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HARMONIC CURRENT AC FILTERS AT A LARGE ACCELERATOR

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The harmonic currents associated with a thyristor converter which acts as a power supply for the magnet of a large accelerator were investigated. The experiment and the computer calculation were both carried out for the KEK system.

The ac filters were constructed in accordance with the specification made by the detailed investigation. The operation and the results were satisfactory.

1 INTRODUCTION

In operation of the KEK accelerator, electric power is taken from and returned to a power grid depending on excitation and de-excitation of the magnet.

Large power swings from the operation certainly will cause voltage flickers on the commercial power grid. This is not acceptable and it is necessary to isolate the accelerator from the commercial grid by using a motor generator. However, because of possible mechanical failure of the rotating machine system during the past decade and its cumbersome maintenance, modern accelerators tend to be connected directly to the existing power grid with the aid of the flicker suppressor and the harmonic filter.

It is the purpose of this paper to describe harmonic problems associated with thyristor converters and to show how to suppress them by filters.

Harmonic problems have been already noted and well studied in a field of dc power transmission because of involvement of a large thyristor converter in a conversion between ac and dc. Every project of dc power transmission in the world has regulation of voltage distortion by harmonics. They are less than 4% (12ϕ) at Sardina in Italy, less than 2%(12ϕ) at the Nelson River Project in Canada and so on.

On the other hand, the electric council in England recommended permissible harmonic currents in 1967 as shown in Appendix A.

2 CHARACTERISTIC HARMONIC CURRENT IN A BRIDGE CONVERTER

Any wave can be expressed by Fourier analysis as follows:

$$f(\theta) = \frac{a_0}{2} + \sum_{n=1}^{\infty} (a_n \cos n\theta + b_n \sin n\theta), \tag{1}$$

where

$$a_0 = \frac{1}{\pi}\int_0^{2\pi} f(\theta)\mathrm{d}\theta \tag{2a}$$

$$a_n = \frac{1}{\pi}\int_0^{2\pi} f(\theta)\cos n\theta \,\mathrm{d}\theta \tag{2b}$$

$$b_n = \frac{1}{\pi}\int_0^{2\pi} f(\theta)\sin n\theta \,\mathrm{d}\theta. \tag{2c}$$

As a special case, harmonic current from a bridge converter has usually no even term and the above equations are expressed as follows:

$$a_n = \frac{2}{\pi}\int_0^{\pi} f(\theta)\cos n\theta \, d\theta \tag{3a}$$

$$b_n = \frac{2}{\pi}\int_0^{\pi} f(\theta)\sin n\theta \,\mathrm{d}\theta. \tag{3b}$$

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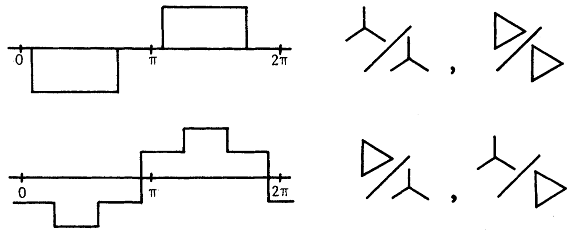

FIGURE 1 AC line currents for two different connections of six-phase rectification with no commutation angle.

For example, line currents in a three-phase bridge converter (Grätz configuration) are shown in Figure 1. The reactance of the transformer, hence the commutating angle, is neglected. This means that the current transfers from one thyristor to another without overlap. In this case, the current is as follows:

$$I = \frac{2 \cdot 3^{1/2}}{\pi} I_d[\cos \omega t \mp \tfrac{1}{5} \cos 5\omega t \pm \tfrac{1}{7} \cos 7\omega t - \tfrac{1}{11} \cos 11\omega t + \tfrac{1}{13} \cos 13\omega t + \cdots], \tag{4}$$

where I_d is the dc current of the converter and the sign of each term implies the cases of the $y - y$ and $y - \Delta$ connected transformers respectively. This means that the harmonic number of the harmonic current for a three-phase bridge converter, n, is expressed as $n = 6\,m \pm 1$, where m is an integer. The harmonic current I_n is also simply expressed as

$$I_n = \frac{1}{n} I_1 \doteqdot \frac{1}{n} I, \tag{5}$$

where I_1 is the current for the fundamental frequency and I is the total current.

We assume a twelve-phase system composed of two six-phase converters connected as $y - y$, $y - \Delta$, or $\Delta - \Delta$, $y - \Delta$. The waveform of the line current is shown in Figure 2. The opposite signs in Eq. (4) are cancelled and 11, 13, 23, 25,... terms remain to the last. That is $n = 12\,m \pm 1$, where m is integer.

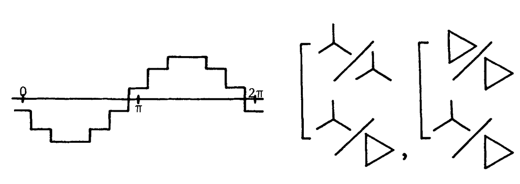

FIGURE 2 AC line current for twelve-phase rectification with no commutation angle.

When the commutating angle is counted for the characteristic harmonic problem it is not basically different from the previous discussion. For this case the detailed analyses are omitted in this paper because they can be found in many publications.[1,2] A few examples of the calculated harmonics are shown in Figure 3. The contents of harmonic currents related to the fundamental current are shown in this figure.

It is clear from the figure that the harmonic currents are reduced more by increase of the commutation angle u than that of the ignition angle α. This implies that the rectifier transformer, in other words, its internal reactance must be considered seriously in harmonic problems of the bridge converter.

The above discussions can be summarized as follows:

1) The even terms of the harmonics are cancelled.

2) The terms of the nth order, where n is $3(2k + 1)(k = 0, 1, 2, \ldots)$, are always zero.

3) In case of $y - y$ or $y - \Delta$ connection,

a) for $n = 6(2k + 1) \pm 1, \quad k = 0, 1, 2, \ldots$ namely for 5, 7, 17, 19, ...

$$(a_n)_{yy} = -(a_n)_{y\Delta} \tag{6a}$$

$$(b_n)_{yy} = -(b_n)_{y\Delta} \tag{6b}$$

b) for $n = 12(k + 1) \pm 1, \quad k = 0, 1, 2, \ldots$ namely for 11, 13, 23, 25,

$$(a_n)_{yy} = (a_n)_{y\Delta} \tag{7a}$$

$$(b_n)_{yy} = (b_n)_{y\Delta}. \tag{7b}$$

Therefore, the harmonics of $n = 6k \pm 1$ orders are generated in a six-phase rectifier. For a twelve-phase rectifier, the harmonic currents of $n = 12k \pm 1$ orders emanate into the power grid from the bridge converter, and so those of $n = 6(2k + 1) \pm 1$ orders flow revolving around the $y - y$ and $y - \Delta$ connected transformer windings.

3 UNCHARACTERISTIC HARMONIC CURRENT

The uncharacteristic harmonic current, which is omitted in the previous section, comes from unbalances existing between three-phase lines. The unbalances are not only that of the supplied power

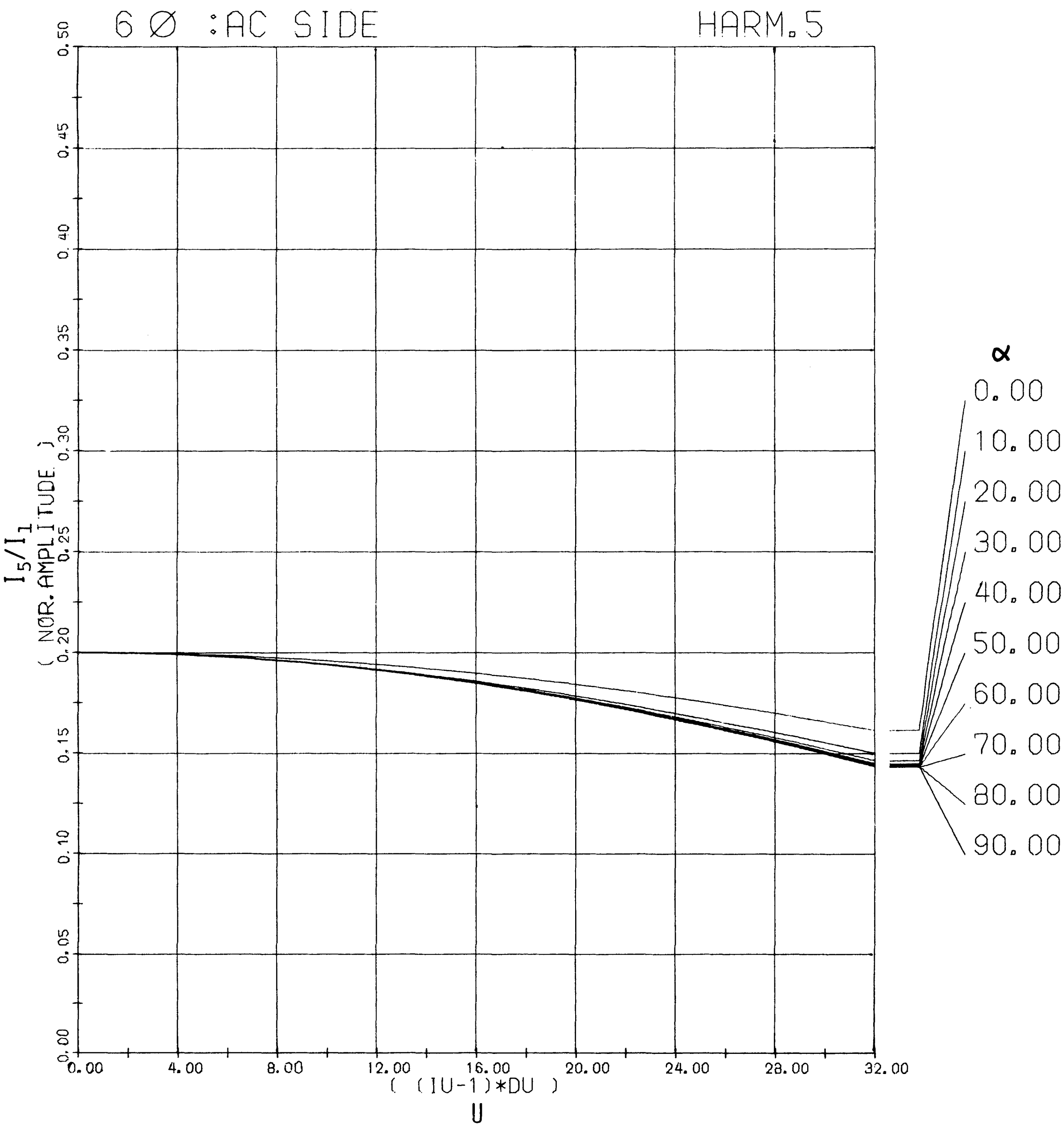

FIGURE 3(a) The 5th harmonic current of six-phase rectification.

