SPECIAL QUESTIONS OF INDUSTRIAL NETWORKS

HARMONICS

Martti Tuomainen , ***NOKIAN CAPACITORS***

1. SOURCES OF HARMONICS

1.1 Thyristor convertors

The current drawn from the supply network by a thyristor convertor is not sinusoidal. Because of this non-sinusoidal character thyristor convertors are, with regard to the supply, sources of harmonics, the order of the harmonics fed into the supply being dependent on the construction of the convertor. A characteristic feature of a convertor is its pulse number (p). Knowing the convertor pulse number the order of the harmonics produced by it may be obtained from the equation

$$n = k \cdot p \pm 1 \qquad (1)$$

where

n = order of harmonic
p = pulse number
k = 1, 2, 3 ...

The 6-pulse convertors in common use feed into the supply harmonics of order 5, 7, 11, 13 etc. as given by the above equation. If the convertor has a 12-pulse configuration, the 5. and 7. harmonics do not, practically speaking, appear. A 12-pulse convertor generally comes into consideration only for high powers because of its heavy cost. In general we may say that the greater the convertor pulse number, the less the harmonics fed into the supply. Lack of symmetry in the supply network and specific faults in the convertor cause uncharacteristic harmonics such as 2., 3., 4. to appear in the harmonic series.

In the ideal case the magnitude of the harmonic currents produced by the convertor is dependent only on the magnitude of the fundamental current and the order of the harmonic concerned according to the following equation:

$$I_N = \frac{I_1}{n} \qquad (2)$$

where

I_1 = fundamental mains current
n = order of harmonic
I_N = n. harmonic current

Equation 2 presupposes that the convertor is fed from a strictly symmetrical, stiff three phase network and that the direct current is fully smoothed. In practice the magnitude of the harmonic currents produced is, in addition to the order of the harmonic and the magnitude of the fundamental frequency current, also affected by the short-circuit power at the connection point of the convertor, and the ripple on the direct current. Decrease of short-circuit power (network reactance increases) lengthens the commutation time, in other words the commutation angle increases and the AC current harmonic content is reduced. Since the circuit inductance is not able to smooth the direct current completely, ripple remains on this. Direct current ripple has the effect of increasing some of the harmonics and reducing others. Figure 1.1 shows the effect of overlap angle and ripple on the harmonic content of the AC supply current.

1.2 Frequency convertors

The relation between fundamental frequency and harmonics fed into a supply network by a frequency convertor does not differ materially from what has been stated with regard to thyristor convertors. The order of the harmonics is also in accordance with equation no. 1 of the preceding section. There are considerable differences, however, in the harmonic currents fed into the supply network by different types of frequency convertors, due to the fact that the fundamental frequency currents taken at the same torque and frequency are of different magnitudes for different frequency convertors.

The magnitude of the fundamental current is at a specific frequency and torque dependent on the structure of the frequency convertor input circuit, namely whether this is a thyristor or diode bridge. Since the thyristor bridge also takes reactive control power from the supply network, the fundamental current taken by it in the range

$f/f_N < 1$

is greater than the fundamental current taken by the diode bridge and consequently the harmonic currents fed by the thyristor bridge are also greater than those from the diode bridge.

1.3 Thyristor switches

In recent years there has been an increasing use in industry of thyristors controlling resistive loads. The most general control methods are the so-called integral-cycle or burst firing control and phase control.

In burst firing control thyristors always conduct for one or several complete cycles, after which the ignition pulse is removed similarly for one or several complete cycles. Figure 1.3 shows examples for three different degrees of control, namely a = 0.5, a = 0.333 and a = 0.25.

Figure 1.4 shows the frequency spectrum of the corresponding currents. As can be seen from the figure burst firing control produces also non-harmonic frequencies.

In phase control thyristors are fired during each half cycle and power is controlled by varying the firing angle (a). See Fig. 1.5. Harmonic analysis of the currents of Figure 1.5 results in the harmonic contents shown in Figure 1.6.

In controlling a resistive load by phase control it is observed that the current fed also includes a lagging reactive component. Figure 1.7 shows the dependence of active and reactive power on control angle for the circuit of Figure 1.2.

1.4 Cyclo-convertors

Cyclo-convertors are static frequency convertors which convert multi-phase fundamental frequency voltage to single or multiphase voltage at a lower frequency. A characteristic feature of cyclo-convertors is that they operate in most cases without circulating current.

A 3-phase cyclo-convertor generally consists of three inverse parallel connected 3-phase thyristor convertors which together provide the output for the lower frequency three phase system. Figure 1.8.

The order of the harmonics in the input current of the cyclo-convertor depends on the pulse number of the input thyristor bridges (equation 1). In addition to these so-called typical harmonics a 3-phase cyclo-convertor produces harmonics the order of which depends on the cyclo-convertor output frequency f_2 as follows:

$$n = (k \cdot p \pm 1) \pm 6 \cdot m \cdot \frac{f_2}{f_1} \qquad (3)$$

where
- n = order of harmonic
- k = 1, 2, 3...
- p = pulse number
- m = 0, 1, 2
- f_1 = supply network frequency
- f_2 = cyclo-convertor output frequency

If the output frequency of the cyclo-convertor is 3 Hz, for example, there appear components on each side of the fifth harmonic. Examples of these are components of frequencies 268 Hz and 232 Hz.

The cycloconvertor harmonic amplitudes are dependent on the load, load power factor, degree of firing angle and control mode. In some cases the non-harmonic components may be of greater amplitude than the harmonics.

1.5 Arc furnaces

Since the current drawn by arc furnaces is, particularly in the initial melting phases, appreciably non-sinusoidal, these furnaces are also sources of harmonics. According to one source measurements on different arc furnaces have shown that furnace current includes almost all harmonics. Average and instantaneous harmonic currents for arc furnace current are, according to the same source, as in table 1.1.

2. DISTRIBUTION OF HARMONICS

In recent years the harmonic producing part of total load has increased continuously. Power electronics is being used more extensively in industry for the control of various processes. A consequence of this has been an increase in harmonic voltages and currents in the supply networks of industrial establishments and electricity undertakings. Harmonics cause additional losses in network components. In addition harmonics may interfere with the operation of telephone and network remote control equipment and also with different industrial controls.

If compensating capacitors are used in a network subject to harmonics, resonance may cause the harmonic currents and voltages to be multiplied. In order to avoid the harmful effects of harmonics it is necessary to be informed of the possibility of their appearance whilst still in the planning stage and if necessary to carry out a network harmonic study. In a network already in use a harmonic analysis will become necessary if, for example, convertor power increases considerably. An increase in compensation power also generally makes a harmonic analysis necessary. The better the electrical values of the different network components and their frequency dependencies are known the more exact will be the picture of harmonic distribution given by the harmonic study.

For the analysis of harmonics there are now available various computer programs, which are able to take into account the frequency dependence of different components, calculate the distribution of harmonics, find possible resonance situations and are of assistance in the electrical design of filter circuits.

In calculations a source of harmonics is represented by constant current generators relative to the harmonics. From this it follows that the harmonics are distributed among the different components of the network so that, at the frequency in question, the part of the network with lowest impedance carries relatively the greatest part of the harmonic currents arising. The impedance used are the short-circuit impedances of the different components. Figure 2.1 shows the distribution of harmonics in an industrial network. In Figure 2.2 the new distribution of harmonics is calculated when using compensation capacitors, which are connected to the same busbar as the source of harmonics.

In examining what factors affect the network resonance frequency and the distribution of harmonics it is noticed that increase of short-circuit power (network inductance decrease) raises the network resonance frequency and a still greater part of the harmonics flows in the direction of the supplying network. Squirrel gage motors loading the network also increase the resonance frequency, but at the same time damp the resonance.

A resistive load does not affect the resonance frequency markedly, but damps the resonance considerably. Raising the degree of reactive power compensation by capacitors reduces the resonance frequency of the network. Figure 2.3 shows the effect of different loads in damping and shifting the resonance frequency.

3. MEASUREMENT OF HARMONICS

Measurement of harmonics in industrial networks and those belonging to electricity undertakings is usually carried out by making use of the network's own current and voltage transformers. In some cases the use of a separate clamp-on current transformer comes into question.

For reliable measurement results it is necessary to ascertain whether the voltage and current transformers used in the measurements are capable of reprodu-

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cing the higher frequencies reliably. In general it may be said that current transformers reproduce reliably harmonics with frequencies of some kiloherz, while on the other hand the reproduction range of voltage transformers may only be some hundreds of herz.

