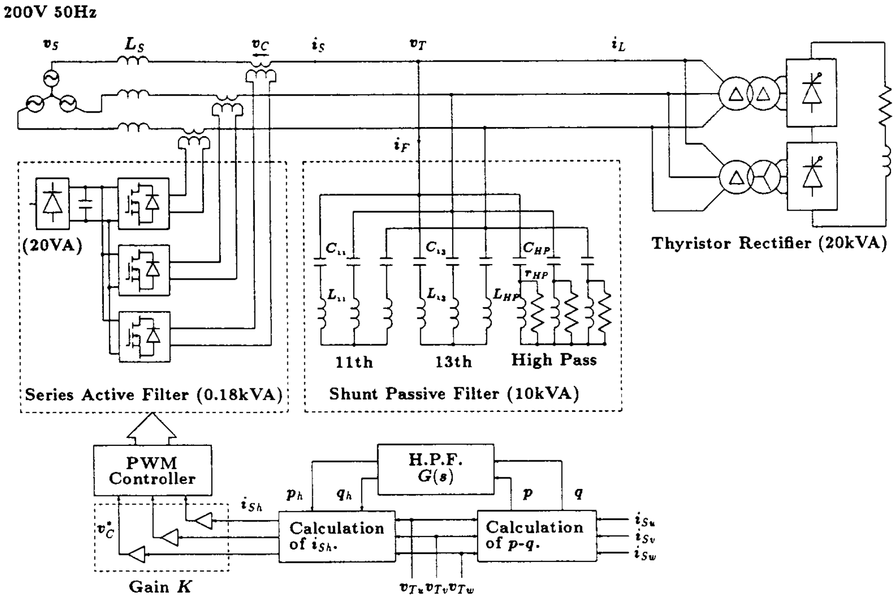


Fig. 1. Combined system of series active filter and shunt passive filter.

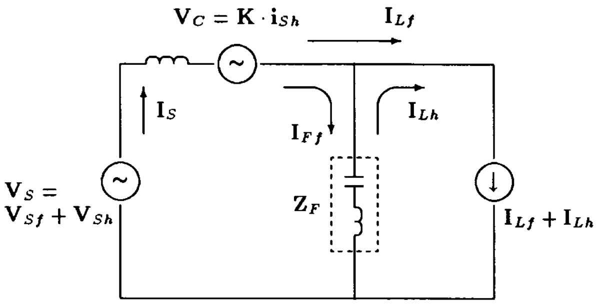


Fig. 2. Single-phase equivalent circuit.

If $\mathbf{K} \gg |\mathbf{Z}_F|$, all the harmonic currents produced by the load would sink into the shunt passive filter. If $\mathbf{K} \gg |\mathbf{Z}_S|$, $\mathbf{K}$ would dominate the filtering characteristics. Applied to the series active filter, $\mathbf{V}_{Sh}$ does not appear in the terminal voltage. In addition, $\mathbf{K}$ acts as a resistor to damp parallel resonance between $\mathbf{Z}_S$ and $\mathbf{Z}_F$.

DESIGN OF SHUNT PASSIVE FILTER

As mentioned above, the combined filter system can improve the characteristics of the shunt passive filter, and eliminate the series and parallel resonance. These advantages make it easy to design the shunt passive filter used with the series active filter, compared with that used alone. Let's discuss the shunt passive filter, which can reduce the required rating of the series active filter.

Design Strategy

Let's assume an ideal condition, where no harmonic current escape to the source. By setting $K = \infty$ in Eq.(4), the output voltage of the series active filter is given as follows.

$$\mathbf{V}_C = \mathbf{Z}_F\mathbf{I}_{Lh} + \mathbf{V}_{Sh} \tag{5}$$

The current flowing through the series active filter is a vector sum of the fundamental current of the load, $\mathbf{I}_{Lf}$ and the fundamental leading current of the shunt passive filter, $\mathbf{I}_{Ff}$. The required rating of the series active filter is given by

$$|\mathbf{Z}_F\mathbf{I}_{Lh} + \mathbf{V}_{Sh}| \cdot |\mathbf{I}_{Lf} + \mathbf{I}_{Ff}|.$$

$\mathbf{I}_{Lh}$ and $\mathbf{I}_{L}f$ in this equation are not controllable because they are given by operating condition of the load. Usually, $\mathbf{I}_{Ff}$, which is directly dependent on the capacity of the shunt passive filter, is designed to improve the load power factor. Accordingly, to minimize the harmonic voltage across the shunt passive filter is the only way to reduce the required rating of the series active filter in the design of $\mathbf{Z}_F$.