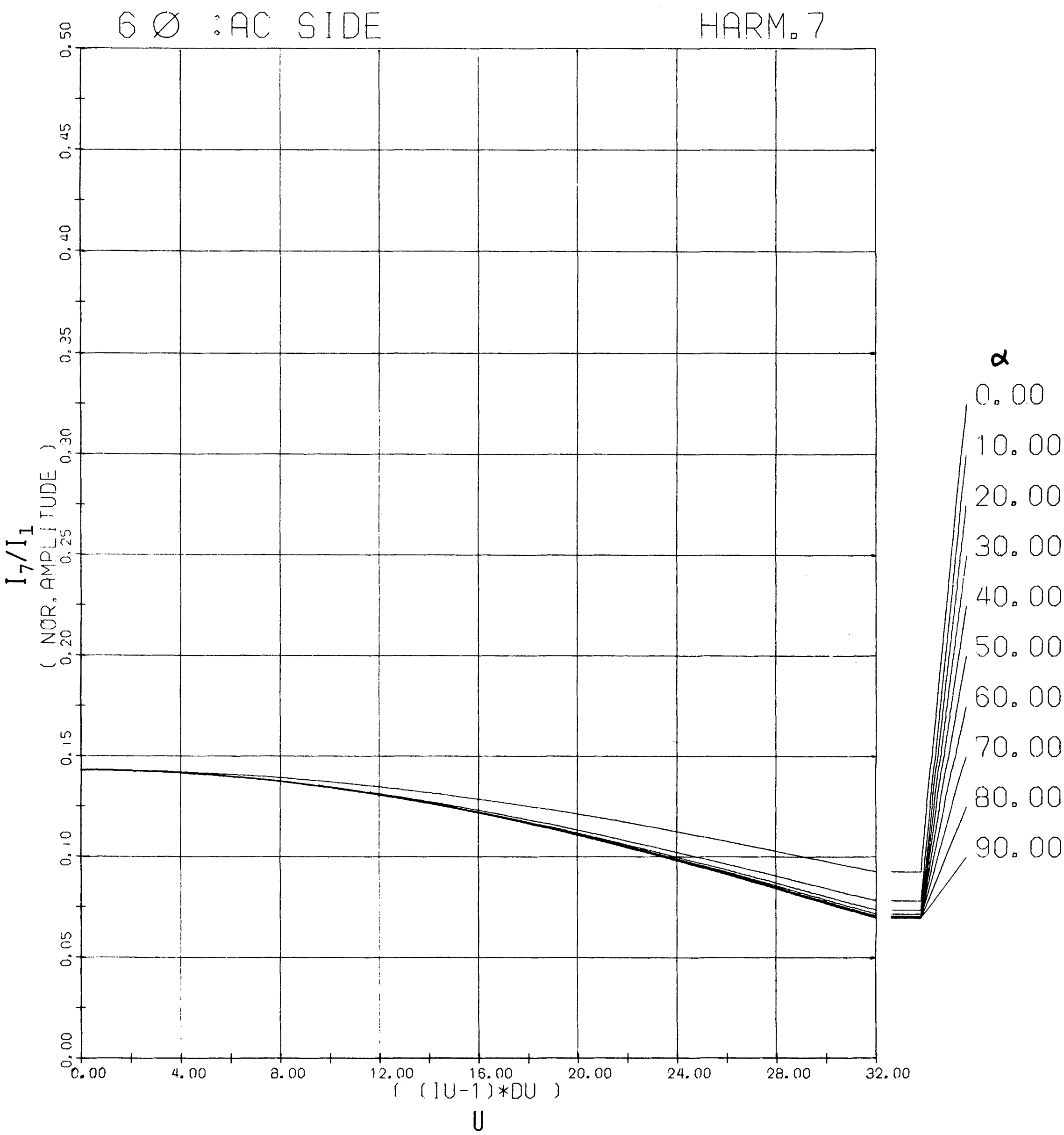

FIGURE 3(b) The 7th harmonic current of six-phase rectification.

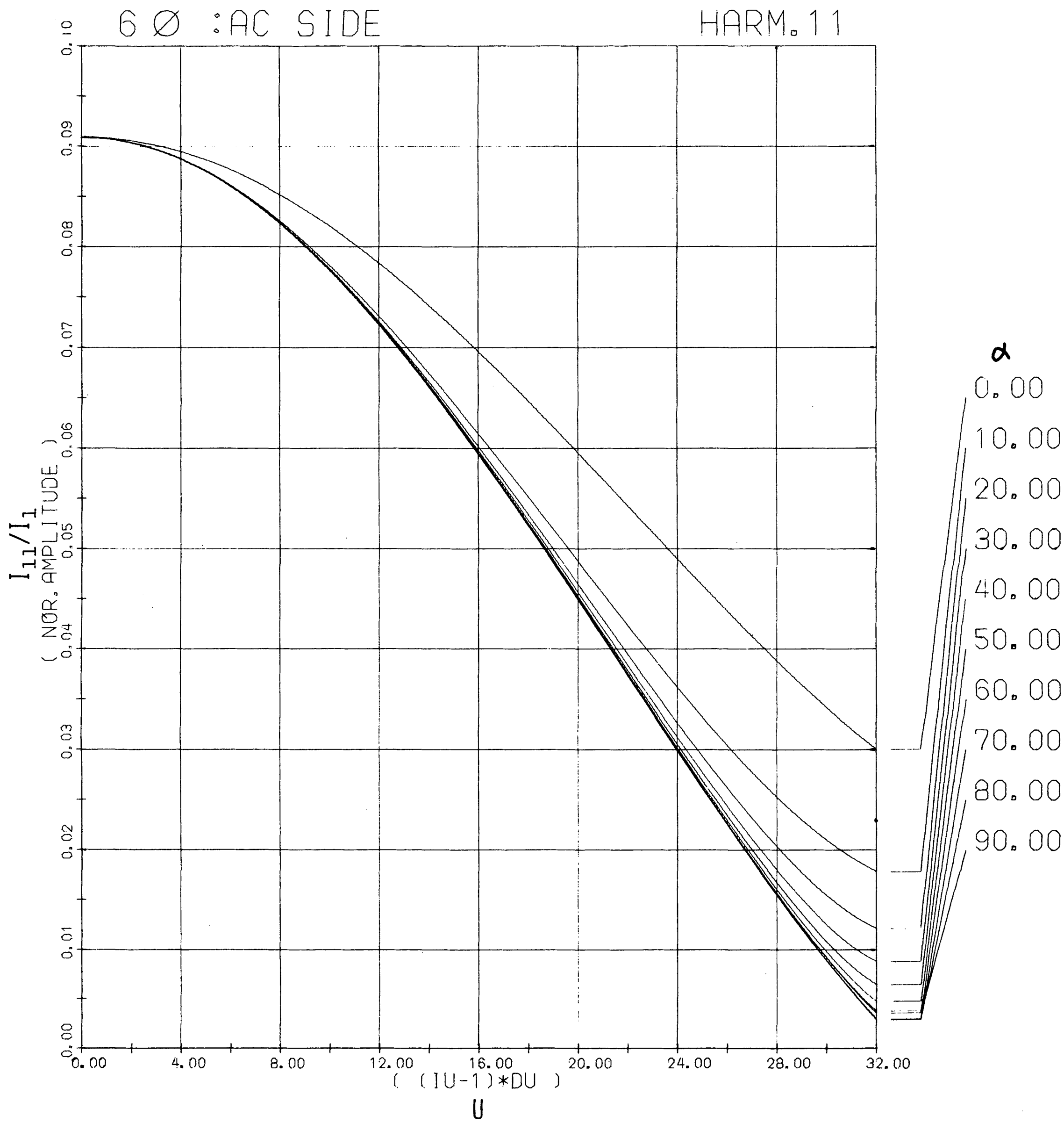

Figure 3(c) The 11th harmonic current of six-phase rectification.

