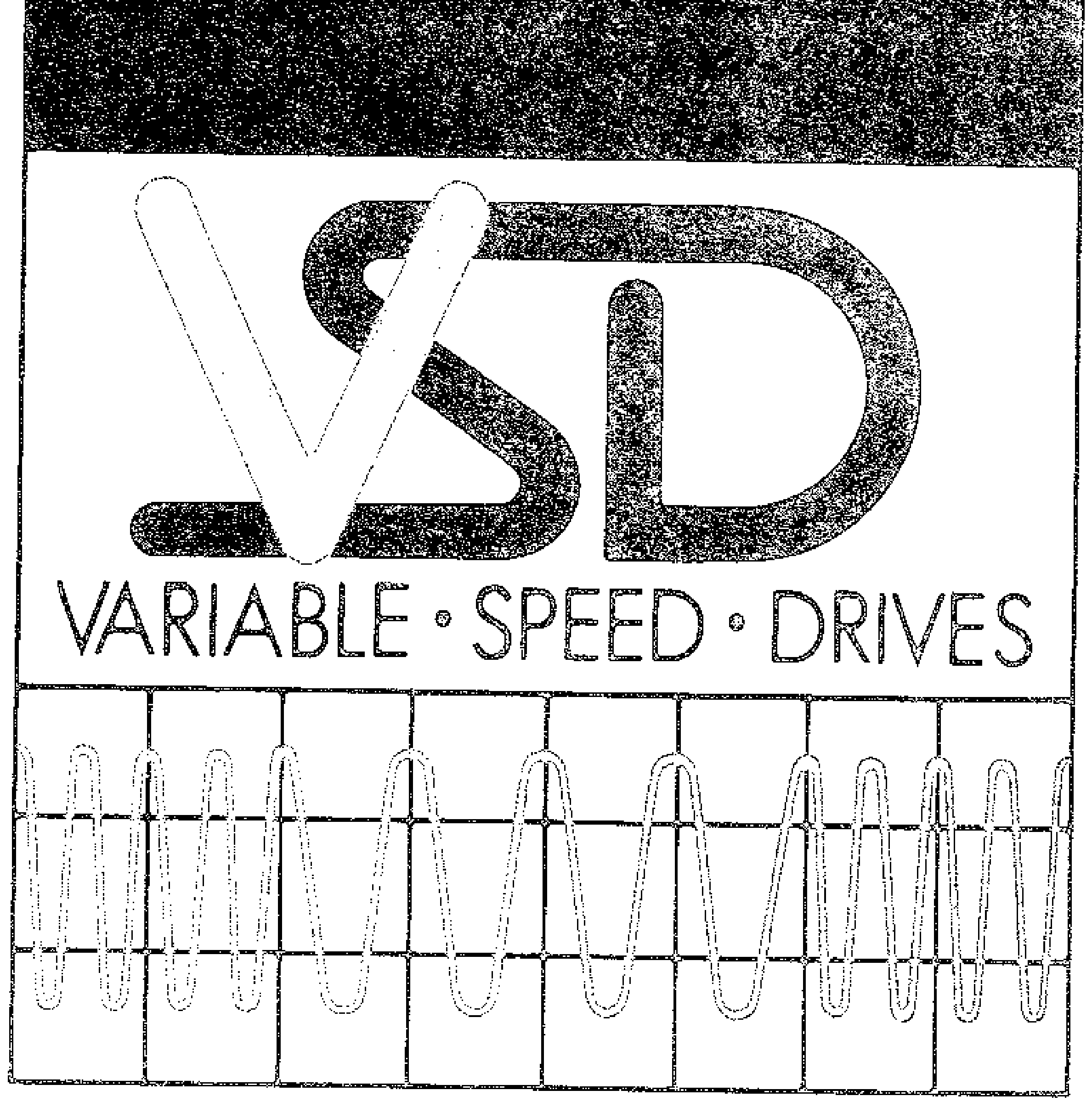
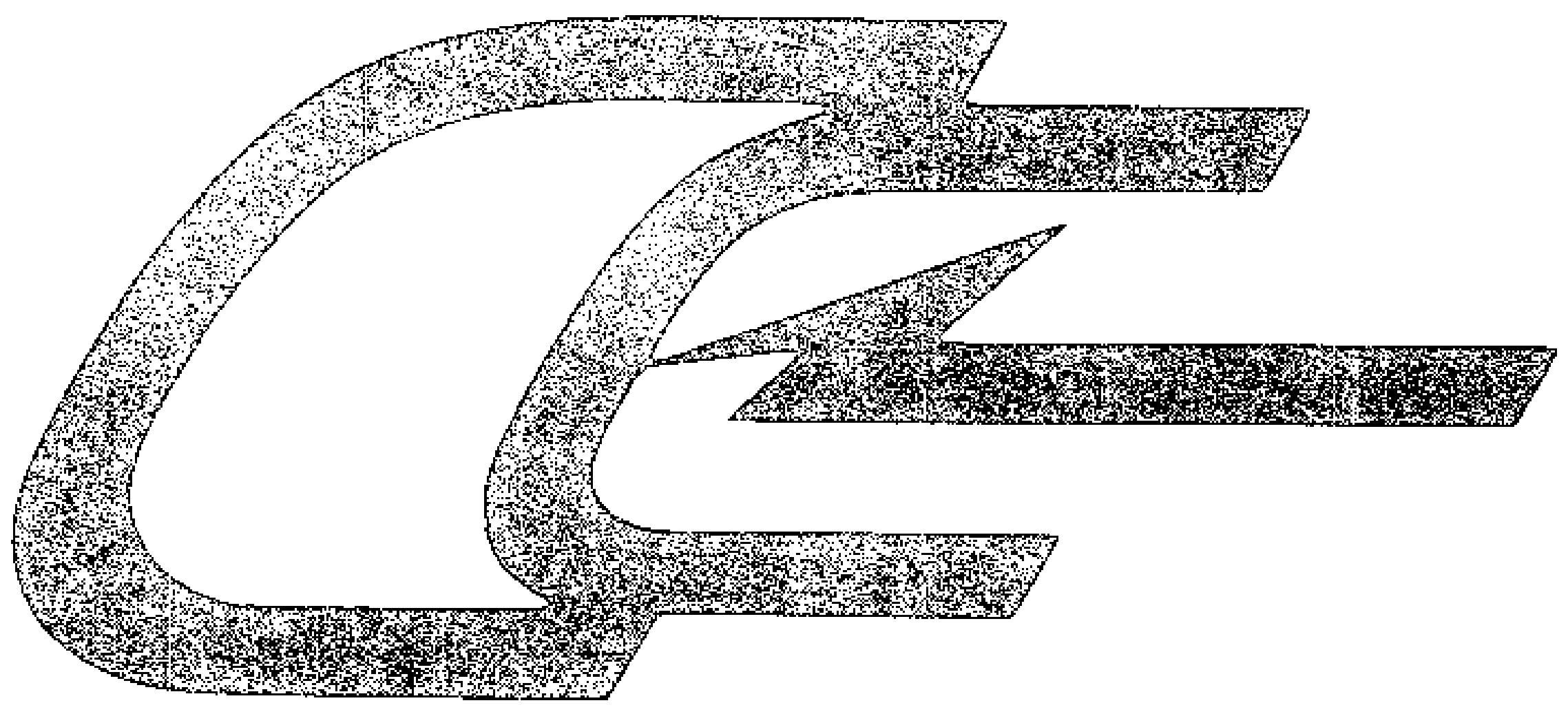