The output voltage of the series active filter should be discussed in peak value instead of rms value, because the maximum rating of a PWM inverter depends on maximum voltage and current of its switching devices. If current transformers having the same turn ratio are used, reduction of the maximum voltage of the switching devices and dc capacitor results from minimizing the peak output voltage of the series active filter. The peak output voltage must be calculated from load harmonic current having both amplitude and phase information. The nth-order output voltage $\dot{V}_{Cn}$ is given by

$$\dot{V}_{Cn} = \dot{Z}_F(jn\omega_0)\dot{I}_{Ln}, \tag{6}$$

where $\dot{I}_{Ln}$ is the nth-load harmonic current. The waveform of the output voltage is calculated by the vector sum of the output voltage in all harmonic frequencies as follows.

$$v_C(t) = \sum_{n=2} \left\{ \mathrm{Re}(\dot{V}_{Cn}) \cos n\omega_0 t + \mathrm{Im}(\dot{V}_{Cn}) \sin n\omega_0 t \right\} \tag{7}$$

The maximum value of $v_C(t)$ in the range of $0 \leq t \leq 2\pi/\omega_0$ means the peak output voltage of the series active filter.

The circuit constants of the shunt passive filter are obtained by a repeat calculation minimizing the peak output voltage. Then the following requirements should be considered.

- Total capacity of the shunt passive filter is constant.
- Quality factor of each reactor is constant.
- Each LC filter is tuned at a specific frequency.

In case of the system shown in Fig.1, these requirements make only four circuit constants independent, which are capacitor arrangement (C_{11} and C_{13}) and circuit constants of a high-pass filter (L_{HP} and r_{HP}).

Design Example

Figs.3 and 4 show relationships between the peak output voltage and circuit constants of the shunt passive filter in Fig.1. A curved line indicates the points obtaining the same peak voltage. Here the total capacity of the shunt passive filter = $800\mu F$, quality factor $Q = 100$, and the current waveform of the thyristor rectifier is assumed as a trapezoidal shape having overlap angle of 5°. Harmonics, of which frequencies is lower than the 64th-harmonic frequency, are considered for calculations.

Fig.3 shows relationship between the peak output voltage and capacitor arrangement. Then the circuit constants of the high-pass filter are calculated to minimize the peak output voltage on each point. The peak output voltage is minimum in the point of $C_{11} = 16\%$ and $C_{13} = 14\%$. Thus 70% of the total capacitor is assigned to the high-pass filter.

Fig.4 shows relationship between the peak output voltage and circuit constants of the high-pass filter. The capacitors are set to constant values minimizing the peak output voltage. In Fig.4, the smallest output voltage is obtained at the point of $L_{HP} = 24\mu F$ and $r_{HP} = 100\Omega$. However, the output voltage is minimized by setting the damping resistor $r_{HP} = \infty$. It is interesting that the high-pass filter is tuned at the 26th- rather than the 24th-harmonic frequency. Table 1 shows the constants of the passive filter, which minimizes the peak output voltage of the series active filter.

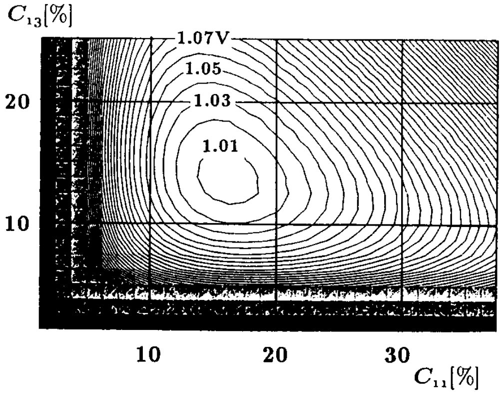


Fig. 3. Relationship between capacitor arrangement and peak voltage.

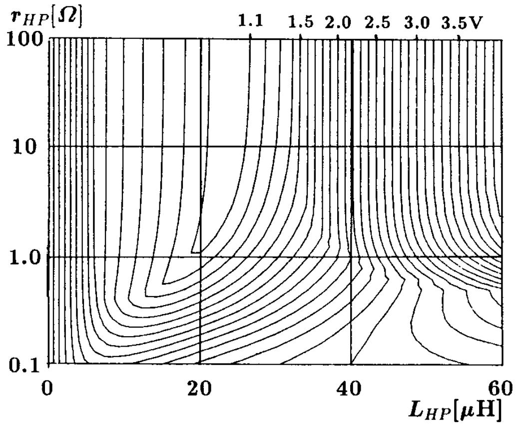


Fig. 4. Relationship between high-pass filter constants and peak voltage.