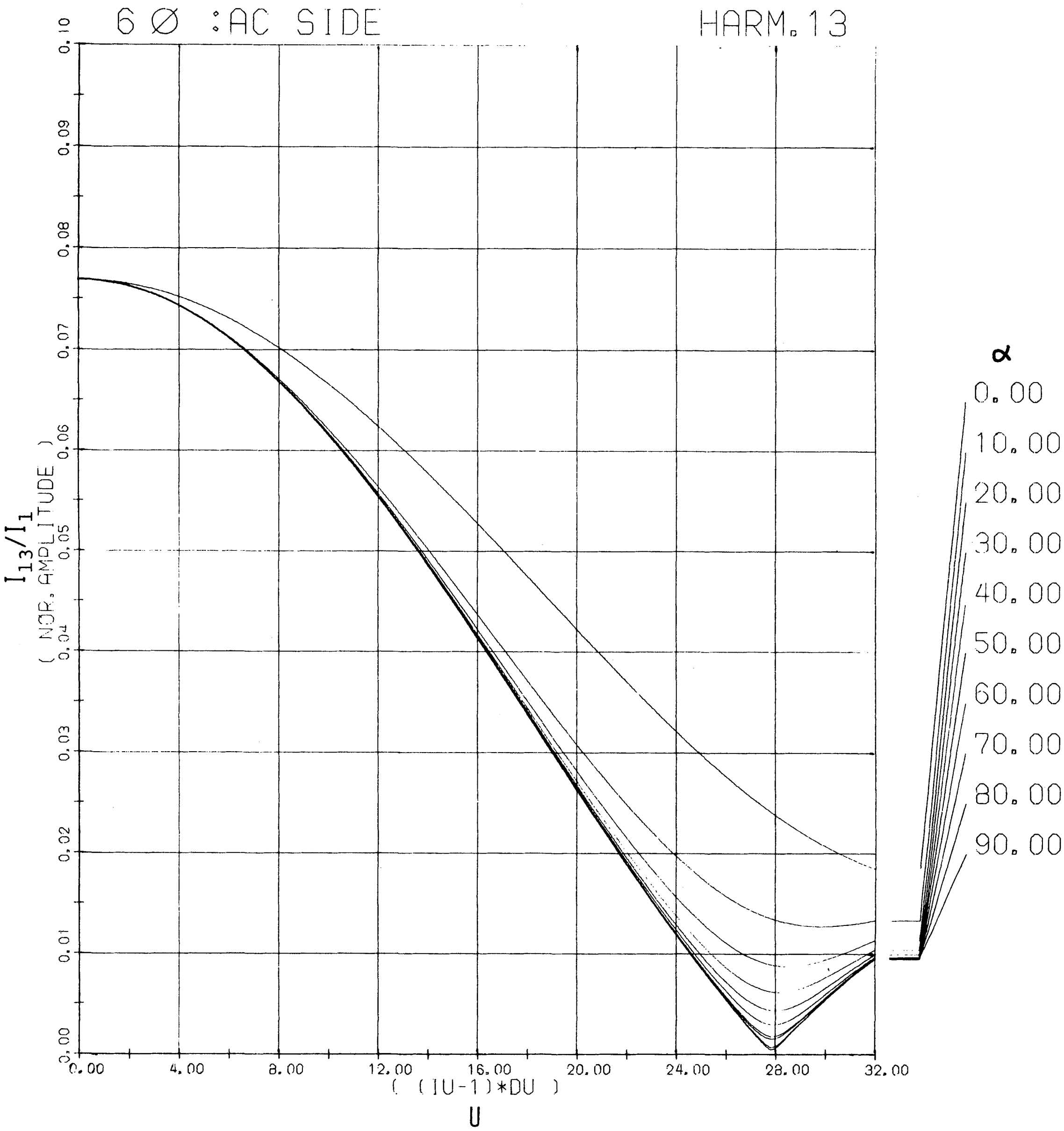

FIGURE 3(d) The 13th harmonic current of six-phase rectification.

grid but that of a rectifier transformer and of control mechanisms of multi-phase switches which at present are thyristors. The unbalances in the ignition angle of a rectifier will generate uncharacteristic harmonics of even and odd orders. The odd-order harmonics, which are multiplied by three and $6(2k + 1) \pm 1$ in twelve-phase rectification, are generated by the change of ignition angles in the same direction. On the contrary, the change in the opposite direction generates even-order harmonics.

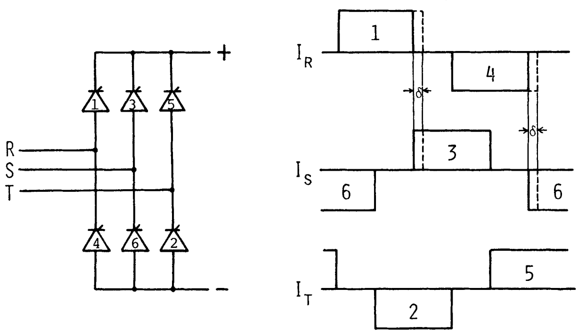

FIGURE 4(a) AC line currents with disturbance of ignition angles. The third and the 6th thyristors are ignited late by δ.

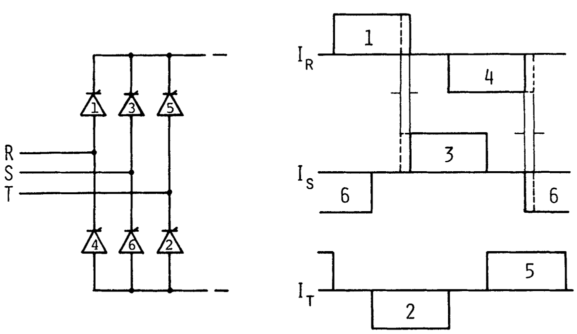

FIGURE 4(b) AC line currents with disturbance of ignition angles. The third thyristor is ignited early by δ and the 6th thyristor is ignited late by δ.

For instance, in a six-phase rectifier as shown in Figure 4(a), a line current is distorted by existence of a δ-degree delay in the ignition angles of the third and the 6th thyristors. The commutation angle is neglected for simplicity in the figure. The rms current of the nth order, I_n, to the fundamental current I_1 is given as follows:

$$I_n/I_1 = \frac{\sin\frac{n}{2}\left(\frac{2}{3}\pi + \delta\right)}{n\sin\left(\frac{\pi}{3} + \frac{\delta}{2}\right)}. \tag{8}$$

In the case of the third harmonic,

$$\frac{I_3}{I_1} \simeq \frac{\delta}{3^{1/2}}. \tag{9}$$

Suppose δ is one degree, I_3/I_1 is about 1%.

For the even harmonics it is as follows:

The difference of duration of the current between positive and negative pulses as shown in Figure 4(b) will generate even harmonics, when the third thyristor is ignited early by an angle of δ, while the 6th thyristor is ignited late by the same angle. The ratio of an even harmonic of nth order except those of order $6k$ to the fundamental wave is as follows:

$$\frac{I_n}{I_1} = \frac{\sin n\delta}{3^{1/2}} \simeq \frac{\delta}{3^{1/2}}. \tag{10}$$

Then the even harmonics do not depend on the orders of harmonics but the change of the ignition angle. For example for $\delta = 1°$, the ratio is about 1%. The calculated uncharacteristic harmonics for various conditions are given in Figures 5.[3]

From these considerations the uncharacteristic harmonic currents are generally one order smaller than the characteristic ones, but their frequencies are always lower than that of the characteristic harmonics even with the aid of multiphase operation of the converters. Suppression of low frequency harmonics is thus an important and difficult problem. The difficulty is not only technical but also economical. The technical difficulty is rather on the stimulation of the other resonances due to equipments of the ac filters for the lower frequencies and the economical difficulty is the preparation of the large-scale filters for such lower frequencies. It is important to say that when the whole filter system is planned, the lower frequencies should not be considered as only the problem of the suppression of the harmonics from the uncharacteristic operation of the converters but stimulation of power system instability caused by newly changed system constants. The situation is rather self-contradictory in some cases.

4 WAVE DISTORTION DUE TO HARMONICS

When the harmonic current emanates into the supplied power system from the bridge converter, it certainly causes harmonic voltage and so gives distortion to the wave of the supplied line voltage. If the nth-order harmonic current is I_n and the system reactance for the fundamental frequency is

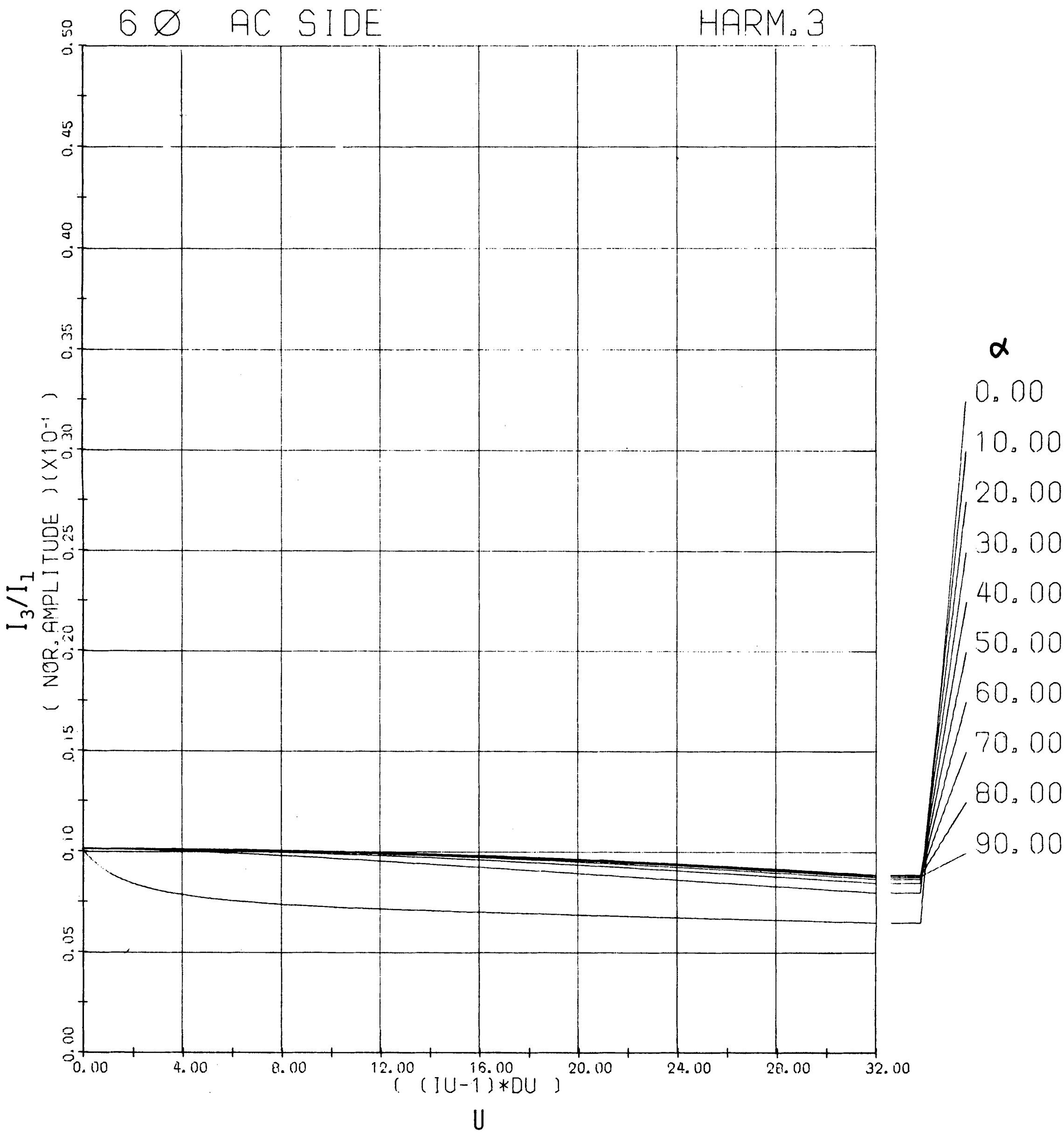

FIGURE 5(a) The third harmonic current of six-phase rectification with the condition in Figure 4(a).