In harmonic measurements the measuring equipment used is nowadays almost exclusively some kind of frequency analyser, which shows directly the different frequency components of the input signal and their amplitudes.

Inputs to measuring equipment are generally voltage inputs, so that in measuring current harmonics it is necessary to connect a low ohmic resistor to the secondary circuit of the current transformer at the measurement point. The voltage drop across this resistance is proportional to the current and is conducted to the measuring equipment, Figure 3.1. In choosing this resistance care should be taken not to exceed the permissible secondary burden of the current transformer. In measuring voltage harmonics the voltage is matched with the measuring equipment by means of a suitable potential divider, Figure 3.2.

With a two channel harmonic analyser it is possible to measure simultaneously current and voltage components and the phase angle between them.

From the phase angle the direction of the harmonic with respect to the network may be determined. According to one source a part of the network is receiving harmonics when the angle between voltage and current for the same order harmonic is between -90 and +90 degrees. Correspondingly harmonics are being produced if the phase angle is between +90 and +270 degrees.

4. MEASUREMENT RESULTS

Measurements of the harmonics of the secondary current of the feeding transformer were carried out for the network of Figure 4.2.

The sources of harmonics were two exactly similar 6-pulse thyristor bridges, the control angles of which were not dependent on each other. As can be seen from the results of the measurements in table 4.1 the 5. harmonic content relative to the fundamental frequency is only 3.4 %, though according to section 1.1 it should be of the order of 20 %. The reason for the low 5. harmonic content is revealed by measuring the feeding waveform, from which it is apparent that the control angles of the bridges are different (the commutation notches are not at the same point, Figure 4.1). For this reason the 5. harmonics from the sources are not in phase, and due to the vector summation of the harmonics the measured results at the control angles in question were only, for example, 3.4 % of the fundamental frequency.

Regulating the thyristor bridge control angles so that they were almost identical (Fig. 4.3) gave the results of table 4.2 in which the magnitudes are of the same order as those of section 1.1.

The harmonic sources of the network of Figure 4.4 were frequency convertors equipped with fixed intermediate circuit voltage (input circuit diode bridge) of total power about 1 MVA. For frequency convertors with diode bridge input circuits the harmonics sum arithmetically, since there is no difference between the control angles. Table 4.3 presents measurements of harmonics of the secondary current of the supply transformer. Values are of the same order as those of section 1.1.

The source of harmonics in the network of Figure 4.5 was a 3-phase thyristor switch controlling a resistive load. Control mode was phase control. As can be seen from the results in table 4.4 the 3-phase thyristor switch behaved in the same way with respect to harmonics as the 6-pulse bridge.

In the foregoing it has been shown how different station convertor loads affect the supply network. Figure 4.6 shows how, according to one source , compensation for the 5. harmonic by means of a filter circuit affects the harmonics of a 6-pulse convertor and the supply network in a certain case.

Table 4.5 gives the measured results for

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the harmonics produced by a 6-pulse convertor, with and without compensation by means of a 5. harmonic filter circuit.

The measured results in tables 4.3 and 4.6 are for cases in which reactive power compensation was carried out by a simple shunt capacitor without regard to harmonics. As the results show, some harmonics resonate strongly, also causing considerable voltage distortion.

5. REACTIVE POWER COMPENSATION BY HARMONIC FILTERS IN NETWORKS CONTAINING HARMONICS

5.1 Technical principles and features of harmonic filters

The function of a harmonic filter is to remove harmonics appearing in a network and to produce capacitive reactive power at the fundamental frequency. By frequency tuning, filters present a low impedance between phase and star point or between phases, so that the frequency tuned harmonic flows into the filter and does not spread otherwise into the feeding network. Harmonic filters are connected at an appropriate voltage level in each network. Harmonic filters consist, according to requirements, of one or more branches, each of which is tuned to harmonic frequencies appearing in the network in question.

5.2 Filter tuned to one frequency, Fig. 5.1.

A filter tuned to one frequency consists of a capacitor bank and a reactor connected in series.

The capacitance of the capacitor bank is generally determined by the compensating power required for the fundamental frequency. The inductance of the filter reactor is chosen so that together with the capacitor it forms series resonant circuit at the desired frequency.

5.3 Wideband filter, Fig. 5.2.

In a wideband filter a resistor is connected in parallel with the reactor, as a result of which frequencies above the tuned frequency may also be filtered. The resistance, however, weakens the filtering effect at the tuned frequency. The purpose of the capacitor C2 is to reduce fundamental frequency current flowing in the resistance R and the consequent loss in the resistor.

5.4 Information required for filter design

Filters are always designed according to the requirements at the point of use, so that technical and economic factors can be taken into account in the best possible way.

For filter design the following information is required from the customer:

- desired reactive power at the fundamental frequency
- service voltage and its possible range of variation
- rated frequency
- insulation requirements if these differ from normal
- actual short-circuit power at filter connection point and possible range of variaton
- information of load generating harmonics
- permissible harmonic content
- installation environment (outdoor/indoor, pollution etc.)

5.5 Necessity of harmonic filters

In a publication of the Finnish Association of Electricity Supply Undertakings, Restriction of Harmonics in Electrical Networks, there are presented recommendations for maximum harmonic contents and methods for evaluating the magnitude of harmonics.

In spite of the fact that the above mentioned values for harmonic content are not exceeded, the filters have, however, proved essential in providing reactive power compensation. This is particularly

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so because of the fact that it is generally not possible to provide compensation in a network containing harmonics by capacitor banks alone, due to the danger of resonance and possible overloading of the capacitors.

According to one source reactive power compensation should be accomplished by filters if the part of the load producing harmonics is greater than 20 % of the feeding transformer rated power. In cases in which the need for reactive power at the fundamental frequency is fairly large, >30 % relative to the rated power of the transformer, an even smaller part of the load producing harmonics may make filters necessary.

If a parallel capacitor alone is used in a network containing harmonics, then the capacitance together with the inductance of the feeding network forms a resonant circuit, the resonant frequency fr of which may be calculated from the equation

$$f_R = f_1 \cdot \sqrt{\frac{S_K}{Q_C}} \qquad (4)$$

where

f_1 = fundamental frequency (for example, 50 hZ)
S_K = short circuit power at capacitor bank point of connection
Q_C = capacitor bank compensation power

If the natural frequency calculated by equation (4) is near to some harmonic appearing in the network, then the said harmonic is amplified considerably. The biggest amplification factors may be of the order of 20.

5.6 Choice of filter

In designing a filter the simplest possible construction is aimed at which will satisfy the requirements for reactive power compensation and filtering and will be economically priced. In practice this may mean that the lower 5. and 7. harmonics may be filtered by filters tuned to single frequencies and the upper harmonics by a single wideband filter.

Filter compensation power affects filter characteristics: the greater the compensation power the better the harmonic suppression. (Fig. 5.3) The different branches of a harmonic filter may be connected each to its own circuit breaker and use, for example, a reactive power regulator to control them according to the reactive power requiremenmt, or use one common circuit breaker. When each branch has its own circuit breaker, connection of the different branches to the network should take place in the order of the harmonics, beginning with the lowest, and disconnection from the network should take place in the reverse order. Switching order is important in order to avoid possible harmonic resonances.

In choosing and designing a filter a central factor is the distribution of compensation power between the different branches of the filter. This should be carried out as far as possible so that

- the same capacitor units may be used in different branches
- capacitor banks are used at rated voltage (no excess voltages)
- parallel resonant frequencies occurring at frequencies between those of the absorption circuits do not coincide with harmonics which may appear in the network, for example even harmonics
- branch powers are suitable for (existing) switchgear used
- filter inductors are reasonable to assemble
- filtering results are adequate

5.7 Effects of filters

Filters are able to reduce 60...90 % of harmonics. Filtering results depend on the relation between the impedance of the supply network and the filter. However the solution is always a question of a compromise, since the filter removes

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those harmonics for which it has been designed, but increases harmonics at intermediate frequencies. In fact these seldom appear and mostly in connection with big electrolytic rectifiers. This situation is presented in the example of Figures 5.4, 5.5 and 5.6, in which the filter consists of 5. and 7. harmonic single frequency tuned units and an 11. harmonic wideband filter.