SYMPOSIUM ON ELECTRIC VARIABLE SPEED DRIVES



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SYMPOSIUM ON
ELECTRIC VARIABLE
SPEED DRIVES

Harmonics and Technical Barriers

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HARMONICS AND TECHNICAL BARRIERS

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ABSTRACT

All Thyristor variable speed drives, unlike fixed speed, generate harmonics to some degree. Harmonics are currents and voltages that are multiples of the fundamental 60 Hz frequency. Any power converter, which converts AC to DC or DC to AC, can be considered to be a source of harmonics. This paper reviews the characteristics of harmonics produced by a variable speed drive system, methods of reducing them, and presents installation examples.

INTRODUCTION

From the standpoint of the main power system harmonics, only the AC to DC power converter is a factor. The DC link isolates the motor converter and motor from the power system. The Thyristor rectifier chops the AC current waveform by allowing current to flow during a portion of the cycle. These harmonics may produce harmful effects on equipment connected to the plant or electric utility system or neighbouring industrial plant. On the other hand, the motor converter also produces harmonics which can cause motor overheating. This paper analyzes the presence of harmonics in both 6-pulse and 12-pulse converter systems, and highlights the differences between 3-phase and 6-phase machines in suppressing these harmonics. The effect of the use of harmonic filters and special transformer winding arrangement in reducing harmonics is also discussed. Harmonics measurements for two actual installation are presented and analyzed.