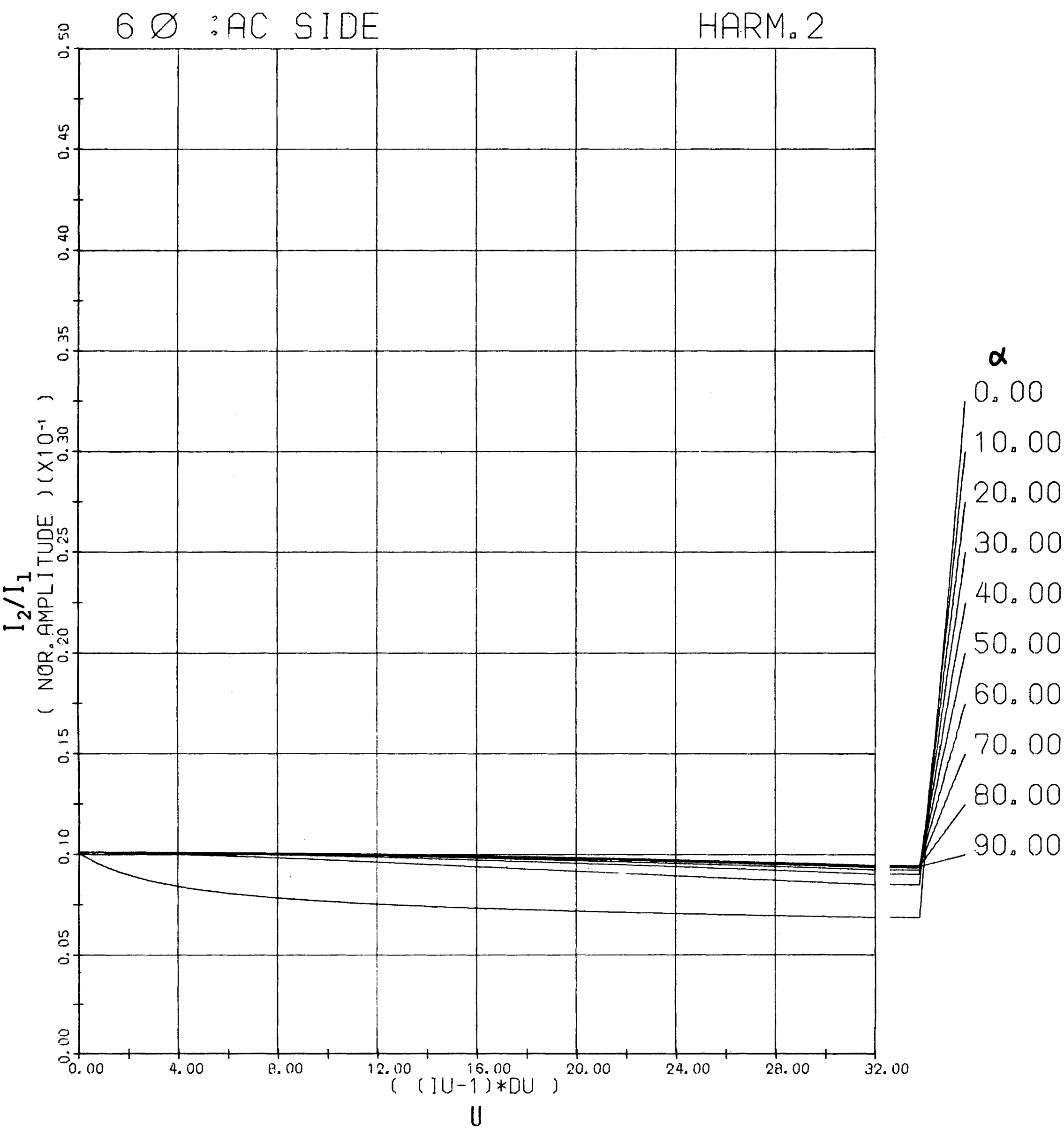

FIGURE 5(b) The second harmonic currents of a six-phase rectification with the condition in Figure 4(b).

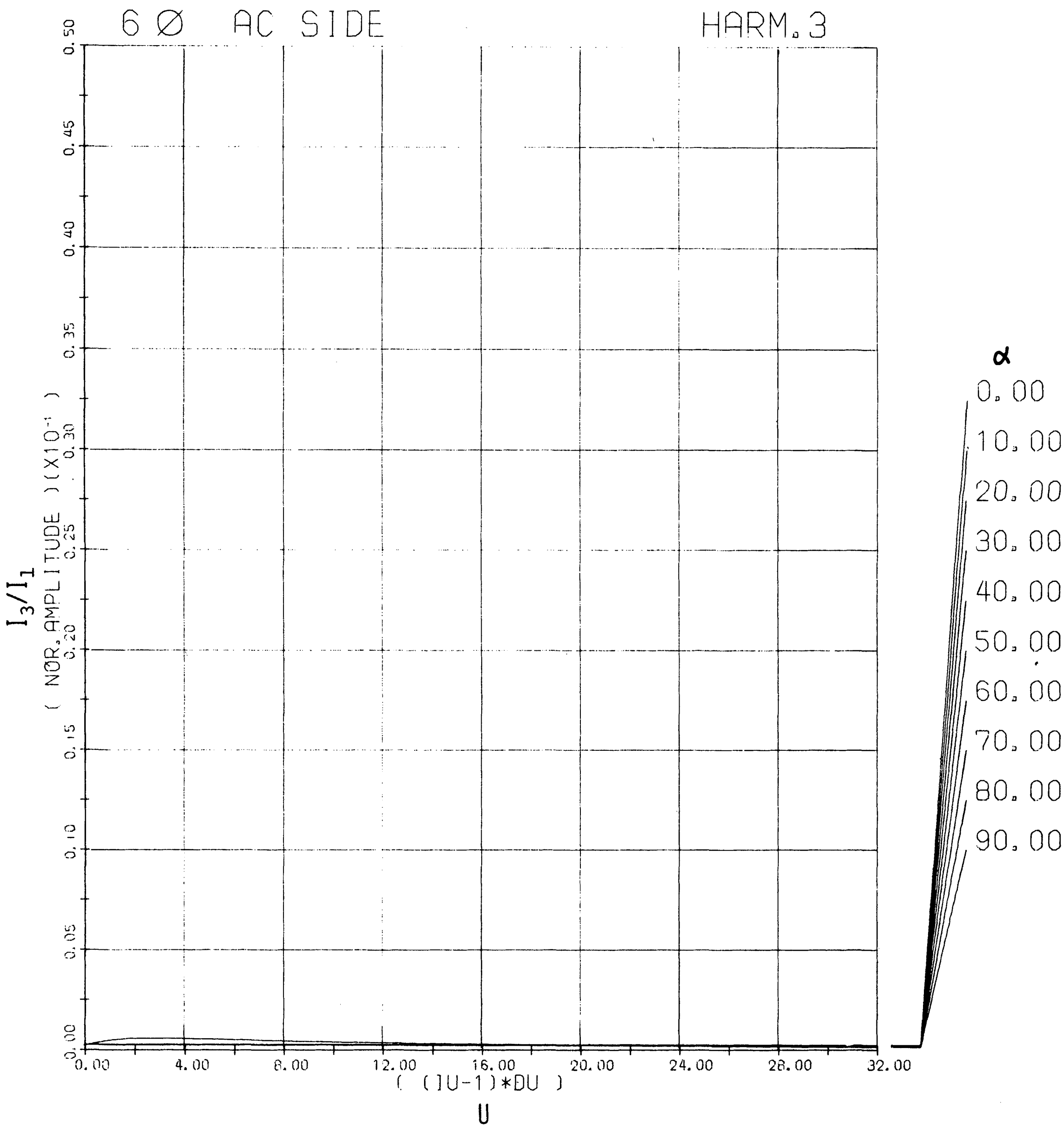

FIGURE 5(c) The third harmonic currents of a six-phase rectification with the condition in Figure 4(b).

X_s, the voltage distortion is given as

$$V_n(\%) = \frac{I_n \cdot n \cdot X_s}{E} \times 100(\%), \tag{11}$$

where E is the line voltage of the ac system. In general, the resistance can be neglected as compared with the reactance.

On the other hand, X_s is expressed as

$$X_s = \frac{E^2}{P_s}, \tag{12}$$

where P_s is the short-circuit power of the considered ac system.