Figure 5.4 shows the circuit diagram for a filter example and its single phase equivalent circuit. In Figure 5.5 is presented the supply network and filter impedance curves as functions of frequency. In Figure 5.6 the common impedance of the filter and the network is seen as a function of frequency. Three resonance points can be observed in the impedance curve. Of these the lowest frequency resonance point is produced by the total capacitance of the filter together with the inductance of the network and the filter reactor and this resonance frequency is always less than the lowest tuned frequency of the filter. Two other resonance points represent resonances between the separate branches of the filter.

In region 2, where the common impedance of filter and network is less than the network impedance, harmonics are filtered (in the relation of the impedances) and in region 1, where filter and network common impedance is greater than network impedance, harmonics are amplified.

5.8 Practical solutions of compensation by filters

Figure 5.7 shows part of a big industrial electrical network with sources of harmonics and filters connected to it.

The good filtering results (about 93 %, 5. harmonic) are mainly due to the fairly large fundamental frequency compensating power of the filter relative to the rated power of the transformer. The small 7. harmonic content may be explained with the aid of Figure 1.1. Distortion is reduced by the filters to about one quarter of is original value.

In Figure 5.8 there is also shown part of a large industrial electrical network, in which reactive power compensation is carried out by means of a 5. harmonic filter and centralised at the medium voltage level. Table 5.2 gives harmonic measurement results for the supply current with and without the filter. As can be seen from the results the filter practically removes 5. harmonic and to some extent also the 7. and 11. harmonics.

Figure 5.9 shows a complete fairly large industrial electrical network. Reactive power compensation was originally carried out by shunt capacitor banks. As operations increased, the load producing harmonics also increased everywhere except for one transformer of the plant.

In the year 1983 information came from the plant that in certain capacitor banks there had been thermal destruction of wiring and fuse bases. On carrying out harmonic measurements it became evident that the whole distribution network was polluted with harmonics, principally 5. harmonic. In Figure 5.9 the voltage distortion measured is marked at several points. It is noteworthy that also in the case of the transformer which did not have a load causing harmonics, the capacitor bank resonated strongly with the inductance of the supplying network thus further increasing voltage distortion.

Figure 5.10 shows the same networks with its distortion after compensation has been carried out principally by filters. In the new situation, an ordinary shunt capacitor bank may naturally be used with the transformer which has a load not producing harmonics, and this will not cause resonance situations.

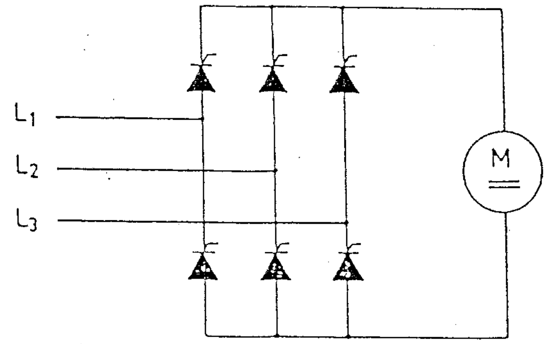


FIG 1
6-PULSE THYRISTOR BRIDGE.

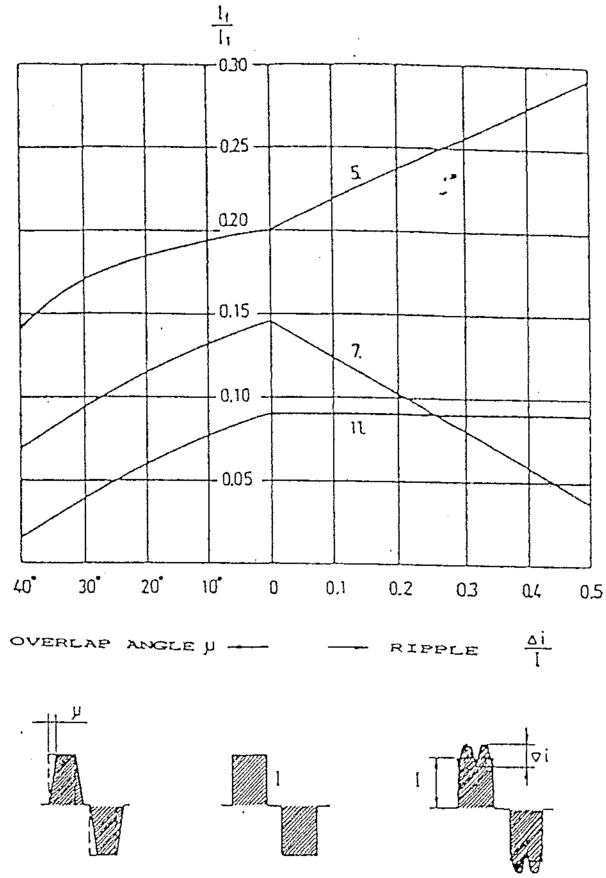


FIG 1.1
EFFECT OF DIRECT CURRENT RIPPLE
AND OVERLAP ANGLE ON HARMONICS.

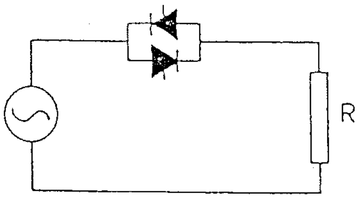


FIG 1.2
THYRISTOR SWITCH.

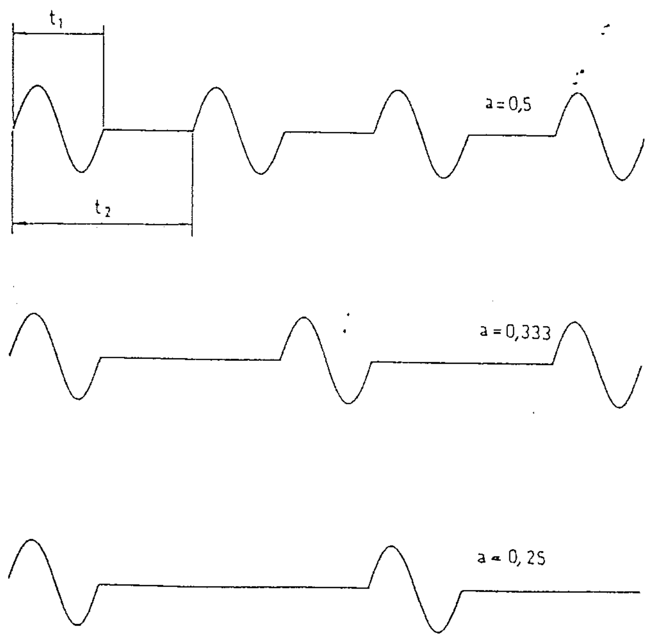


FIG. 1.3
PRINCIPLE OF RESISTIVE LOAD
BURST FIRING CONTROL.

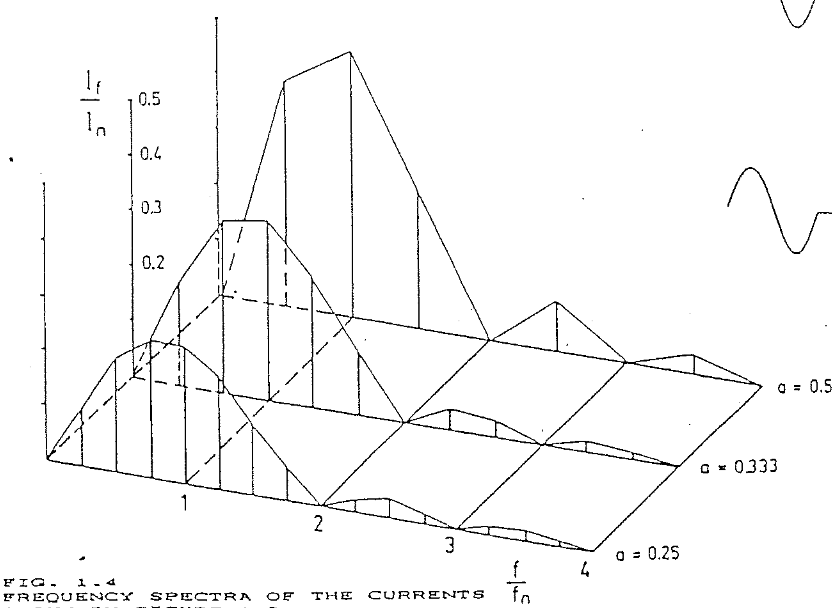


FIG. 1.4
FREQUENCY SPECTRA OF THE CURRENTS
SHOWN IN FIGURE 1.3.