SOURCE OF HARMONICS

The common sources of harmonics in utility or industrial electrical systems are the following:

- Rectifiers
- DC motor drives
- Variable frequency AC drives
- Uninterruptible power supplies (UPS)
- Arc furnace
- Static VAR generator
- Cyclo converter

The presence of these harmonic producing devices in a system does not necessarily constitute a problem. The harmonics may be of sufficiently low magnitude and therefore harmless at one extreme, or they may be of such magnitude to cause damage to equipment in the system. If in existing system there is no history of harmonic related problems such as motor failures, capacitor fuse blowing, capacitor failures, telephone interference, etc., then there is likely no harmonic problem and a harmonic analysis study is probably not warranted. However, when 20% of the plant load consist of harmonic producing sources, then a harmonic analysis study is recommended. Such a study can be used to determine both the magnitude of harmonic currents and voltages, and as an aid to designing a special filter to reduce these harmonics.

HARMONICS

A harmonic is defined as a sinusoidal component of a periodic wave having a frequency that is an integral multiple of the fundamental frequency. For example, a component, the frequency of which is five times the fundamental frequency, is called a fifth harmonic. The theoretical maximum amplitude of each harmonic current produced by a converter is equal to that of the fundamental component divided by harmonic order. For example, the 5th harmonic is equal to 20% of the load current; and the 7th harmonic is equal to 14.3%; and so on. These values are for an idealized square wave and, in practice, will be less because of system impedance. The harmonic components are shown in Fig. 1 and each harmonic is assumed to be in phase with the fundamental. Fig. 2 shows how the addition of 3rd, 5th and 7th harmonics, also in phase, results in a flat top waveform. The resulting wave shape will depend on the magnitude and the phase relation of each of the harmonic components.

A static power converter generates harmonic currents the order of which is given by the equation:

$$n = kp \pm 1$$

where,

n = order of the harmonic
k = is an integer 1, 2, 3 ....
p = number of pulses of the converter system

A 6-pulse converter, as shown in Fig. 3 would generate harmonic currents of the order, 5th, 7th, 11th, 13th, 17th, 19th, 23rd, 25th, etc. For a 12-pulse converter configuration, as shown in the Fig. 4, the harmonic generated are 11th, 13th, 23rd, 25th, etc. Therefore, a 12-pulse converter system provides a significant reduction in the voltage distortion and, equally important, it eliminates (assuming balanced conditions) the lowest order harmonics of 5th and 7th which are typically of most concern.

In order to compare the level of harmonic distortion in a power system, a figure of merit is required. The figure of merit most commonly used is the harmonic distortion factor (HDF). This is defined in IEEE Standard 519-1981 as:

$$\mathrm{HDF} = \left(\frac{\text{Sum of Squares of Amplitudes of all Harmonics}}{\text{Square of Amplitude of Fundamental}}\right)^{\frac{1}{2}} 100\%$$

The harmonic distortion factor is a quick way to gauge the total effect a distribution of harmonics is having on the fundamental bus voltage. The IEEE Standard 519-1981 specifies guidelines with regard to limiting the harmonic voltage distortion factor. A summary of these guidelines is given in Table 1.

The amount of voltage distortion that can be tolerated on a power system is dependent upon the equipment connected to it and this equipment's susceptibility to nonsinusoidal wave shapes. If voltage distortion is kept within the limits given in Table 1, other equipment will operate satisfactorily. Power utility companies may be more stringent or relaxed in their specifications for the harmonic distortion factor, and may use different formulas than those given in IEEE Standards. For example, the harmonic distortion factor requirements by Hydro-Quebec is not the same as Ontario Hydro and both are different than the IEEE Standards. It is therefore necessary to check with the power company as to their requirements in limiting harmonic voltages and currents.

EFFECT OF HARMONICS ON ELECTRICAL MACHINES

In examining the effects of harmonics on power system components, one can make a major division between static non-rotating devices (such as transformers, cable and capacitors) and motors. The concern over harmonics in static devices is of a single dimension, i.e. increased heating. This also is of concern in motors, but is a more complicated evaluation because of the different manner in which the harmonics are impressed on the stator and rotor, and the significant differences in the physical design and thermal response to harmonic heating of the stator and rotor. The other dimension involved in the analysis of rotating machines is the potential exists for harmonics to excite complex vibration mode involving structural resonances in the rotor elements of connected equipment, such as the blades of a compressor. This complexity and the large variety in types and designs of electric motors means there are no precise application guidelines available for machines operating in nonsinusoidal waveform environments. One should be aware, however, of the general effects that harmonics will have on electric motors.