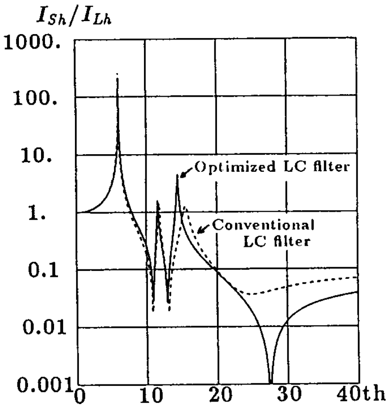
Comparison of Characteristics

Table 2 shows an example of a conventional shunt passive filter, which is referred to 10kVA on the basis of [4]. The shunt passive filters shown in Tables 1 and 2, are similar in their configuration, except that no damping resistor is connected to the high-pass filter in Table 1.

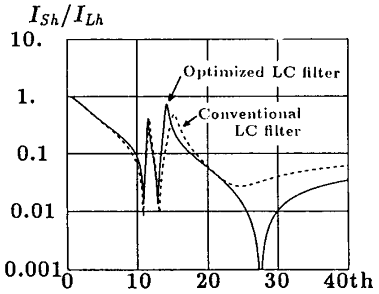
Fig.5 shows compensation characteristics in case of the source impedance $Z_S = 3.5\%$, where the plots indicate a ratio of the source harmonic current to the load one. In case that the shunt passive filter is used alone in (a), both passive filters amplify the harmonics at the 7th- and 15th-

Table 1. Constants of optimized passive filter.

11th	$C_{11} = 130\mu F$	$L_{11} = 0.65mH$	$Q = 100$
13th	$C_{13} = 110\mu F$	$L_{13} = 0.55mH$	$Q = 100$
H.P.	$C_{HP} = 560\mu F$	$L_{HP} = 24\mu H$	$r_{HP} = \infty$



(a) Passive filter used alone.



(b) Combined use of passive and active filter.

Fig. 5. Compensation characteristics for load harmonic current.

harmonic frequencies because of the parallel resonance between the shunt passive filter and the source. The shunt passive filter in Table 1 causes greater amplification than that in Table 2 does. In case of the combined filter system shown in (b), such parallel resonance is suppressed. For the frequency region over the 24th-harmonic frequency, the shunt passive filter in Table 1 shows good characteristics, compared with that in Table 2.

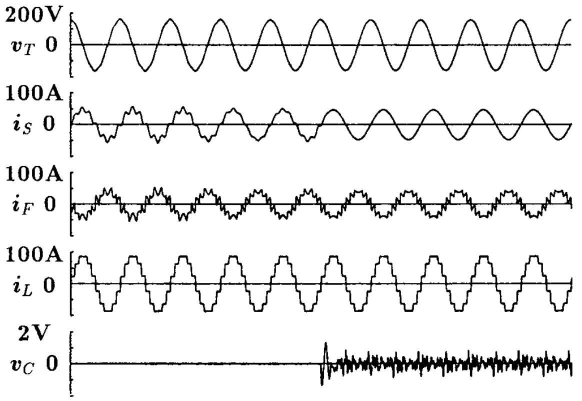


Fig. 6. Simulation waveforms in case of using optimized shunt passive filter in Table 1.

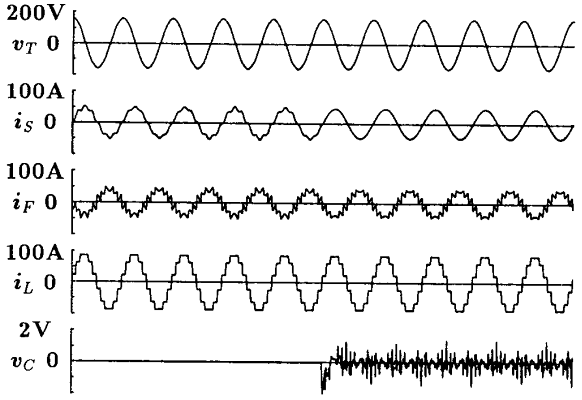


Fig. 7. Simulation waveforms in case of using conventional shunt passive filter in Table 2.