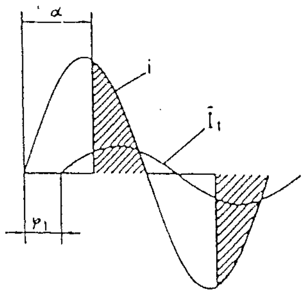


FIG. 1.5
PRINCIPLE OF PHASE CONTROL OF A RESISTIVE LOAD.

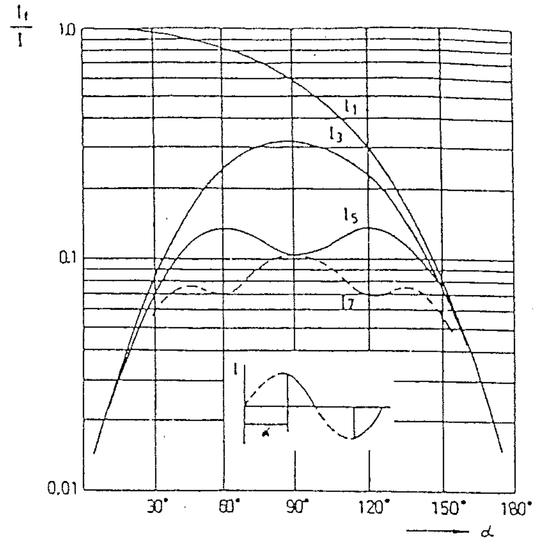
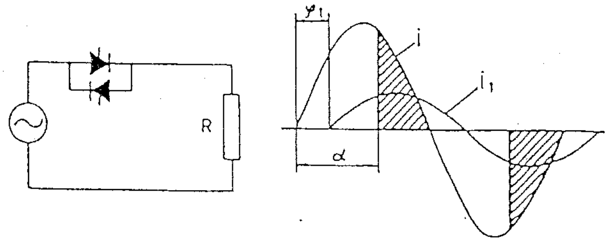


FIG. 1.6
HARMONIC CONTENTS OF THE CURRENTS SHOWN IN FIGURE 1.5 AS A FUNCTION OF CONTROL ANGLE.



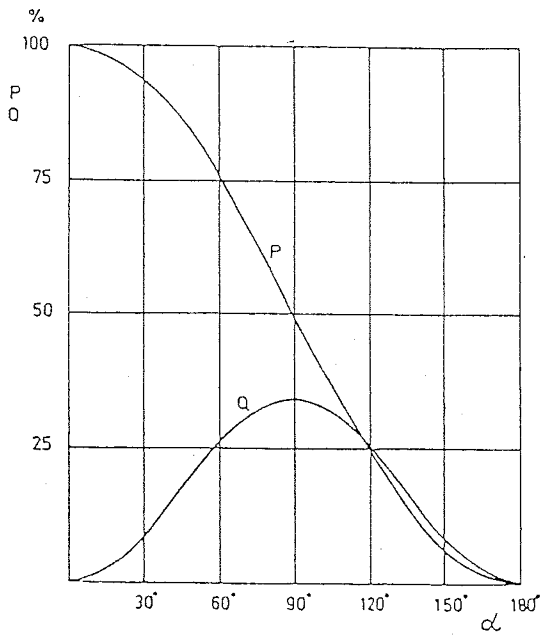


FIG. 1.7
DEPENDENCE OF ACTIVE AND REACTIVE POWER ON CONTROL ANGLE.

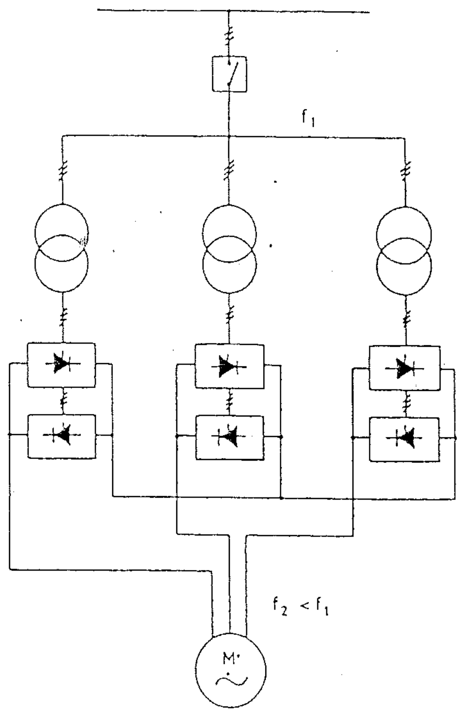


FIG. 1.8
3-PHASE CYCLO-CONVERTOR.

ORDER OF HARMONIC	AVERAGE HARMONIC CONTENT % OF FUNDAMENTAL CURRENT	MAXIMUM HARMONIC CONTENT % OF FUNDAMENTAL CURRENT
2	4 - 9	30
3	6 - 10	20
4	2 - 6	15
5	2 - 10	12
6	2 - 3	10
7	3 - 6	8
9	2 - 5	7

TABLE 1.1
HARMONICS OF AN ARC FURNACE.

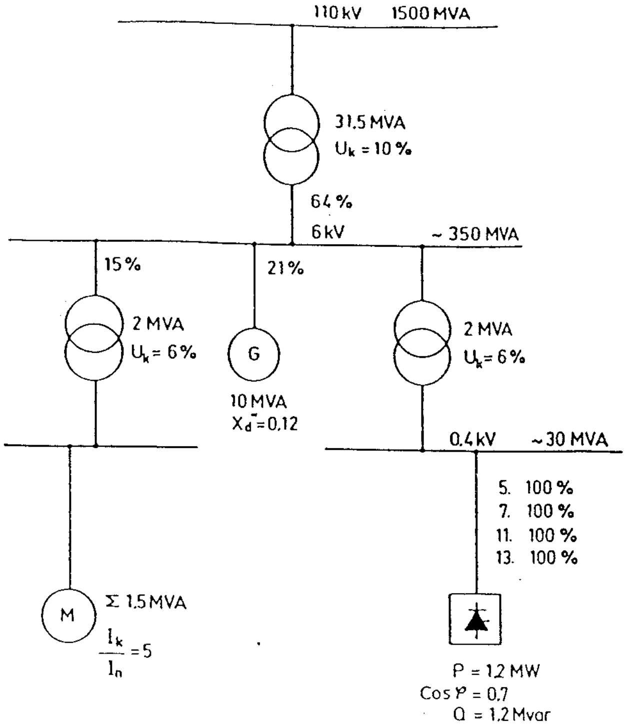


FIG. 2.1
DISTRIBUTION OF HARMONICS IN AN INDUSTRIAL NETWORK.

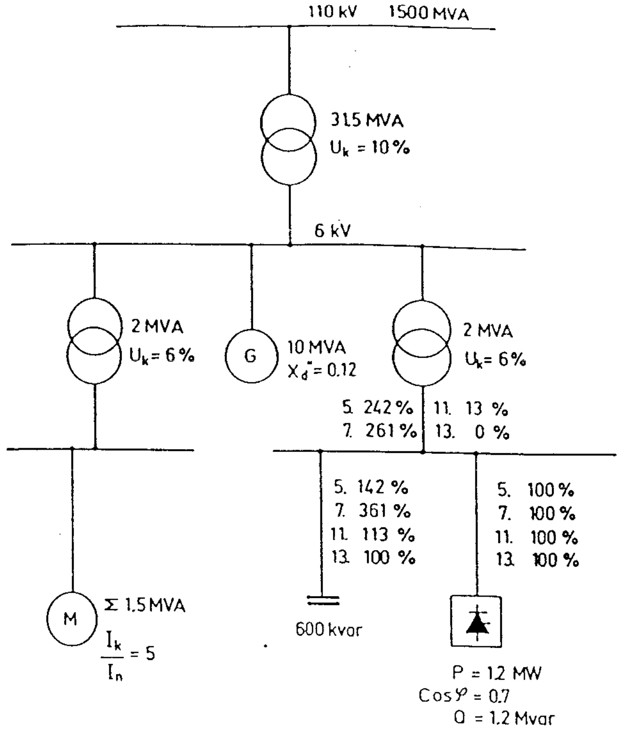


FIG. 2.2
DISTRIBUTION OF HARMONICS WHEN COMPENSATING CAPACITORS ARE CONNECTED TO THE SAME BUSBAR AS THE SOURCE OF HARMONICS.