When a nonsinusoidal voltage generated by a converter is impressed on the stator winding, the result is a circulating harmonic current. The magnitude of harmonic current depends on the stator winding configuration, i.e. 3-phase or 6-phase, harmonic reactances, and rotor damping effect. Each harmonic voltage of the 5th, 7th, 11th, etc., will induce a corresponding harmonic current in the stator winding. Note that each of these harmonic orders can be defined as positive or negative sequence in accordance with symmetrical component theory. These harmonic currents will generate additional heating in the stator winding which will add to the temperature rise caused by the fundamental flow of current. Of even greater concern, is the flow of harmonic currents in the rotor. The flow of each harmonic in the stator will produce a series of space harmonic m.m.f.'s (magnetomotive force) in the air gap which will induce current flow in the rotor. Just as each harmonic current can be defined as being positive or negative sequence, the rotation of space harmonic m.m.f.'s will be either forward or backward with respect to the rotor rotation.

The space harmonics of the stator m.m.f. available in the air gap are determined by the following equation:

$$h = 2\ km \pm 1$$

where,

h = order of space harmonic

m = number of stator winding phases, 3 or 6

k = any integer

Tables 2 and 3 show the space harmonics produced in 3-phase and 6-phase winding arrangements, respectively. It can be seen that the 6-phase winding arrangement suppresses more space harmonics than in the 3-phase. The resultant rotor heating and pulsating output torques in 6-phase machines will therefore be less than in 3-phase. In the event, when a 6-phase machine is connected to 12-pulse converter, the level of harmonic currents in the stator and rotor will be greatly reduced.

In the case of a synchronous motor, the frequency of induced harmonic currents in the rotor is determined by the relationship:

$$f_{n_h} = (n \pm h)\ f_1$$

Any space harmonic of order $h = n$ is stationary with respect to the rotor and interacts with any rotor harmonic of the same order to produce synchronous torque in a similar manner to the interaction of the fundamental components of stator and rotor magnetomotive forces.

INSTALLATION EXAMPLES

In order to better understand the presence of harmonics in a variable speed drive, harmonics measurement for two installation are presented and analyzed. The first installation covers the 6-pulse system and the second a 12-pulse system. The effect of harmonic filters and isolating transformer winding arrangement in reducing harmonics is also reviewed.

CASE 1

Fig. 5 shows a simplified single line diagram for the first drive installation. It consists of the following:

1. Line filters connected to 4 KV incoming power supply. Individual 5th, 7th, 11th and 13th harmonic filters are used.
2. 3-phase, 3000 KVA, isolating transformer with delta primary and star secondary.
3. 6-pulse line converter system (rectifier).
4. Reactor.
5. 6-pulse load converter system (inverter).
6. 3-phase brushless synchronous motor rated at 3000 HP, 1000 V, 1800 rpm, 4 poles.

Figs. 6 and 7 show the motor current waveform and harmonic components. It can be seen that the waveform is distorted and the major harmonic components are the 5th, 7th, 11th and 13th. These harmonics must be carefully considered when designing the motor in order to keep the temperature rise in the stator and rotor within the design limits. In this installation, the harmonics were not properly accounted for and the result was temperature rise in the rotor exceeding the design limits. The problem was only discovered during commissioning stage when conducting heat run test. The measured rotor temperature rise was satisfactory when connected to conventional 60 Hz supply, but it was above design limits when energized from load commutated inverter. A new laminated rotor had to be built to replace the original solid pole in order to correct the overheating problem. Harmonic currents fed back to the 4 KV supply were kept within acceptable level by using individual harmonic filters for 5th, 7th, 11th, 13th and 24th as shown in Fig. 5.

CASE 2

Fig. 8 shows a simplified single line diagram for the second drive installation. It comprises of the following:

1. Line filters connected to 25 KV incoming power lines.
2. 3-phase/6-phase isolating transformer rated at 21 MVA. The primary is delta connected rated at 25 KV. The secondary consists of two 3-phase winding, one being connected in star and the other in delta. The secondary voltage is 7.3 KV.
3. 12-pulse line converter system (rectifier).
4. Reactor.
5. 12-pulse motor converter system (inverter).
6. 6-phase brushless synchronous machine rated at 17 MW, 7200 V, 6000 rpm, 2-poles.

Figs. 9 and 10 show the motor applied voltage and motor input current. It can be seen that both waveforms contain harmonics, the principle ones being the 5th, 7th, 11th and 13th. Theoretically, the 5th and 7th harmonic voltages generated by a 12-pulse system must be zero, but because of some asymmetry they do in fact exist. The effect of these harmonic voltages on 6-phase machine is less when compared to 3-phase because of cancellation of certain space harmonics. Damper bars in 3-phase or 6-phase machine are also used to reduce the harmonic losses in the rotor surface.