As the harmonic current I_n to the fundamental current is given in Eq. (5), V_n is given as

$$V_n(\%) = \frac{I \cdot E}{P_s} \times 100(\%) = \frac{P_{\text{con}}}{P_s} \times 100(\%) \tag{13a}$$

or

$$V_n(\%) = \frac{I_1 X_s}{E} \times 100(\%) = V_1(\%), \tag{13b}$$

where P_{con} is the power of the converter which is nearly IE. This implies that distortion of the line voltage by harmonics of the converter is determined by the rating power of the converter and the short-circuit power of the power grid. It is approximately equal to the voltage drop for the fundamental frequency.

Actually, the harmonic current depends on the commutation angle and phase angle. Then the above discussion presents the maximum case. The actual voltage distortion is slightly less than the above. When one wants to keep the voltage distortion of the power system less than the desired value, the converter should be connected to a system having large capacity, otherwise, the system reactance has to be decreased to the desired value by other methods. The ac filter system is one.

5 ENVIRONMENTAL EFFECT OF THE HARMONIC CURRENT

The best-known effect of the harmonic current is influence on telephone circuits. But a more important effect is a resonance coupled with capacitors which have been installed at the factories of power consumers on the same power grid. A very small amount of harmonic current has never given considerable effect to the voltage distortion of the power grid, but is still effective in stimulating local resonances. If a local resonance occurs, harmonic current flows into the capacitor. Frequently, it trips the circuit breaker or overheats the capacitor in the worst case. As generally the system and/or the power grid are rather inductive, the reactance for the nth harmonic is nE^2/P_s. On the other hand, the reactance of the capacitor is $E^2/nP_{C(1)}$ where $P_{C(1)}$ is the power rating of the capacitor on the fundamental-wave base. At resonance

$$nE^2/P_s = E^2/nP_{C(1)} \tag{14a}$$

and

$$n^2 = P_s/P_{C(1)}. \tag{14b}$$

For instance, when a 2 MVA capacitor is connected to the system of capacity 100 MVA, it resonates at the 7th harmonic, in other words 350 Hz for 50 Hz fundamental.

Surveys have been carried out to find the resonance conditions in the region extended about 50 km from our laboratory. The survey was strenuous and precise. It has given assurance of safety on harmonic problems for the power system to which the converter in KEK was to be connected. With negotiation with the electric power company as the basis of the survey, the permissible value of the voltage distortion on the 66 kV line which is the commercial power line to KEK was tentatively determined as 0.5% for each harmonic.

6 AC HARMONIC FILTERS

The filter is essentially composed of inductance and capacitance, and it resonates at a given frequency. The resonance condition between the inductance and the capacitance is as follows

$$X_{L(1)} = \frac{X_{C(1)}}{n^2}, \tag{15}$$

where $X_{L(1)}$ and $X_{C(1)}$ are the reactances for the inductor and the capacitor for the fundamental frequency respectively.

The terminal voltage of the capacitor is

$$V_{C(1)} = \frac{-X_{C(1)}}{X_{L(1)} - X_{C(1)}} E = \frac{n^2}{n^2 - 1} E \tag{16}$$

and the rating power for the fundamental frequency is

$$P_{C(1)} = \omega C V_{C(1)}^2 = \omega C E^2 \left(\frac{n^2}{n^2 - 1}\right)^2. \tag{17}$$

TABLE I
Characteristics of transformers and equipments for each bank installed at KEK.

Bank		No. 1	No. 2	No. 3
Transformer	capacity (MVA)	12	12	12
	short circuit voltage %	7.5	7.5	7.5
Equipments		Main Ring Power Supply (12 MW rms) 12ϕ Thyristor Reactive Power Controller (14 MVAr max) 6ϕ	Bubble Chamber Power Supply (2.7 MW) 12ϕ Beam Line Power Supply (5 MW) 12ϕ Capacitor for Improvement of Power Factor 2 MVA	Booster PS Power Supply (0.5 MW) 6ϕ General Equipment Capacitor for Improvement of Power Factor 2 MVA

Generally the capacitor of the ac filter can serve as the capacitance for improving the power factor. $P_{C(1)}$ can also compensate the reactive power of the converter. It should be noted that, if voltage distortion is decreased to the recommended value, 0.5%, in the system, the prepared capacitor tends to compensate excessively reactive power of the converter. Sometimes additional inductance should be prepared to compensate again the excess lead reactive power.

7 AC FILTERS IN KEK

The power system in KEK has three lines. Each line has a 12 MVA transformer which steps down the voltage from 66 kV to 6.6 kV. The short circuit voltage is 7.5% on a 12 MVA base. Number 1 line is the exclusive line for the power supply of the main ring magnet, and No. 2 and No. 3 lines are for the bubble chamber, the booster, the beam line and general purpose. This is shown in Table I.

The major generators of harmonics are the power supplies for the main ring magnet, for the bubble chamber magnet and for the beam line magnet. In all cases, the generator of harmonics is the thyristor converter. A filter for a total power of 14 MVA† is prepared for No. 1 line. A 5-MVA† filter is prepared for No. 2 line and will also be prepared for No. 3 line.

† All of these are the rating powers of the capacitors for the fundamental frequency.

As for No. 1 bank the filter has several branches for different frequencies, that is for the 3rd, 5th, 7th and higher orders. The capacity of each branch of the filter should be chosen to absorb most effectively the harmonic currents. So sharing of the capacities for the branches is the most important choice in the filter. It depends on types of sources of the harmonic currents and their operating conditions, for instance, the number of phases of rectification, the phase angle α, commutation angle u and other converter characteristics.

Simulation of the power system was done by a computer for various sharing conditions of the filter and a typical result is shown in Table II. The table gives the data in the case that 2 MVA, 4 MVA, 4 MVA and 10 MVA branches are prepared for the 3rd, 5th, 7th and higher orders respectively. It is surprising that certain harmonics are not suppressed but remained constant. It is particularly apparent at the third harmonic. Some resonances must occur between the inductance of the system and the capacitance of the filter. Thus, and as already said, the sharing of the capacity for each branch of the filter is important. The calculated result has shown that the big filter could decrease the distorting rate of the 66 kV wave to less than 0.5% which is recommended by the electric power company.

The total capacity of the capacitor, however, is 20 MVA and exceeds the required capacity for compensating the lag reactive power of 14 MVAr in the power supply. The 6 MVAr overcompensation must be again compensated by the inductor. The above choice does not seem ingenious and it is doubtful that this is the better one in the future.

TABLE II

Calculated current to each 6.6 kV line from the installed equipment.

Harmonic Order	No. 1 Bank Current to 6.6 kV line Without Filter	With Filter	Limitation	No. 2 Bank Current to 6.6 kV line Without Filter	With Filter	Limitation
3	39A	39A	58A	20.4A	34.9A	58A
4	—	—	—	3.8	28.9	44
5	207	12.8	35	12.3	0.7	35
6	—	—	—	2.6	4.6	29
7	128	4.3	25	8.7	0.5	25
8	—	—	—	1.9	1.2	22
9	—	—	—	6.8	5.3	19.4
10	—	—	—	1.5	0.6	17.5
11	206	6.4	15.9	56.7	15.9	15.9
13	175	5.7	13.5	47.1	10.4	13.5
15	—	—	—	4.1	0.9	11.7
17	31	1.2	10.3	3.6	0.8	10.3
19	24	1.2	9.2	3.2	0.8	9.2
21	—	—	—	2.9	0.7	8.3
23	85	4.3	7.6	26.6	6.3	7.6
25	78	4.0	7.0	24.5	5.8	7.0

No. 1 Bank: Condition 3th 2 MVA; 5th 4 „; 7th 4 „; HP 10 „

Harmonic Current
characteristic $1/n$
uncharacteristic $1/n^2$

No. 2 Bank: Condition 5th 2 MVA; 7th 1 „; HP 2 „

Harmonic Current
characteristic $1/n$
uncharacteristic (odd) $1/10n$
„ (even) $1/40n$

After careful consideration, the filter of which the total capacity is 14 MVA has been installed in KEK. Sharing of the capacities is 2 MVA, 3 MVA, 3 MVA and 6 MVA for the 3rd, 5th, 7th and higher orders respectively.

The 14 MVA filter for the No. 1 bank also serves as the capacitor for the compensation of the 14 MVAr lag reactive power which comes from the system of the thyristor reactive power controller (TQC)[4] and the thyristor converter of 25 MW.

As for the No. 2 bank the same survey was done for making up the filter. The sharing is shown in Table II. It is noticeable that the harmonic currents of lower orders are not suppressed. At the beginning the filter was shared into 2 MVA for the 5th and the 7th orders in combination and 2 MVA for higher order. Finally the former 2 MVA branch was reconstructed for the 5th and a new 1 MVA branch was installed for the 7th order.

The total system of harmonic filters is shown in Figure 6 and Figure 7. The principal specifications are shown in Table III.

8 TESTS OF THE HARMONIC FILTERS

The tests were carried out for No. 1 and No. 2 banks independently. The sources of the harmonic current were TQC (14 MVAr) for No. 1 bank and the thyristor power supply of the buble chamber (2.7 MVA) for No. 2 bank.

For No. 1 bank, TQC is a 3ϕ thyristor device and generates the harmonics of $6n \pm 1$ order and at the same time the slight amount of uncharacteristic harmonics. The attenuation rates of the harmonics by use of the filter were measured. The result is shown in Figure 8. The typical spectra of the harmonic voltage taken by the real time spectrum analyzer are shown in Figure 9. Background harmonics are also shown in Figure 10 for 66 kV line voltages.