Simulation results using the shunt passive filter in Tables 1 and 2 are shown in Figs.6 and 7. In these simulation, the load harmonic current included the 7th-harmonic current of 0.5% which was an untheoretical harmonic component. Before the series active filter was started, the source current was including the 7th-harmonic current amplified by the parallel resonance. The 7th-harmonic current in Fig.6 was larger than that in Fig.7. After started, the source current became sinusoidal, because the series active filter can damp the parallel resonance. Although the peak output voltage of the series active filter in Fig.6 was over 1.0V in the transient state, it was 0.8V in the steady state. The peak output voltage in Fig.7 was about 1.4V even in the steady state. Thus the shunt passive filter in Table 1 makes it possible to reduce the rating of the series active filter to 60%, compared with that in Table 2.

Table 2. Constants of conventional passive filter.

11th	$C_{11} = 220\mu F$	$L_{11} = 0.39mH$	$Q = 100$
13th	$C_{13} = 150\mu F$	$L_{13} = 0.39mH$	$Q = 100$
H.P.	$C_{HP} = 430\mu F$	$L_{HP} = 41\mu H$	$r_{HP} = 1.1\Omega$

Effect of Load Current Waveform

Table 3 shows the circuit constants of the shunt passive filter, which is designed for the load current having overlap angle of 15°. Compared with the shunt passive filter shown in Table 1, the capacitor for the high-pass filter is small, because high-order harmonics decrease according to increase of overlap angle.

Table 4 shows the relationship of the peak output voltage against the overlap angle of the load current. In case of overlap angle of 5°, the smallest output voltage is given

Table 3. Constants of optimized passive filter under overlap angle of 15°.

11th	$C_{11} = 240\mu F$	$L_{11} = 0.35mH$	$Q = 100$
13th	$C_{13} = 140\mu F$	$L_{13} = 0.42mH$	$Q = 100$
H.P.	$C_{HP} = 420\mu F$	$L_{HP} = 14\mu H$	$r_{HP} = 2.5\Omega$

Table 4. Peak voltage against overlap angle.

Overlap angle[deg]	5°	10°	15°
Filter in Table 1	1.02V	0.55V	0.41V
Filter in Table 2	2.02V	0.86V	0.54V
Filter in Table 3	1.91V	0.95V	0.18V

by using the shunt passive filter in Table 1. But in case of overlap angle of 15°, the shunt passive filter shown in Table 3 makes it minimum. This tells us that the load current waveform for calculation should agree with that in practical load condition. Moreover, in case that the overlap angle is variable in a range, the shunt passive filter should be designed on the basis of the current waveform having the smallest overlap angle in the range. The reason is that the series active filter is required to output the largest peak voltage in the range.

EXPERIMENTAL RESULTS

Experimental results are shown in Figs.8, 9, 10 and 11, which are obtained by the prototype model shown in Fig.1. The shunt passive filter having quality factor $Q = 15$ was designed and used, because the source voltage was 200V. Table 5 shows the circuit constants of the shunt passive filter used in the experiments.

Fig.8 shows experimental waveforms, and Fig.9 shows the frequency spectra before and after the series active filter was started respectively. The input current of the load thyristor rectifier was including not only the 11ht- and 13th-harmonics but also some amount of 5th- and 7th-harmonics, as shown in Table 6. Before the series active

Table 5. Constants of optimized passive filter in experiments ($Q = 15$).

11th	$C_{11} = 220\mu F$	$L_{11} = 0.38mH$	$Q = 15$
13th	$C_{13} = 200\mu F$	$L_{13} = 0.30mH$	$Q = 15$
H.P.	$C_{HP} = 380\mu F$	$L_{HP} = 40\mu H$	$r_{HP} = \infty$

Table 6. Harmonic components contained in load current.