Fig. 11 shows the current waveform in the converter transformer secondary side for 12-pulse system. The 5th harmonic current is 10% of fundamental current and the 7th is 4%. Under symmetrical and balanced loading condition, the 5th and 7th harmonic current should be zero in a 12-pulse system but, in reality, they are present. The 5th and 7th harmonic currents reflected on the primary side can be further reduced or even cancelled when a special transformer arrangement is used. This harmonic reduction is obtained when the primary side is connected in delta and the secondary side consists of two 3-phase winding, one connected in delta and the other in star, with 30° phase shift. The 11th and 13th harmonic currents are not effected by the transformer winding configuration except for the leakage reactance.

It is essential that lower order harmonic currents on the primary side be kept to a minimum in order to meet utility requirement for harmonic distortion factor. The use of 12-pulse system and a special transformer arrangement substantially reduces the 5th and 7th harmonic currents. Harmonic currents may be further reduced by the use of filters connected to the primary side of the converter transformer. Harmonic filters are normally selected to perform two functions: To improve and maintain an acceptable power factor over the drive speed operating range and to limit the harmonic voltage distortion to permissible levels. In general, for 12-pulse system, it is not necessary to use a separate harmonic filter for each harmonic component. For this installation, one filter is tuned to 342 Hz in order to reduce both the 5th and 7th harmonic voltages at the incoming bus. The second filter is tuned to 702 Hz to absorb the 11th and 13th together, and the third filter is tuned to 1380 Hz to absorb the 23rd and 25th together. Each harmonic filter consists of capacitors, air core reactors and damping resistors. These filters are connected to 25 KV bus and located outdoor in the substation yard and occupy an area of 13.5 m x 7.5 m. Figs. 12 and 13 show the waveforms of the incoming line current and the voltage at 25 KV bus. Both waveforms are almost sinusoidal and harmonic levels are within utility requirement. Fig. 14 shows the total current in the harmonic filters connected to 25 KV.

CONCLUSIONS

It is inevitable that harmonics will be generated whenever a variable speed drive is used. The order and magnitude of these harmonics greatly depend on the drive configuration and system impedance. A 3-phase machine connected to 6-pulse system will generate more harmonics when compared to a 6-phase machine connected to 12-pulse system. Harmonic losses in the stator and rotor must carefully be taken into account during design stages to keep motor temperature rise to acceptable limits. Harmonics fed back to the power system are reduced by the use of filters which are connected to the incoming power supply. These filters are relatively large and occupy substantial space in the substation yard.

There is a need for a common standard to be adopted by utilities specifying acceptable level of harmonics fed back into the power system. This would certainly simplify the requirements for harmonic filters from the user's and manufacturer's point of view.

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3. Power System Relay Committee of the IEEE PES Report, "Sine Wave Distortions in Power System and the Impact on Protective Relaying", 84th 0115-6 PWR.

4. Day, A.L. and Mahmoud, A.A., "Methods of Evaluation of Harmonic Levels in Industrial Plant Distribution Systems". Paper presented at the 1985 Annual Meeting of the IEEE Industry Application Society.

5. Weiss, H.W., "Power Transmission to Synchronous Machines for Adjustable-Speed Pump and Compressor Drive Systems". Record of Conference Papers of the 29th Annual PCIC, 1982.

6. Hanna, R.A. and MacDonald, D.C., "The Six-Phase Generator and Transformer into a Three-Phase Power System". IEEE Transaction on Power Apparatus and System, August 1983.

TABLE 1

HARMONIC VOLTAGE DISTORTION LIMITS

Power System Voltage Level	Dedicated System Converter	General Power Systems
2.4 - 69 KV	8%	5%
115 KV & above	1.5%	1.5%

Notes:
1. These values are taken from IEEE 519-1981 Standard.
2. A dedicated system is one serving only converters or loads not affected by voltage distortion.

TABLE 2

Speed and directions of rotation of components
of stator m.m.f. of 3-phase winding.
Synchronous speed is obtained when n = 1, h = 1.