It was surprising that the filter could clear the power line of harmonics as shown in Figure 9. Almost all harmonics were reduced under the level of -65 dB. The attenuation in voltage is approximately more than 15 dB and is satisfactory

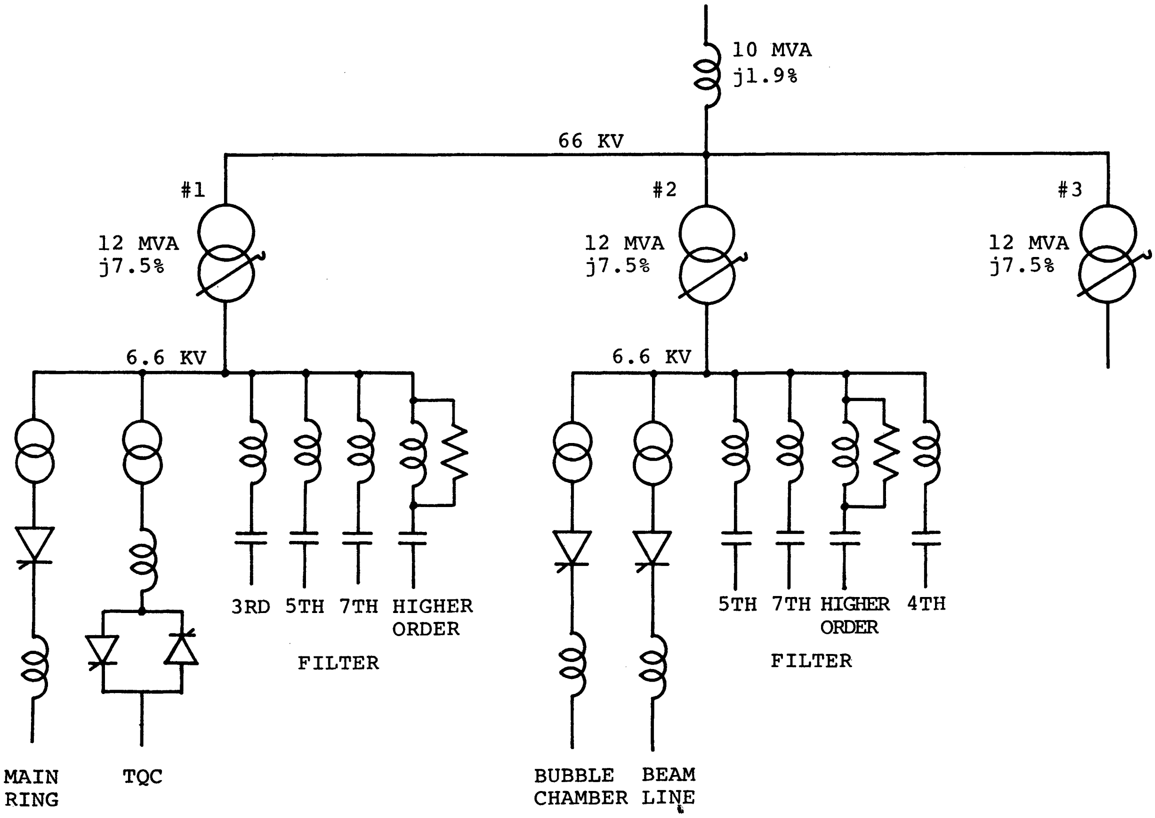

FIGURE 6 The harmonic filters and the other equipments in KEK.

TABLE III(a)

The specifications of the capacitors of the No. 1 bank filter

	No. 1 Bank			
Order of filter	3rd	5th	7th	Higher Order
Rated voltage (kV)		6.6		
Fundamental freq. (Hz)		50		
Capacity for fundamental frequency (MVA)	2	3	3	6
Current for fundamental frequency (A)	175	262	262	525
Voltage for fundamental frequency (V)	4287	3969	3890	3842
Resonance frequency (Hz)	150	950	350	≧550
Capacity for harmonic (kVA)	61	546	160	—
Harmonic current (A)	50	250	160	—
Connection	y	Δ	Δ	y

TABLE III(b)

The specifications of the capacitors of No. 2 bank filter.

	No. 2 Bank		
Order of filter	5th	7th	Higher Order
Rated voltage (kV)		6.6	
Fundamental frequency (Hz)		50	
Capacity for fundamental frequency (MVA)	2	1	2
Current for fundamental frequency (A)	175	87.5	175
Voltage for fundamental frequency (V)	3969	3890	3842
Resonance frequency (Hz)	250	350	≧550
Capacity for harmonic (kVA)	26.4	1.7	—
Harmonic current (A)	44	9.4	—
Connection	y	y	y

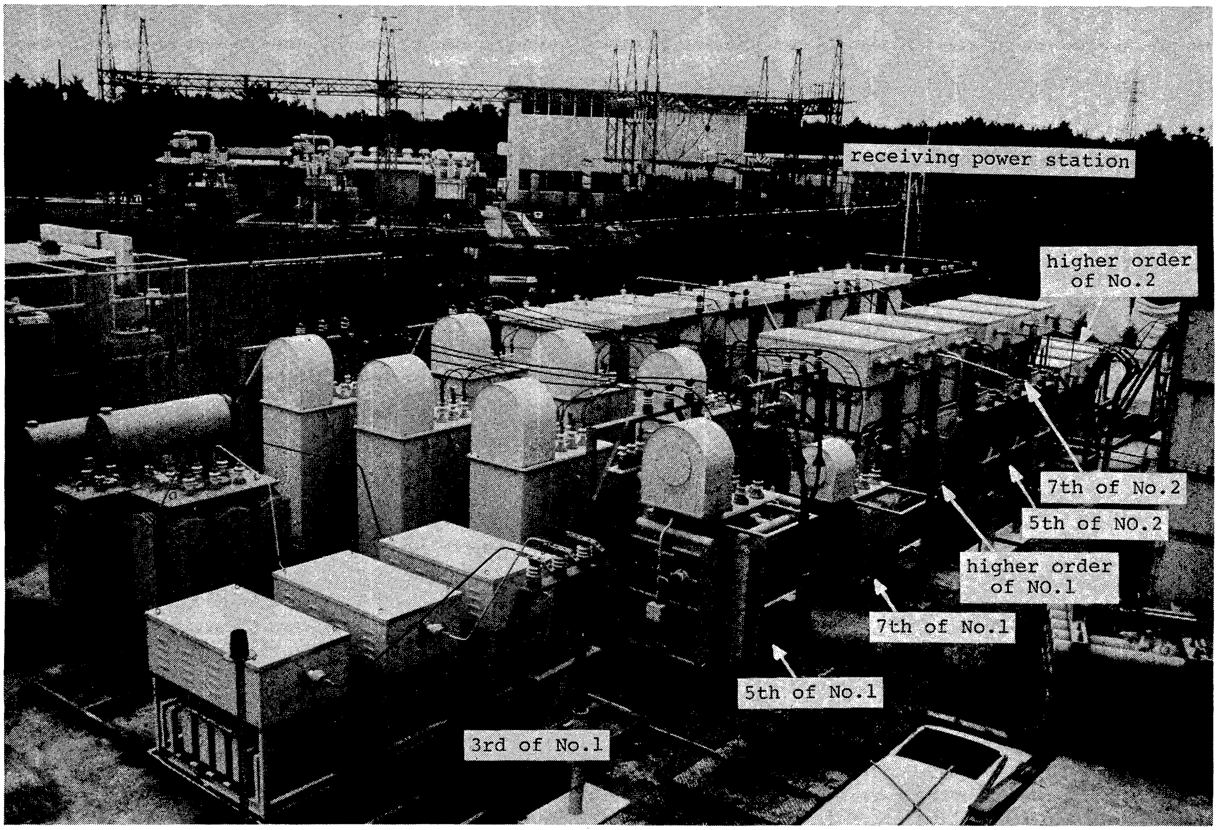

FIGURE 7 An overhead view of the filter systems.

except for the third harmonic as shown by the previous analysis. As was previously feared, the third harmonic was amplified in this case. From Eq. (14(b)), resonance of the system will occur at the order of $n = (P_s/P_{C(1)})^{1/2}$. If the reactance of the supplied power grid is $X_s\%$ at the 10 MVA base, the order of resonance is at

$$n = (10/P_{C(1)}X_s)^{1/2}. \quad (18)$$

As already described, X_s and $P_{C(1)}$ are 8.2% and 12 MVA respectively; then the order of resonance is at

$$n = \left\{\frac{10}{12 \times 8.2 \times 10^{-2}}\right\}^{1/2} = 3.18. \quad (19)$$

This implies the existence of the resonance near the third order. The slight amplification of the harmonics, therefore, has been observed (Appendix B). On the other hand, the third harmonic from the thyristor of the 3ϕ device is uncharacteristic and it was a very small amount as measured. The real third harmonic comes rather from the supplied power grid of 66 kV itself as shown in Figure 10. The third branch of the filter has brought the third harmonic over from the 66 kV to the 6.6 kV line. Even so, the third branch cannot be omitted because of the suppression of the system resonances as already discussed. This is confirmed by the attenuation in current as shown in Figure 8 and also impedance characteristics in Figure 12(a). The problem of the third branch cannot be uniquely discussed and solved. For instance when the system impedance and so the prepared total capacity of the filter are changed, the lowest order branch is not only confirmed to the 3rd, but must be the 2nd or the 4th in some cases depending on the above conditions.