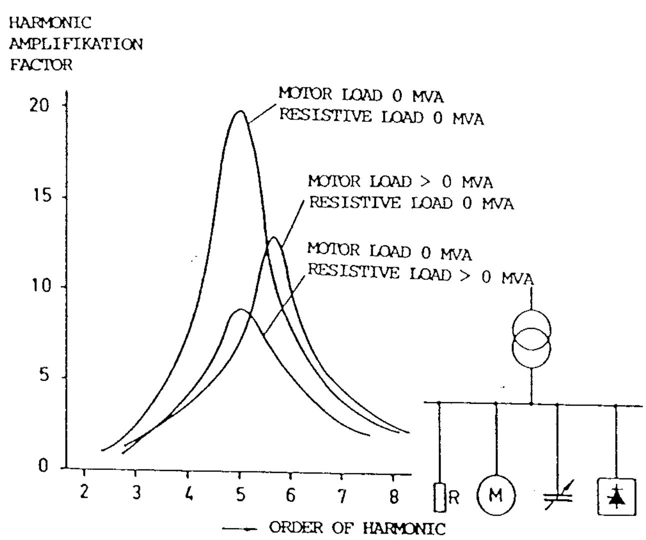


FIG. 2.3
MOTOR LOAD DAMPING AND SHIFTING EFFECT ON RESONANCE AND RESISTIVE LOAD DAMPING EFFECT.

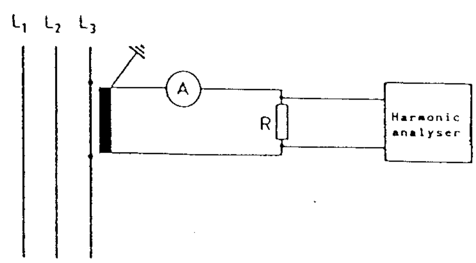


FIG. 3.1
HARMONIC CURRENT MEASUREMENT.

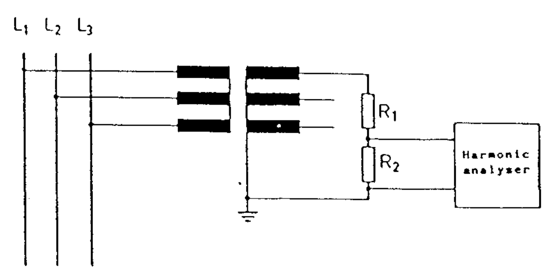


FIG. 3.2
HARMONIC VOLTAGE MEASUREMENT.

NOKIAN CAPACITORS

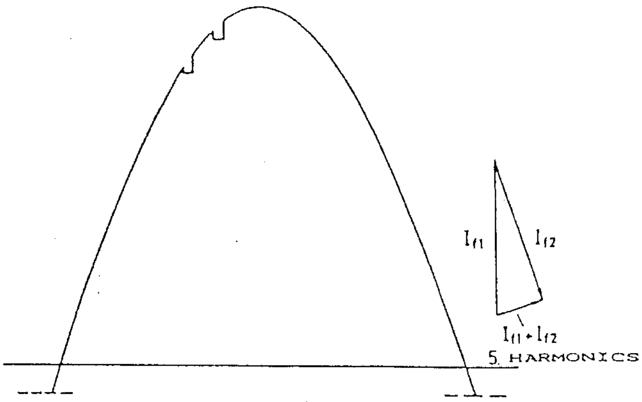


FIG. 4.1
COMMUTATION NOTCHES AND THE VECTOR SUMMATION OF 5. HARMONICS

ORDER OF HARMONIC	I_v/A	%
1	817	100
5	28	3.4
7	29	3.5
11	57	7.0
13	32	3.9
17	11	1.3
19	18	2.2
23	18	2.2

TABLE 4.1

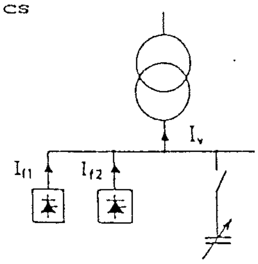


FIG. 4.2

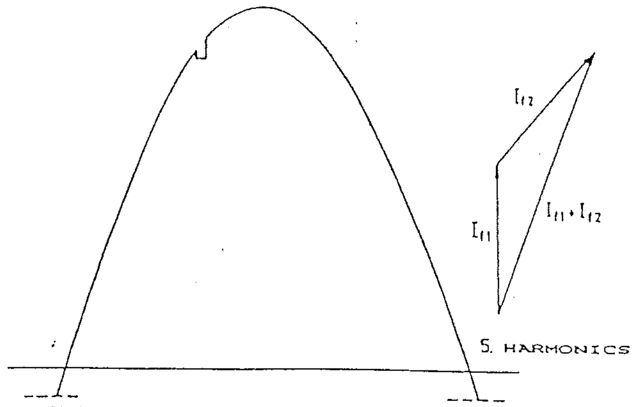


FIG. 4.3
COMMUTATION NOTCHES AND THE VECTOR SUMMATION OF 5. HARMONICS

ORDER OF HARMONIC	I_v/A	%
1	800	100
5	158	19.8
7	71	8.9
11	51	6.4
13	35	4.4
17	23	2.9
19	16	2.0
23	9	1.1

TABLE 4.2

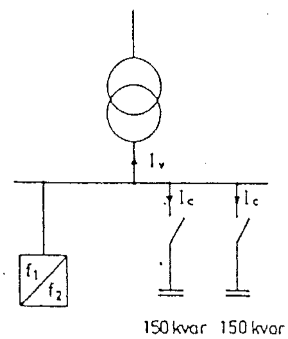


FIG. 4.4

ORDER OF HARMONIC	0 kvar I_v/A	0 kvar %	150 kvar I_v/A	300 kvar I_v/A	150 kvar I_c/A	300 kvar I_c/A
1	1400	100	1300	1200	218	219
5	293	20.9	345	323	38	40
7	97	6.9	131	284	34	78
11	77	5.5	218	248	129	118
13	46	3.3	198	126	198	155
17	37	2.6	58	30	64	55
19	26	1.9	38	29	89	34
VOLTAGE DISTORTION %	4.2		8.3	8.3		

TABLE 4.3
RESONANCE OF HARMONICS AND VOLTAGE DISTORTION FOR DIFFERENT VALUES OF COMPENSATION POWER.

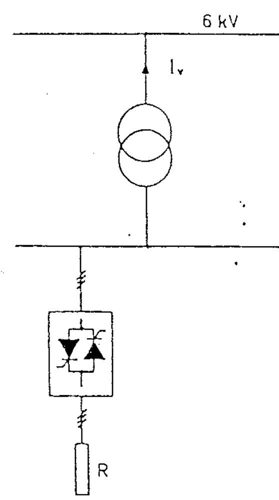


FIG. 4.5

ORDER OF HARMONIC	I_v/A	%
1	172	100
5	50	29
7	13	7.6
11	13	7.6
13	4	2.3
17	4	2.3
19	4	2.3

TABLE 4.4

NOKIAN CAPACITORS

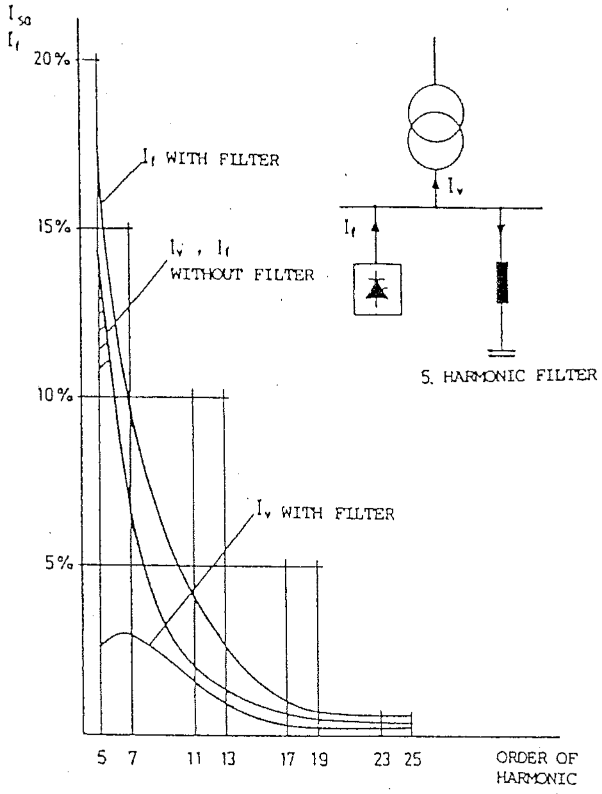


FIG. 4.6
EFFECT OF COMPENSATION ON CONVERTOR AND NETWORK HARMONICS.

