An Investigation of Control Parameters of Active Filters Based on Voltage Detection

Yukihiko SATO, Takeshi KAWASE, Hiraku MACHIDA

Department of Electrical and Electronic Engineering
Tokyo Institute of Technology
2-12-1, O-okayama, Meguro-ku, Tokyo 152-8552, JAPAN

Abstract- **Compensation characteristics of active filters based on voltage detection are investigated. These active filters act equivalently as a passive circuit so that they may not cause practical problems such as stimulation of resonance in the distribution lines. Thus, these active filters can be used as the general-purpose active filters. On the other hand, these active filters may have a possibility of the anti-resonance associated with the line inductance of the distribution lines. In this paper, the relationship between the anti-resonance and the control parameters of the proposed active filters is clarified. Some methods to avoid the problems due to the anti-resonance are investigated. Experimental results are included to confirm the validity of the investigation presented in this paper.**

I. INTRODUCTION

In recent years, active filters have been widely investigated for the compensation of harmonics in electric power systems [1]-[8]. In general, the active power filters are specially designed or adjusted one by one considering the required compensation characteristics and the condition of the point of installation. Thus, the mass production of the standard or general-purpose active filters is not so easy. From the economical point of view, the standard general-purpose active filters that can be used commonly in the distribution lines are desirable.

The active filters are divided into two types: current detection type and voltage detection type. Most of the active filters that have been put into practice are those based on the current detection. These active filters can realize the adequate compensation characteristics under the specific operating condition. But, it is reported that these active filters may cause some practical problems in the distribution lines. For example, these active filters may stimulate the resonant phenomena if the capacitor banks for the power-factor correction and the line impedance act as a resonant circuit. Thus, these active filters based on the current detection are not suitable for the general-purpose active filters in the distribution lines. In our recent papers, we have proposed a new adaptive control strategy for active filters based on the voltage detection [9]. We have also shown the effectiveness of the multiple connections of the proposed active filters as the general-purpose active filters [10]. In the present paper, the effects of the control parameters are investigated considering the condition of the distribution lines as a basis of the establishment of the design procedure.

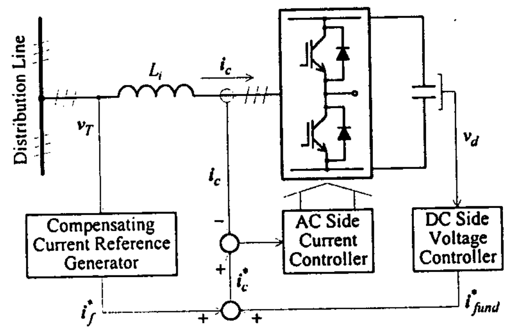


Fig.1. Main circuit and control block diagram of proposed general-purpose active filter.

II. CONTROL PRINCEPLE

Fig.1 shows a schematic diagram of the main circuit and control block diagram of the proposed general-purpose active filters based on the voltage detection. The detail of the control method applied to this system has been discussed in one of our recent papers [9]. In general, the transfer function of the active filters based on the voltage detection has a dimension of impedance. Thus, these active filters act as equivalent impedance. To realize the frequency selectivity concentrated on the harmonic frequencies to be compensated, a real-time digital simulator of the LC filters using a digital signal processor (DSP) is introduced as a compensating current reference generator. The calculation algorithm is based on the real-time simulation of the LC filters using the state equations in the discrete time domain. The single-phase

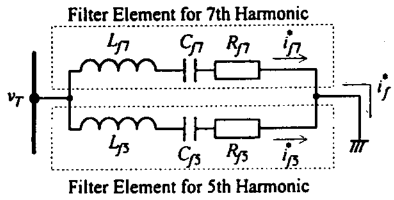


Fig.2. Single-phase equivalent circuit of simulated LC filter.

Table 1. Parameters of experimental system.