For the No. 2 bank, 2 MVA for the 5th and the 7th in combination and 2 MVA for higher harmonics were prepared at first. The test has been carried out for this system and the result is shown in Figure 11. The attenuation rate could not be

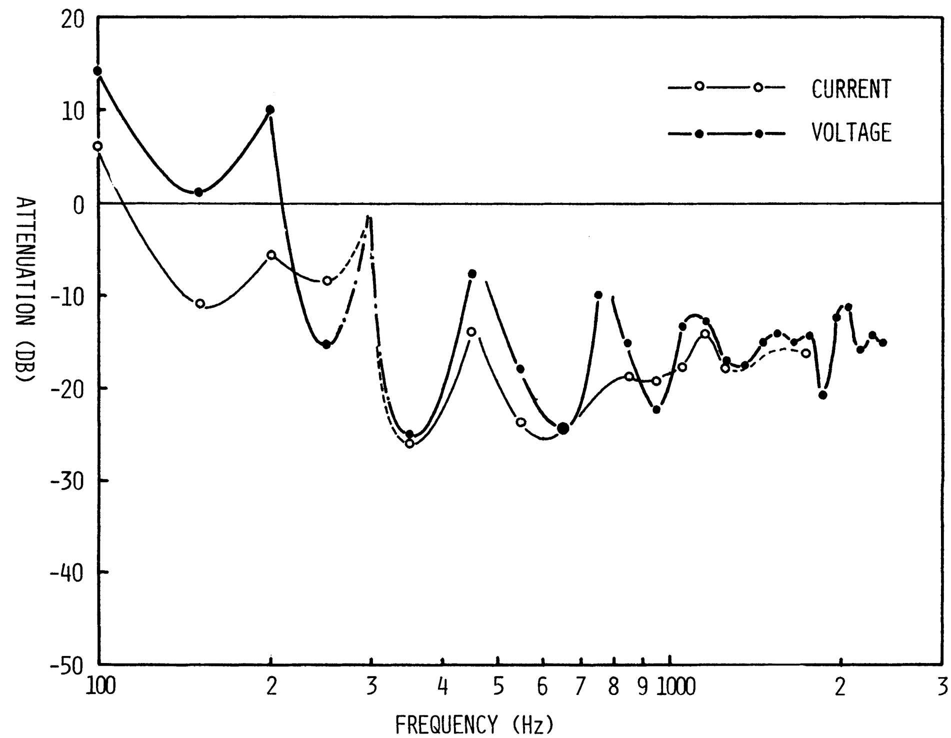

FIGURE 8 The measured attenuation characteristics of voltage and current for No. 1 bank filter.

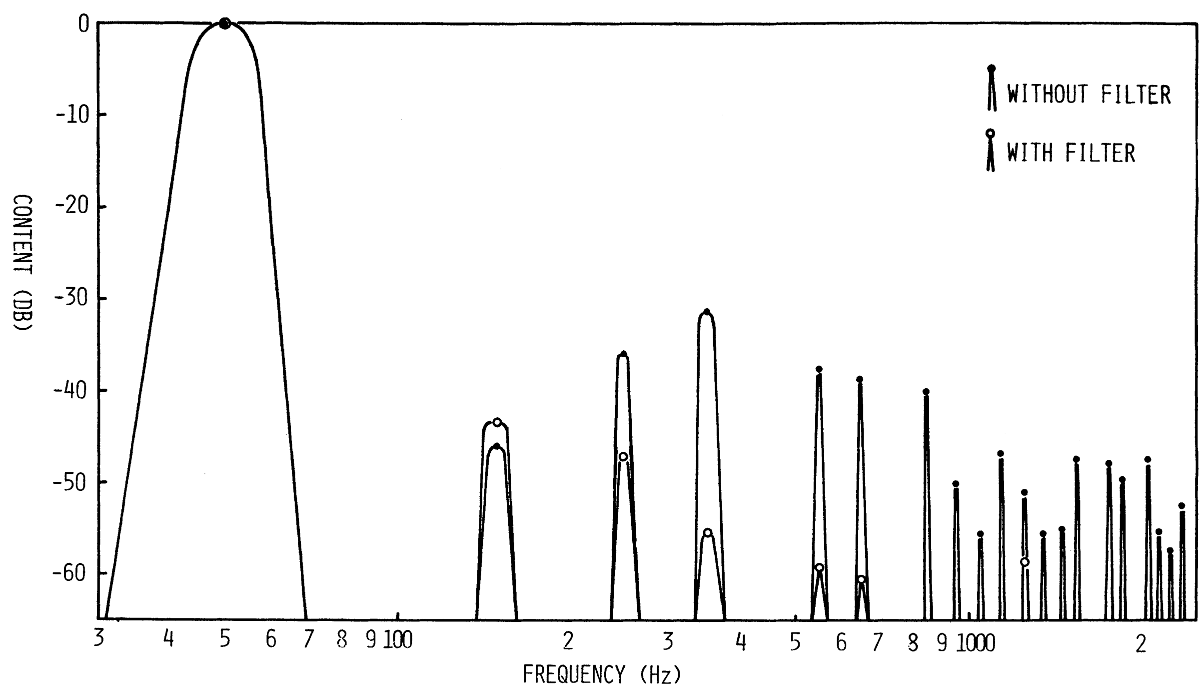

FIGURE 9 Typical harmonic voltage spectrum issuing from No. 1 bank to 66 kV line with and without the filter.

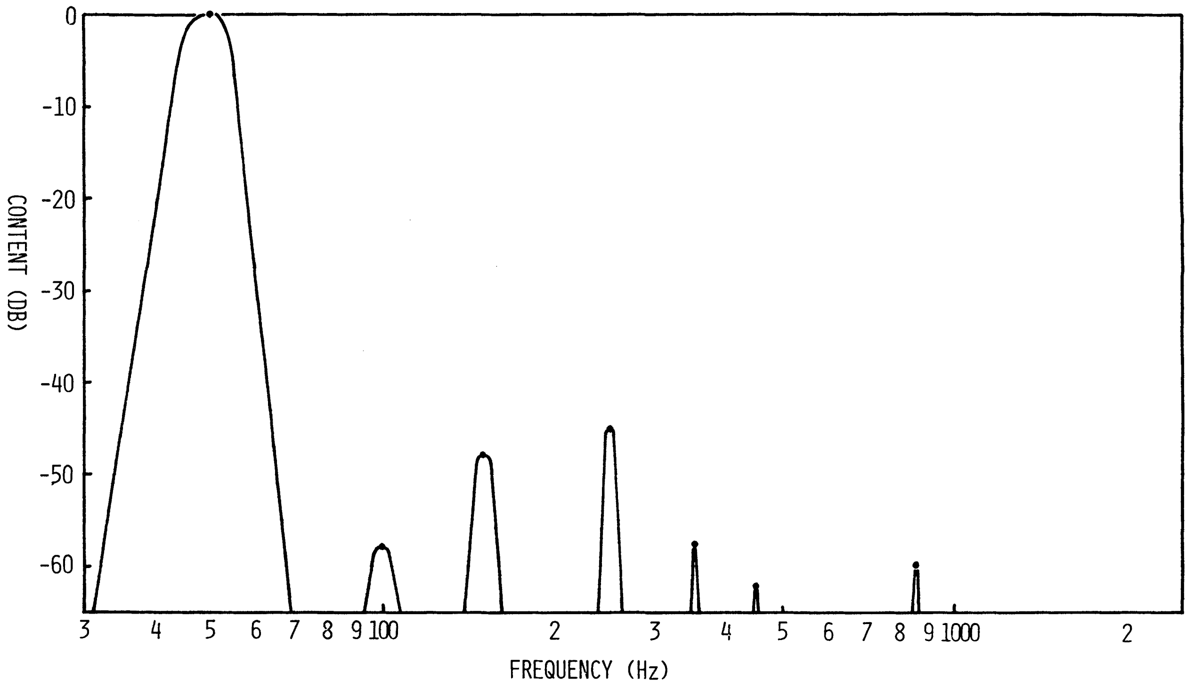

FIGURE 10 The background spectrum of harmonic voltage contained in the 66 kV line.

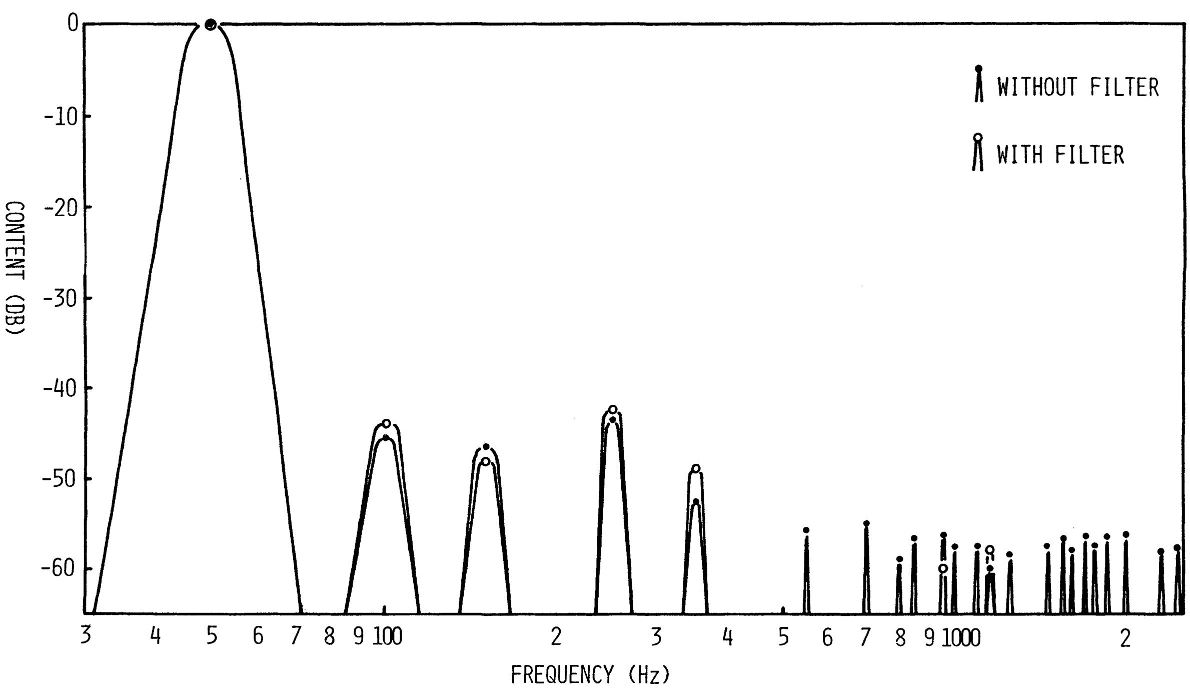

FIGURE 11 Typical harmonic voltage spectrum issuing from No. 2 bank to 66 kV line with and without the filter.