Order of Space Harmonic h	Order of Time Harmonic, n					
	1	3	5	7	11	13
1	+1		-5	+7	-11	+13
3		±1				
5	-1/5		+1	-7/5	$+\frac{11}{5}$	$-\frac{13}{5}$
7	$+\frac{1}{7}$		$-\frac{5}{7}$	+1	$-\frac{11}{7}$	$+\frac{13}{7}$
9		$\pm\frac{1}{3}$				
11	$-\frac{1}{11}$		$+\frac{5}{11}$	$-\frac{7}{11}$	+1	$-\frac{13}{11}$
13	$+\frac{1}{13}$		$-\frac{5}{13}$	$+\frac{7}{13}$	$-\frac{11}{13}$	+1

TABLE 3

Speed and directions of rotation of components
of stator m.m.f. of 6-phase winding.
Synchronous speed is when $n = 1$, $h = 1$.

Order of Space Harmonic h	Order of Time Harmonic, n				
	1	5	7	11	13
1	+1			$-\frac{11}{1}$	$+\frac{13}{1}$
3					
5		+1	$-\frac{7}{5}$		
7		$-\frac{5}{7}$	+1		
9					
11	$-\frac{1}{11}$			+1	$-\frac{13}{11}$
13	$+\frac{1}{13}$			$-\frac{11}{13}$	+1

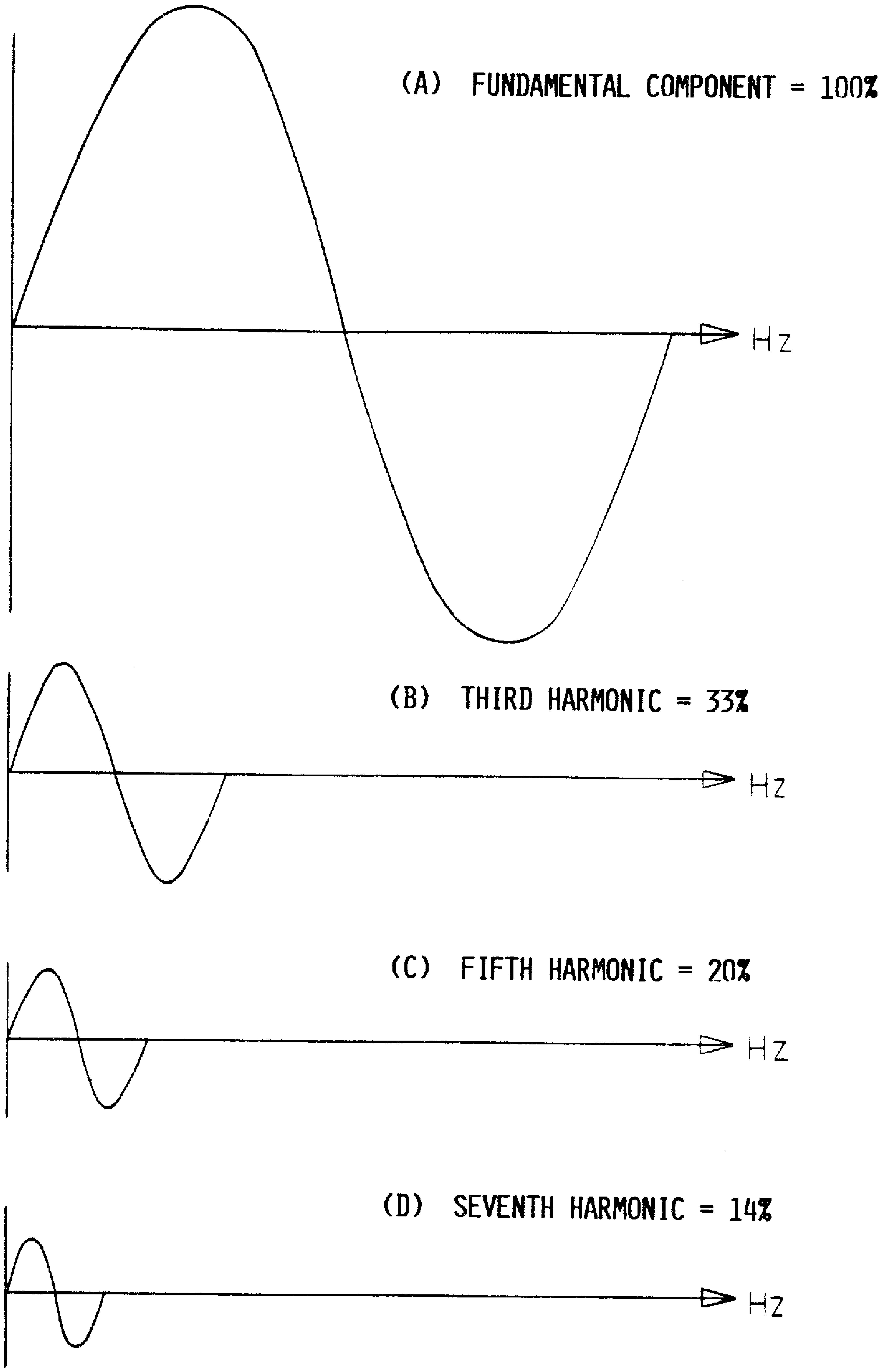

FIG. 1. COMPONTENTS OF SQUARE WAVE:

FUNDAMENTAL AND HARMONIC COMPONENTS EACH OF A MAGNITUDE INVERSE TO ITS ORDER.