Power Source	Voltage (line-to-line)		100V
	Frequency		50Hz
AC Side Inductor	Inductance		5.2mH
	Resistance		0.2Ω
DC Side Voltage			200V
Average Switching Frequency			10kHz
Parameters of Simulated LC Filter	For 5th Harmonic	L_{f5}	10mH
		C_{f5}	40.53μF
		R_{f5}	0.1Ω
	For 7th Harmonic	L_{f7}	50mH
		C_{f7}	4.14μF
		R_{f7}	0.2Ω

equivalent circuit diagram of the LC filter simulated in the DSP is shown in Fig.2. The detected terminal voltage v_T is applied to the real-time simulator of the LC filter. (Hereafter, variables shown by boldface letters such as $\boldsymbol{v}_T$ are three phase quantities.) The LC filter consists of two elements of the tuned LC filter whose resonant frequencies are set to the 5th and 7th harmonic frequencies. $\boldsymbol{i}^*_{f5}$ and $\boldsymbol{i}^*_{f7}$ are the calculated values of the currents which flow through the filter elements tuned for the 5th and 7th harmonics, respectively. The calculated signal $\boldsymbol{i}^*_f$ $(=\boldsymbol{i}^*_{f5}+\boldsymbol{i}^*_{f7})$ of the total current of the LC filter is applied to the AC side current controller as a component of the AC side current reference $\boldsymbol{i}^*_c$. A reference signal $\boldsymbol{i}^*_{fund}$ of the fundamental current component to keep the DC side voltage v_d constant is applied to the AC side current controller as another component of $\boldsymbol{i}^*_c$. In this way, the current component $\boldsymbol{i}_f$ of the ac side current $\boldsymbol{i}_c$ due to the reference signal $\boldsymbol{i}^*_f$ is controlled by the detected terminal voltage $\boldsymbol{v}_T$ using the state equation of the equivalent LC filter. The relationship between $\boldsymbol{v}_T$ and $\boldsymbol{i}_f$ is exactly the same as that of the LC filter shown in Fig.2. Thus, the proposed active filter acts equivalently as an LC filter shown in Fig.2 when it is viewed from the AC side. In this paper, the LC filter shown in Fig.2 that has only two filter elements for the 5th and 7th harmonics is investigated as a simple example. The investigation in this paper can be extended to cases when the number of the filter elements is more than two.

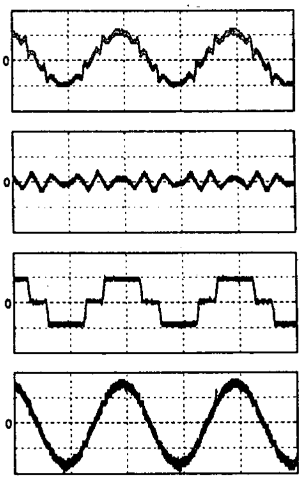


Fig.3. Experimental waveform with proposed active filter. From the top: total line current, compensating current, load current, terminal voltage, 10[A/div], 100[V/div]

As mentioned above, the proposed active filter can be regarded as a passive LC filter implemented by the active circuitry. However, it is completely different from the conventional passive LC filters in the following points. Note that the following properties can overcome the shortcomings of the conventional passive LC filters.

- There are no physical restrictions in the selection of the circuit parameters of the simulated LC filter components, such as the inductance, capacitance, and resistance.
- The parameters of the simulated LC filter, such as the resonant frequency, quality factor, characteristic impedance, can be changed even during the operating condition. This allows the on-line adaptation of the compensating characteristics according to the condition of the connecting point in the distribution line. (The detail of the implementation of the on-line adaptation has been discussed in one of our recent papers [9].)
- All the state variables of the simulated LC filters are stored in the memory of the DSP. Thus, these variables are available in the control system without using additional hardware such as current and voltage sensors.
- The power equivalently dissipated in the simulated LC filter can be returned to the AC line as a fundamental active power component. This provides the loss-less active damping function for the harmonic components.