Fundamental	5th	7th	11th	13th
100[%]	1.4	0.4	8.5	6.3

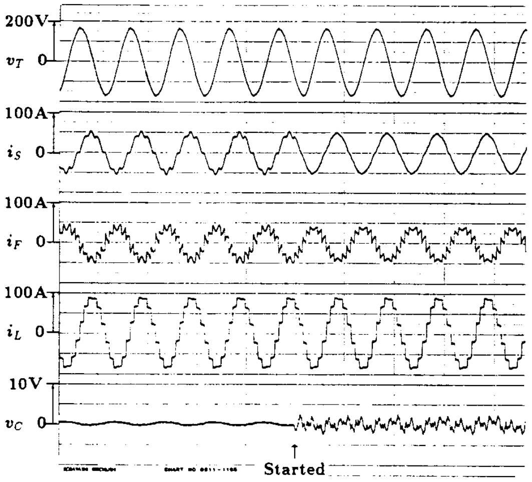
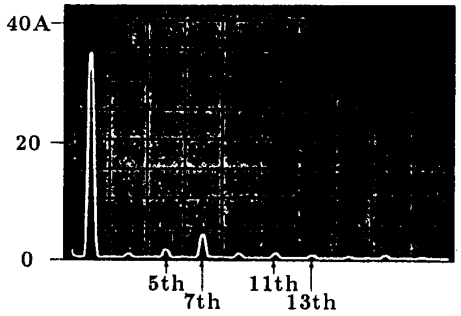
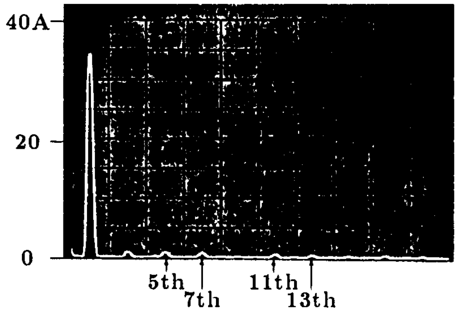


Fig. 8. Experimental waveforms



(a) Before started.



(b) After started.

Fig. 9. Frequency spectra of i_S.

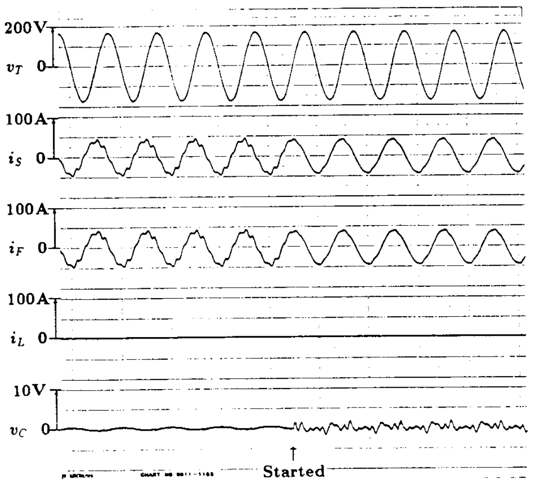
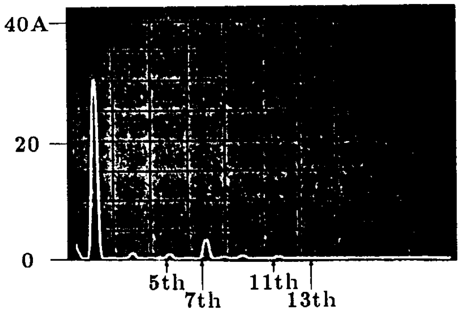
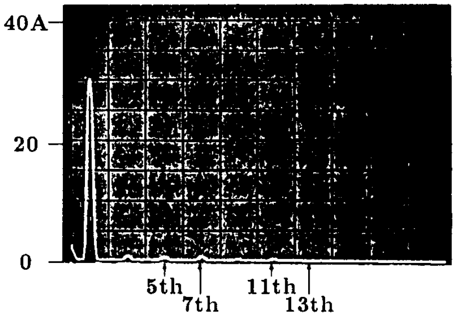


Fig. 10. Experimental waveforms in case of no load



(a) Before started.



(b) After started.

Fig. 11. Frequency spectra of i_S in case of no load.

filter was started, the 7th-harmonic current was amplified and flowing out to the source because of the parallel resonance between the source and shunt passive filter. After started, the 7th-harmonic current in the source was eliminated by the series active filter. The peak output voltage of the series active filter was 2.1V in calculation, but that was 2.5V in experiment. The difference between the two is caused by the source harmonic voltage, which is not taken into account in calculation. Therefore the peak rating of the series active filter was 320VA. The rms output voltage was 1.0V, and the rms rating was 180VA.

Figs.10 and 11 show experimental waveforms and frequency spectra, in case of no load. Before the series active filter was started, the 5th- and 7th-harmonic currents was flowing into the shunt passive filter because of the source harmonic voltage. After started, the series active filter was preventing harmonic current from flowing into. Although the total harmonic distortion factor of v_T was 7.5% before started, it became 2.8% after started.

CONCLUSION

Design strategy of the combined power filter has been presented in this paper. The specially designed shunt passive filter can minimize the output voltage of the series active filter, thus the required rating of the series active filter is reduced to 60%, compared with that in the case of using a conventional passive filter.

The design strategy presented in this paper can be also applied to the series connection system of passive and active filters[5].

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