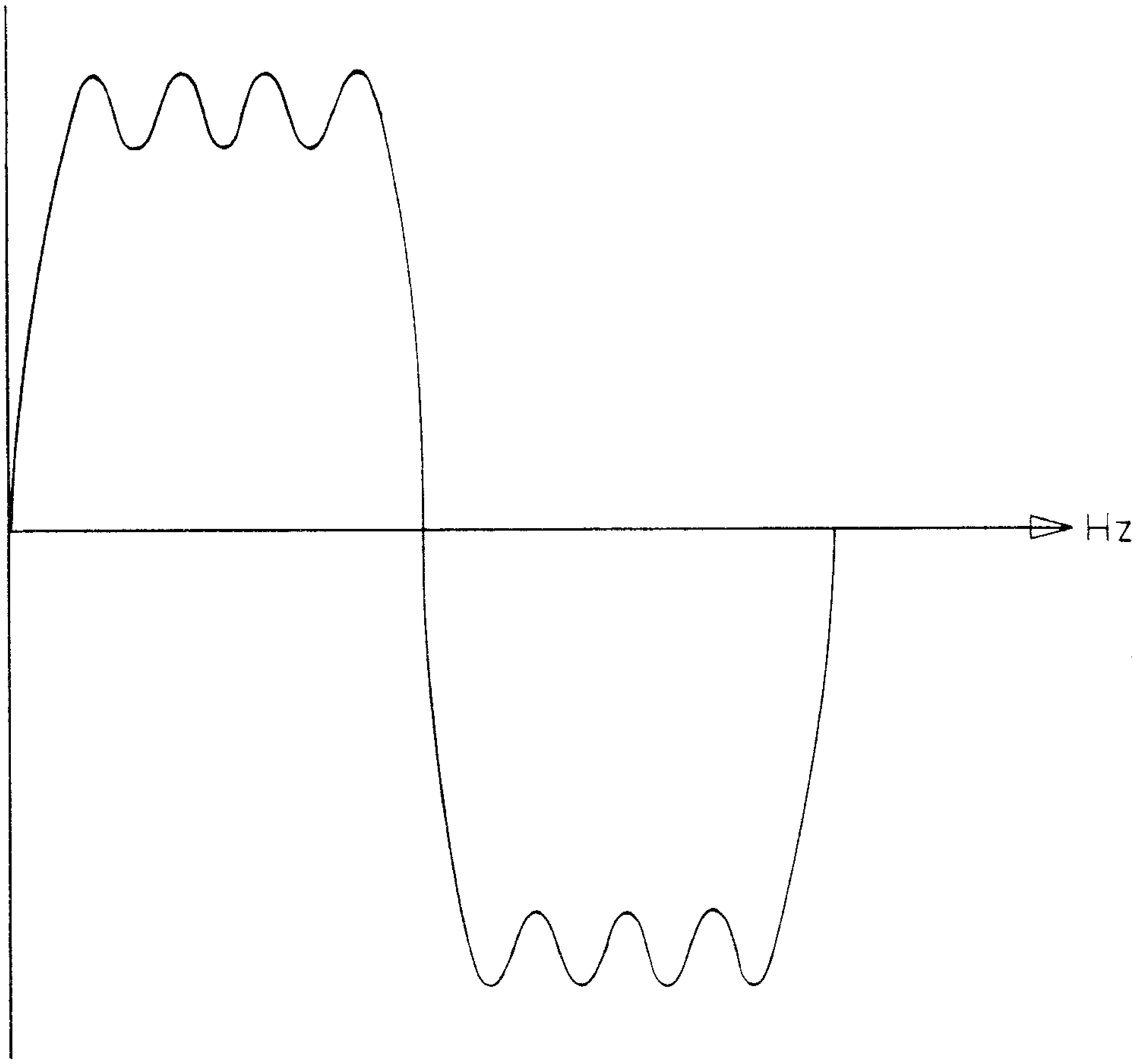

FIG. 2. WAVEFORM RESULTING FROM ADDING FUNDAMENTAL + 3RD + 5TH + 7TH HARMONIC COMPONENTS ALL BEING IN PHASE AND EACH HARMONIC OF A MAGNITUDE INVERSE TO ITS ORDER.