Fig.3 shows an example of the experimental waveforms

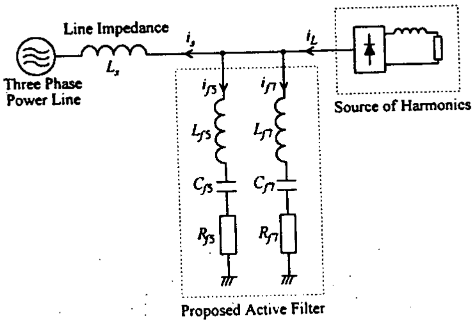


Fig.4. Single-phase diagram of model distribution line for investigation of problems caused by anti-resonance.

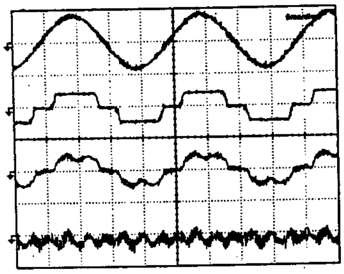
Table.2. Parameter sets of simulated LC filter for investigation of compensation characteristics.

		Case A	Case B	Case C
Filter Element for 7th Harmonic	L_{f7}	10mH	2mH	2mH
	C_{f7}	20.68μF	103.4μF	103.4μF
	R_{f7}	0.5Ω	0.5Ω	0.5Ω
	f_{ar7}	330Hz	250Hz	250Hz
Filter Element for 5th Harmonic	L_{f5}	Not Included		10mH
	C_{f5}			40.53μF
	R_{f5}			0.2Ω

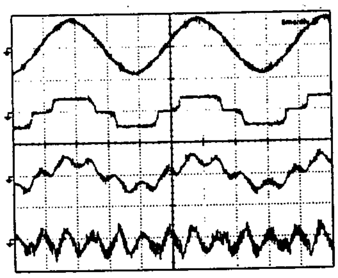
obtained by the laboratory test system. The main circuit and control parameters are listed in Table 1. In this experiment, the harmonic current caused by a diode bridge rectifier with a DC smoothing inductor is compensated. The lower order harmonic components in the load current are effectively compensated by the proposed active filter. From this result, we can confirm the basic effectiveness of the proposed active filter.

III. INVESTIGATION OF ANTI-RESONANCE

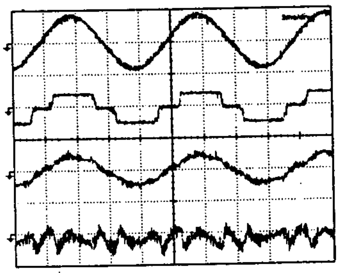
It is well known that the conventional LC filter may cause the anti-resonant problems associated with the line impedance. Basically, the proposed active filter acts as equivalent passive LC filters. Thus, the possibility of the anti-resonance should be investigated in detail. Fig.4 shows a single-phase equivalent circuit diagram for the following investigation. In this figure, the proposed active filter is represented equivalently as the passive LC filters in the dashed box. A three-phase diode rectifier with a smoothing inductor is connected as a harmonic source. Table 2 shows the control parameters used in three different cases investigated. In case A and B, the filter element for the 5th harmonic is not included. Fig.5 shows



(a) Case A



(b) Case B



(c) Case C

Fig.5. Experimental waveforms with simulated filter element for 7th harmonic for three different sets of control parameters. From the top: terminal voltage, load current, total current, compensating current, 200[V/div], 20[A/div].

experimental waveforms of the terminal voltage v_T, the load current i_L, compensating current i_c, and supply current i_s for three different sets of parameters listed in Table 2.

In case A shown in Fig.5(a), only the filter element for the 7th harmonic is realized by the proposed active filter. In this case, the control parameters of the active filter are set appropriately. From Fig.5(a), we can see that the 7th harmonic component in i_L is effectively compensated by the proposed active filter.