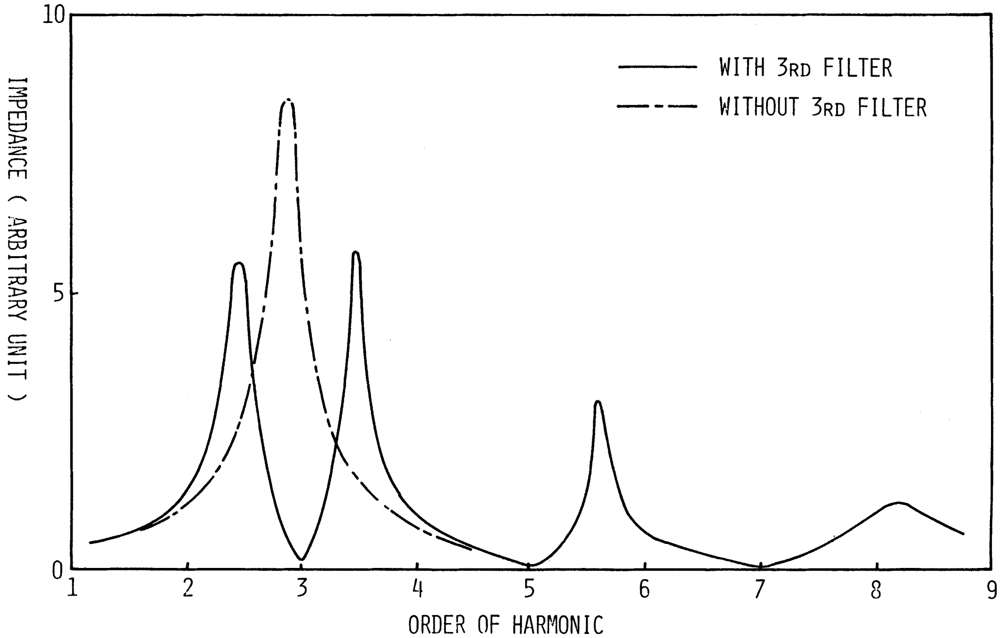

FIGURE 12(a) The calculated frequency characteristics of impedance for the No. 1 bank filter with and without the third branch.

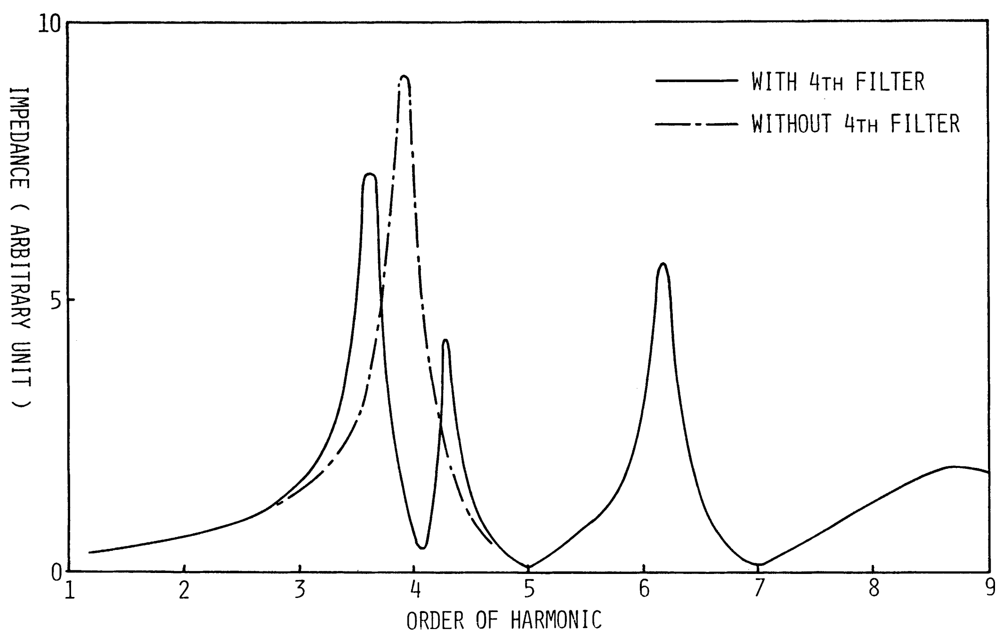

FIGURE 12(b) The calculated frequency characteristics of impedance for the No. 2 bank filter with and without the fourth branch.

measured as for the No. 1 bank because of small harmonic currents from the power supply. It was clarified, however, that the 5th and the 7th harmonics were not decreased by the filter. It is the reason why the 5th and 7th branches in combination were shared in two parts. The additional 1 MVA is being prepared exclusively for the 7th. The existing 2 MVA is being prepared for the 5th exclusively instead of combination use for the 5th and the 7th harmonics.

The existing power supply for the bubble chamber is a hybrid type having diodes and thyristors in the rectifier bridge. It generates even orders of harmonic currents. As is well known, the even order is very dangerous when it flows into the commercial power grid. Today the power supply is already converted to a full thyristor type of 12ϕ rectification.

After improvement of the system, resonance will occur at the 4th order as in Figure 12(b). The filter for the 4th order is not prepared but an existing capacitor and a 6% inductor, which are to improve power factor and installed at many points of the power system, will decrease the impedance for the 4th order of the power system in the figure.

9 CONCLUSION

The ac filters described above have shown good performance in the No. 1 bank and also the No. 2 bank with slight modification. For the No. 1 bank, the source of the harmonics was the unusual operation of the TQC and not the actual multi-phase converters but as only concerned with the harmonic problems the test is regarded as satisfactory.

The principal points to be considered in the designing of ac filters are as follows:

1) how to share the capacitors for each harmonic branch,

2) consider the resonance problem in the total power system, of course, in which the filter is included.

As far as (1) is concerned, the adequate sharing of the capacitors can be determined by a simulation. For (2), it is a serious problem for the power system. It causes amplification of the harmonic current which exists in the power grid itself. The amplified harmonic current must cause the overrating of already installed capacitors and inductors. Particularly for inductors, the overcurrent causes nonlinear effect in inductance and will give complicated and incomprehensible phenomena in the filters.

REFERENCE

1. Y. Sanpoh: *Direct Current Transmission and Frequency Conversion* (Denkishoin Inc., Tokyo, 1965) p. 156 (in Japanese).
2. E. W. Kimbark: *Direct Current Transmission*, Vol. 1 (John Wiley and Sons, Inc., 1971) p. 295.
3. The full calculation is to be published in a KEK report.
4. M. Masuda: "Protection of Flickers and Higher Harmonics Produced from Static Power Supply," *Proc. U.S.-Japan Seminar on High-Energy Accelerator Science*, Tokyo and Tsukuba, Nov. 1973, p. 145. To be published in more detail.

Appendix A

Engineering Recommendation G5/2

39th Chief Engineers' Conference, Oct. 1967, England

Permissible Harmonic Current

The recommendation is for application to converting plant in terms of the production of harmonic current. Harmonic current is defined as the largest value of rms harmonic current of the frequency concerned. For the purpose of this report it is considered that where the harmonic current bursts are of less than about 2 seconds duration, separated by intervals of the order of half a minute, the permissible harmonic current limit may be doubled.

The Limitation of Harmonic Current

The 5th and 7th harmonic currents are to be limited by consideration of voltage distortion and the consequential effects of voltage distortion in producing unbalance effects on 6-pulse groups forming a 12-pulse converter or the separate groups of large pulse number converters. The proposed limits are 1% voltage distortion at the lower voltages and just under 1.2% voltage distortion at the higher voltages where system resonances are more likely.

The permissible 11th harmonic current is to be fixed by the criterion of 10, 20 and 40 A on a 11 kV base for 11, 33 and 132 kV and high voltage networks respectively. This criterion is based on a survey of the results of extensive theoretical studies and by site investigations of voltage distortion and capacitor overloads with special consideration of system resonance. This criterion has not been applied to 415-volt networks because unacceptable 11th harmonic voltages result from the very high system impedance.

Sardina Project in Italy

$$D < 4\% \text{ (at } 12\phi)$$

$$D < 5\% \text{ (at } 6\phi)$$

Nelson River Project in Canada

$$D < 2\% \text{ (at } 12\phi),$$

where D is the harmonic voltage distortion.

Appendix B

Strictly speaking, the resonance condition of the system with the line must be considered as follows. The impedance of the filter of No. 1 bank and the power grid are shown in Figure 13 on the basis of 10 MVA.

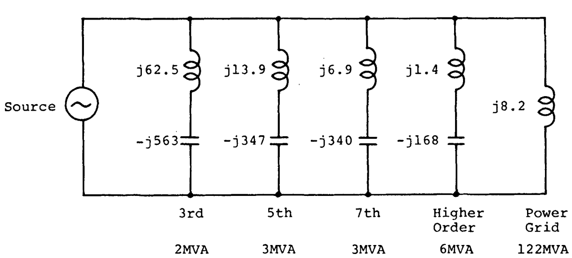

FIGURE 13 The system impedance of the No. 1 bank filter and the power grid for calculation of resonance conditions.

In the case of parallel resonance at nth order the admittance of the whole filter system is

$$Y_n = \frac{1}{j\left(62.5n - \dfrac{563}{n}\right)} + \frac{1}{j\left(13.9n - \dfrac{347}{n}\right)} + \frac{1}{j\left(6.9n - \dfrac{340}{n}\right)} + \frac{1}{j\left(1.4n - \dfrac{168}{n}\right)}. \tag{B-1}$$

The resonance condition comes to be as the following equation:

$$j8.2n + \frac{1}{Y_n} = 0. \tag{B-2}$$

The equation gives orders of resonance and then $n = 2.51$ and 3.44 near the third order.