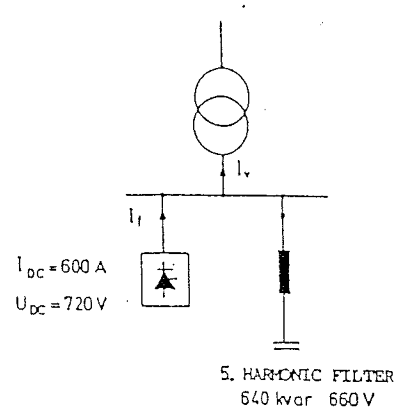
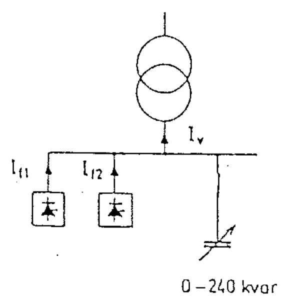


FIG. 4.7

ORDER OF HARMONIC	WITHOUT FILTER		WITH FILTER		CHANGE
	I_f /A	%	I_f /A	%	%
1	472	100	474	100	
5	150	31.8	185	39.0	23
7	19	4.0	34	7.2	79
11	49	10.4	45	9.5	- 8.2
13	10	2.1	9	1.9	- 10
17	25	5.3	23	4.9	- 8.0
19	7	1.5	4	0.8	- 43

TABLE 4.5
EFFECT OF COMPENSATION ON CONVERTOR HARMONICS.



ORDER OF HARMONIC	0 kvar	40 kvar	80 kvar	120 kvar	160 kvar	200 kvar	240 kvar
	I_v/A	I_v/A	I_v/A	I_v/A	I_v/A	I_v/A	I_v/A
1	817	687	638	612	560	541	508
5	28	18	9	15	18	25	38
7	29	35	45	49	57	69	84
11	57	74	113	259	317	108	73
13	32	52	97	125	37	19	16
17	11	36	48	11	27	13	10
19	18	96	14	9	12	6	5
23	18	43	8	5	3	1	1
VOLTAGE DISTORTION %	5.0	8.7	9.0	13.9	13.6	7.5	7.7

TABLE 4.6
HARMONIC CURRENT RESONANCE AND VOLTAGE DISTORTION FOR VARIOUS VALUES OF COMPENSATION POWER.

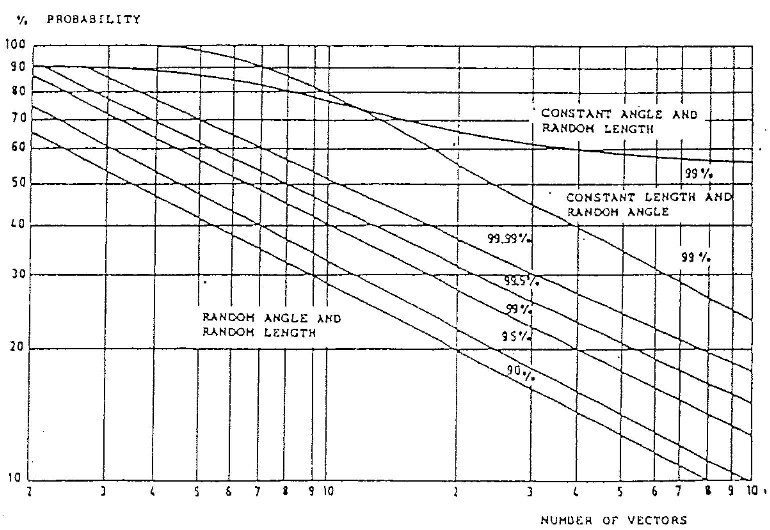
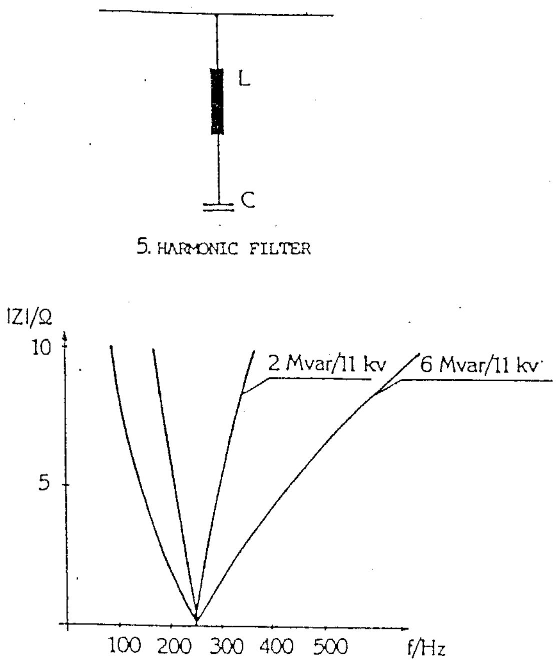


FIG. 4.8
SUMMATION OF RANDOM VECTORS.

NOKIAN CAPACITORS

FIG. 5.1
FILTER FOR ONE FREQUENCY.



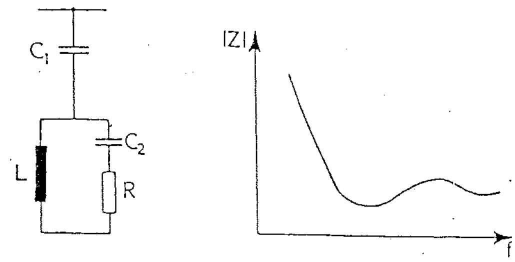
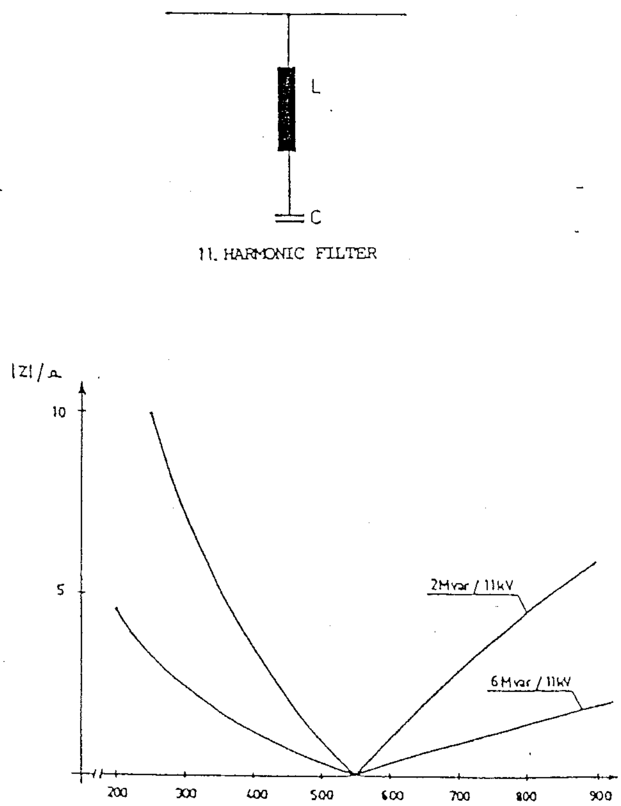


FIG. 5.2
WIDEBAND FILTER.

FIG. 5.3
FILTER FOR ONE FREQUENCY.