In case B shown in Fig.5(b), the parameters of the filter element for the 7th harmonic are set to the undesirable values. The anti-resonant frequency f_{ar7} of the filter element for the 7th harmonic is determined by

$$f_{ar7} = \frac{1}{2\pi\sqrt{(L_{f7}+L_s)C_{f7}}} \tag{1}$$

where L_s is the line inductance per phase. In case B,

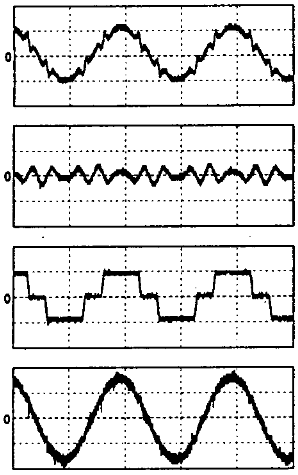


Fig.6. Experimental waveforms with proposed active filter when distribution of parameters of inductance and capacitance in simulated filter element for 5th harmonic is changed. From the top: total line current, compensating current, load current, terminal voltage, 10[A/div], 100[V/div])

f_{ar7} coincides with the 5th harmonic frequency. As a result, the considerable 5th harmonic current circulates through the power source and the active filter. Under this condition, the 5th harmonic current generated by the harmonic source is enlarged by the anti-resonance at the 5th harmonic frequency. To obtain the proper operation, the anti-resonance must be avoided. Thus, the parameters of filters should be selected appropriately considering the line impedance so that the anti-resonance can be avoided. However, it is very difficult in practice because the line impedance is unknown or subject to change.

In case C shown in Fig.5(c), a filter element tuned for the 5th harmonic is added to case B. The values of the line inductance L_s and the parameters L_{f7}, C_{f7}, R_{f7} are the same as those in case B. Thus, the anti-resonant frequency f_{ar7} still coincides with the 5th harmonic frequency. From Fig.5(c), we can see that both the 5th and 7th harmonic currents generated by the harmonic source are compensated effectively by the active filter. The effects of the anti-resonance observed Fig.5(b) is eliminated by the filter element for the 5th harmonic. In the proposed active filter, both the filter elements for the 5th and 7th harmonics are realized simultaneously by a unit of the active filter.

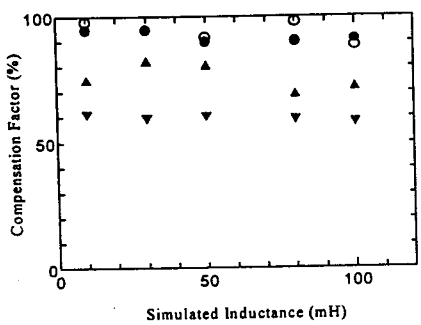
From above discussion, we can summarize as follows. There is a possibility that each filter element of the equivalent LC filter realized by proposed active filter may cause the anti-resonant phenomena associated with the line inductance. In this case, the anti-resonant frequency is lower than the resonant frequency of the corresponding element of the LC filter. If the anti-resonant frequency coincides with the frequency of the dominant harmonic component in the distribution line, undesirable current flows into the active filter. Even in this case, the anti-resonance is eliminated when another filter element whose resonant frequency coincides with the anti-resonant frequency exists. Consequently, we can conclude that an LC tuned filter does not cause the anti-resonant problem when the tuned filter elements for all the dominant harmonic frequencies lower than the resonant frequency of the LC filter exist. In the proposed active filter, this requirement is always satisfied. Therefore, the proposed active filter basically does not cause the anti-resonant problem.