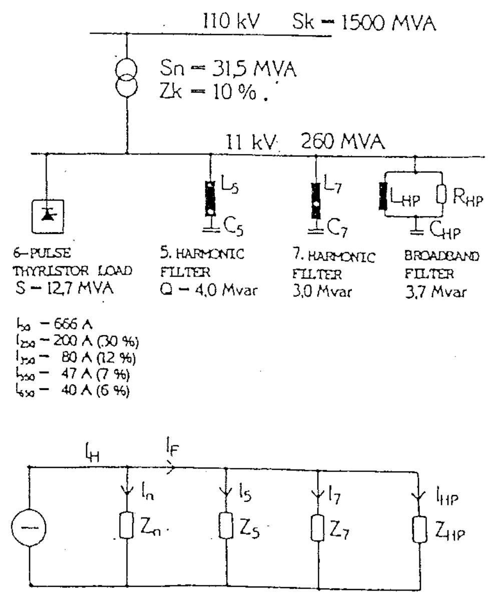


FIG. 5.4
AN EXAMPLE OF HARMONIC FILTER
IN PROCESS INDUSTRY

NOKIAN CAPACITORS

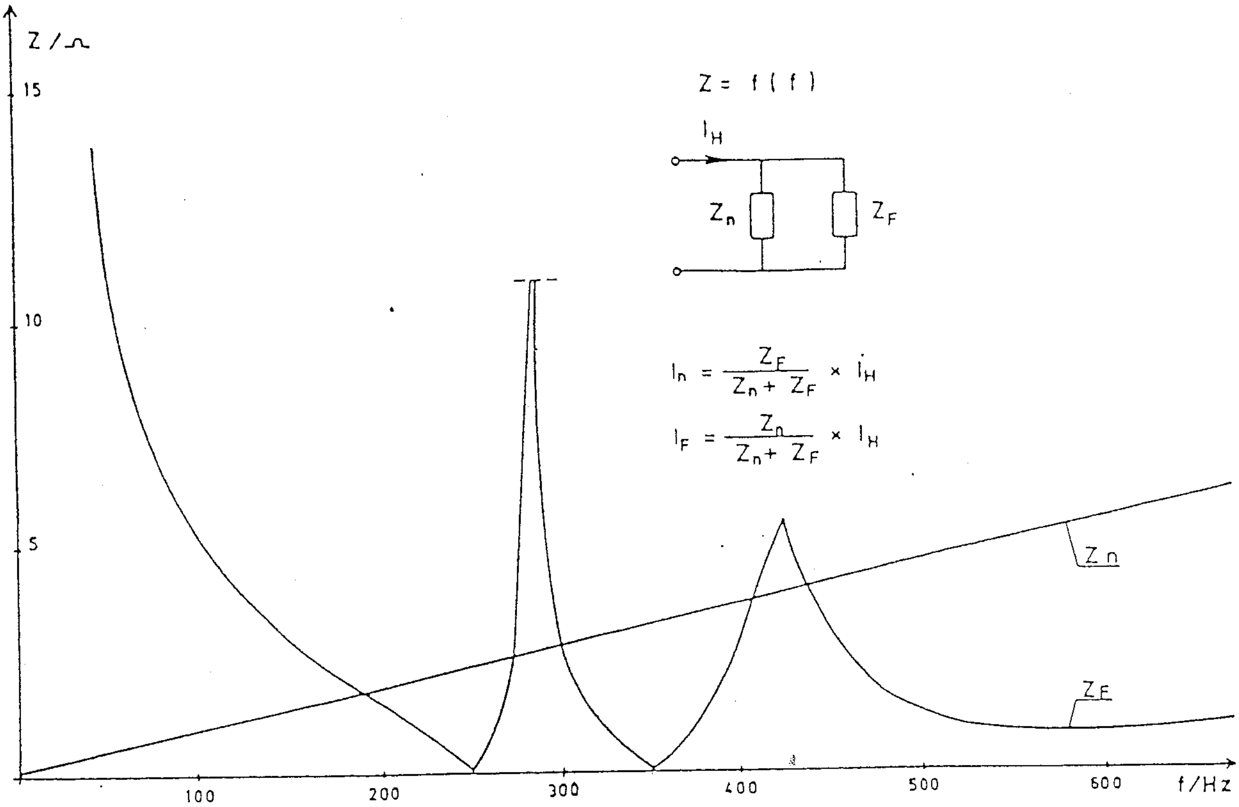


FIG. 5.5

3

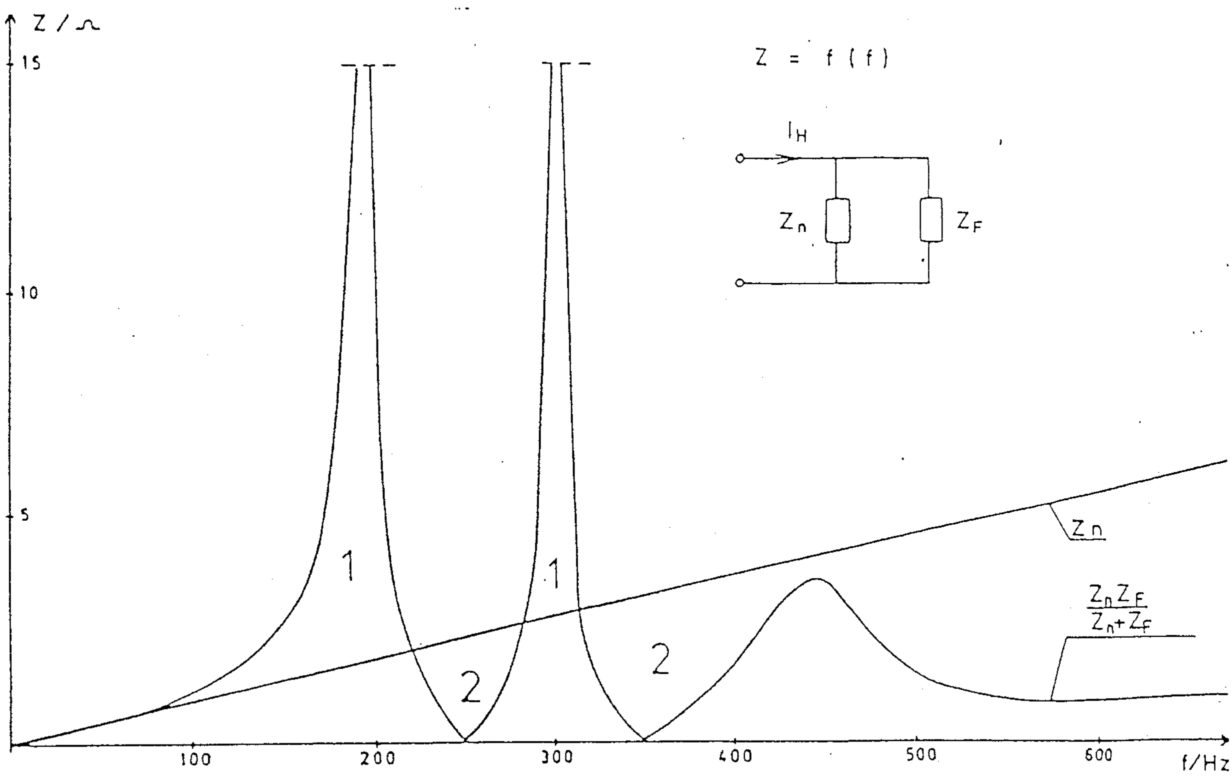


FIG. 5.6

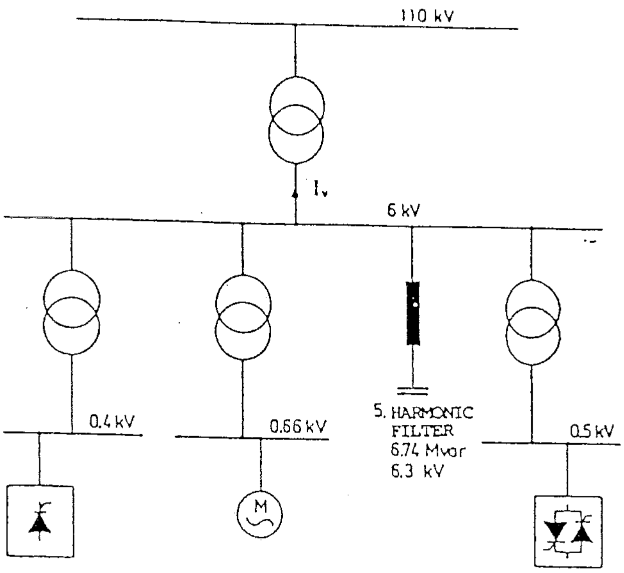


FIG. 5.8

ORDER OF HARMONIC	I_v WITHOUT FILTER A	I_v WITH FILTER A
1	2450	2100
3	20	16
5	53	5
7	34	15
11	19	9
13	10	7
VOLTAGE DISTORTION %	2.7	1.0