IV. Basic Investigation of Automatic Adjustment of Control Parameters

As mentioned in section II, the proposed active filter can change the control parameters even during the operating condition. For the n-th filter element, the equivalent total impedance $Z_n(\omega)$ is given by

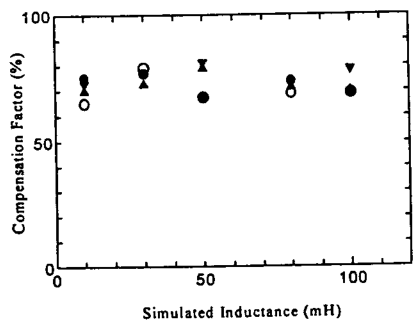
$$Z_n(\omega) = j\omega L_{fn} + \frac{1}{j\omega C_{fn}} + R_{fn} \tag{2}$$

At the resonant frequency $\omega_{rn} = 1/\sqrt{L_{fn}C_{fn}}$, $Z_n(\omega_{rn})$ is equal to R_{fn}. This means that the compensation capability in the steady state is determined only by the value of R_{fn} regardless of the values of L_{fn} and C_{fn}. To confirm this, the experimental waveforms for the different distribution of the values of the simulated capacitance and inductance are shown in Fig.6. In this case, the simulated values of the inductance L_{f5} and capacitance C_{f5} are set to 10 times and one tenth of their original values listed in Table.1, respectively. On the other hand, the simulated value of the resistance R_{f5} is not changed from its original value. The waveforms in Fig.6 are almost same as those in Fig.3. Fig.7(a) shows the effect of the simulated parameters L_{f5}, C_{f5}, and R_{f5} on the compensation factor for the 5th harmonic current. The compensation factor is defined as a ratio of the compensated harmonic current to the generated harmonic current. The compensation factor is almost constant for the variation of L_{f5} and C_{f5}. From the results in Fig.6 and Fig.7(a), we can confirm that the value of R_{f5} determines the compensation capability for the 5th



(a) Compensation factor for 5th harmonic.

○: $R_{f5}=0.1\Omega$, ●: $R_{f5}=0.2\Omega$, ▲: $R_{f5}=0.5\Omega$, ▼: $R_{f5}=1.0\Omega$



(b) Compensation factor for 7th harmonic.

○: $R_{f5}=0.1\Omega$, ●: $R_{f5}=0.2\Omega$, ▲: $R_{f5}=0.5\Omega$, ▼: $R_{f5}=1.0\Omega$

Fig.7. Relationship between simulated inductance of 5th harmonic element and compensation factor for four different values of simulated resistance of 5th harmonic element.

harmonic component regardless of the values of L_{f5} and C_{f5}.

Fig.7(b) shows the effect of the simulated parameters L_{f5}, C_{f5}, and R_{f5} in the filter element for 5th harmonic on the compensation ratio for the 7th harmonic current. We can see that the compensation ratio is almost constant regardless of all the parameters in the filter element for the 5th harmonic. This means that the parameters in the 5th harmonic elements have no effect on the 7th harmonic. From these results, it can be proved that the compensation capability for each order of harmonics is determined independently by the parameters in the filter element for the corresponding order of harmonics.

As seen in (1), the anti-resonant frequency is affected by the line inductance. To avoid the problems caused by the anti-resonance, the anti-resonant frequency must not coincide with the frequencies of the dominant harmonics. The freedom in the selection of the simulated value of the inductance discussed in this section is useful to avoid the anti-resonant problems. However, the values of the simulated inductance and capacitance have effects on the transient response of the active filter. Although the detailed investigation is required, the allowable ranges of these parameters are wide enough practically.

V. CONCLUSIONS

In this paper, the effect of the control parameters on the compensation characteristics of the proposed active filters based on the voltage detection has been investigated. The anti-resonance phenomena associated with the line inductance has examined by some experimental results. In the proposed active filter, the filter elements for the lower order harmonics can eliminate the problems due to the anti-resonance caused by the filter elements for the higher order harmonics. As another solution to elimination of the problems due to the anti-resonance, some experimental results of basic investigation of the automatic parameter adjustment have been included. The implementation of the automatic adjustment of the control parameters is left for the future investigation.

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