TABLE 5.2

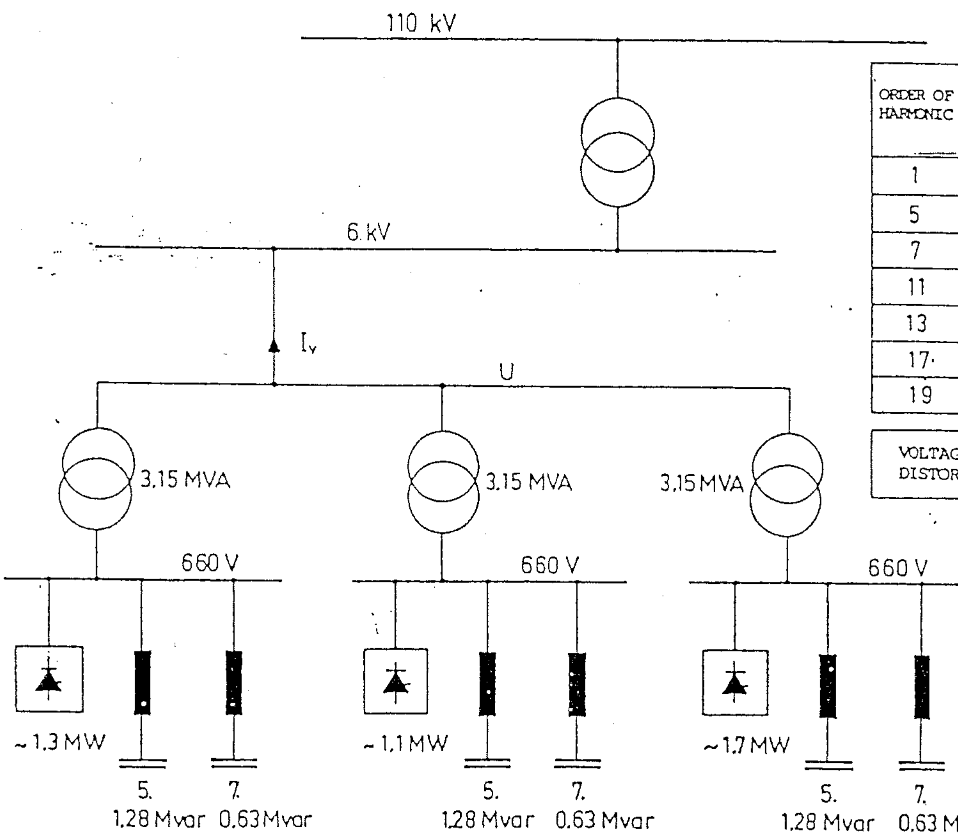


FIG. 5.7

ORDER OF HARMONIC	WITHOUT FILTER		WITH FILTER	
	I_v/A	U/%	I_v/A	U/%
1	679	100	526	100
5	143	3.6	9	0.8
7	9		9	
11	22	1.0	3	0.4
13	4			
17	6	0.4	3	0.4
19	3			
VOLTAGE DISTORTION %		3.8		1.0

TABLE 5.1

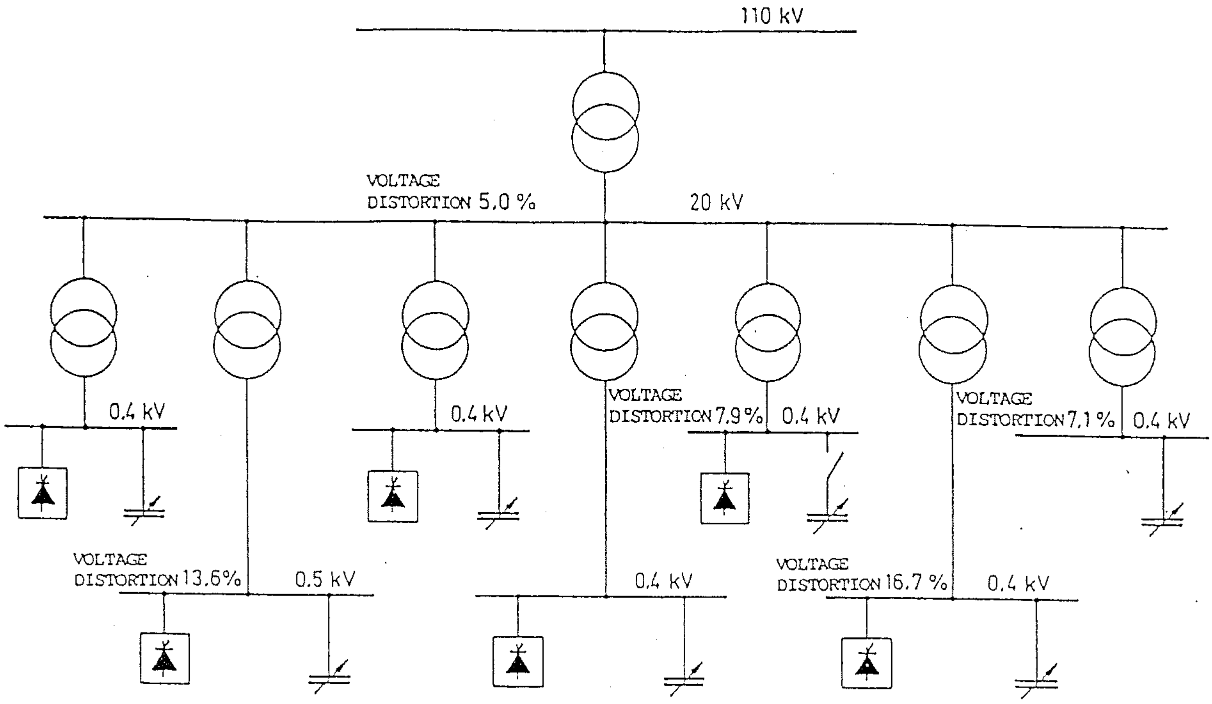


FIG. 5.9
DISTRIBUTION NETWORK OF AN INDUSTRIAL PLANT, BADLY "POLLUTED" BY HARMONICS AND RESONANCES. COMPENSATION WAS CARRIED OUT BY CAPACITOR BANKS.

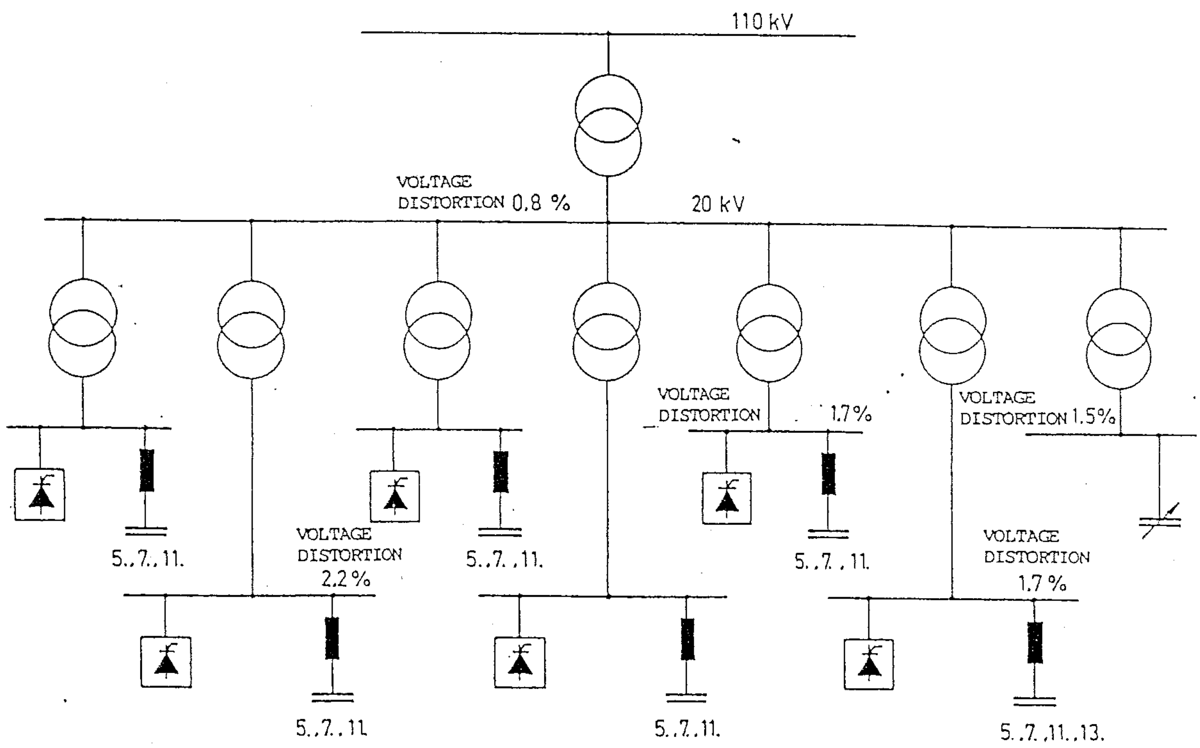


FIG. 5.10
THE INDUSTRIAL NETWORK OF FIG. 5.9 AFTER COMPENSATION HAS BEEN CARRIED OUT BY HARMONIC FILTERS.