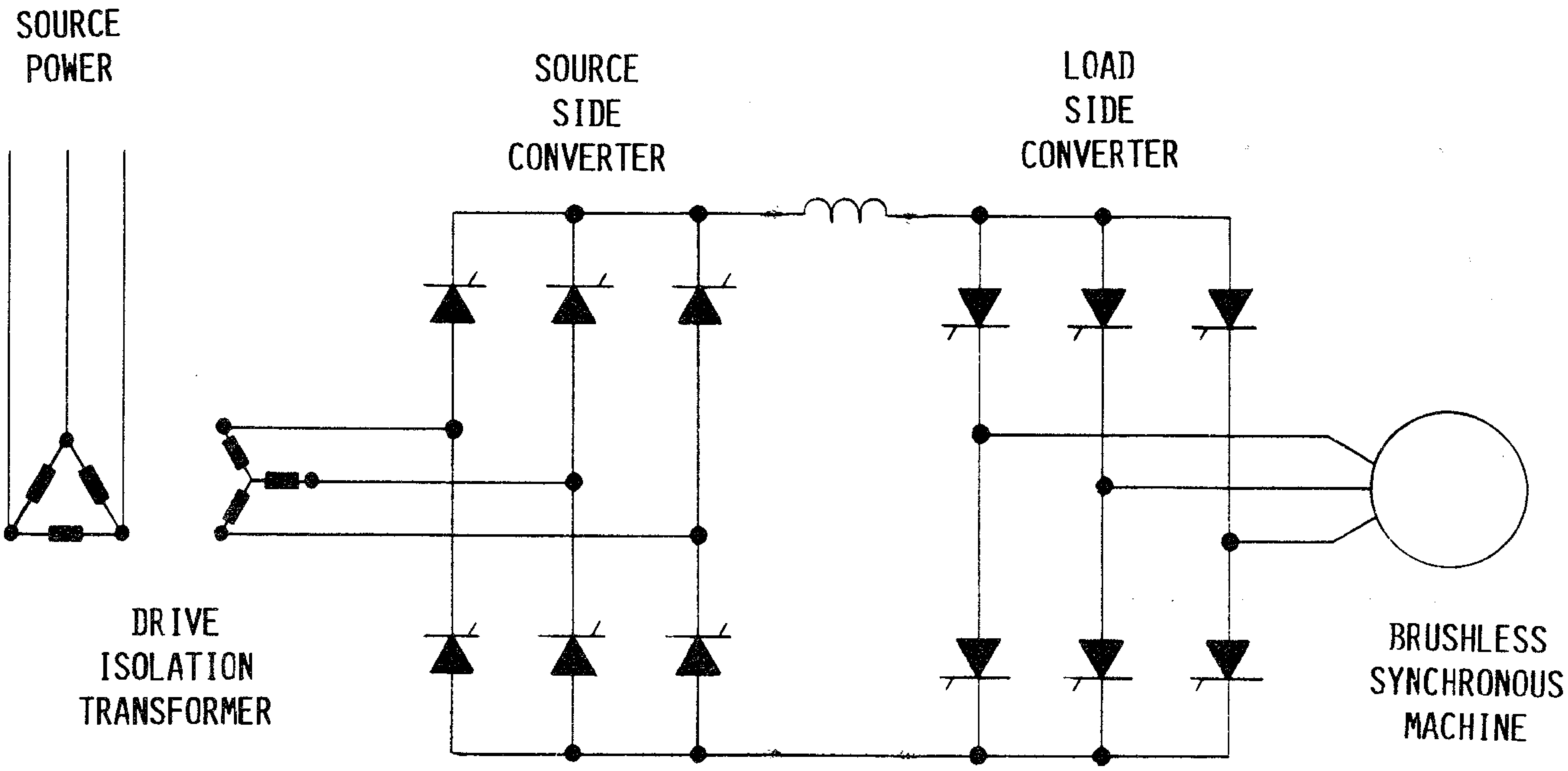

FIG. 3. BASIC CIRCUIT FOR THE SYNCHRONOUS MACHINE VARIABLE SPEED DRIVE SYSTEM. 6-PULSE CONNECTED TO 3-PHASE MACHINE.

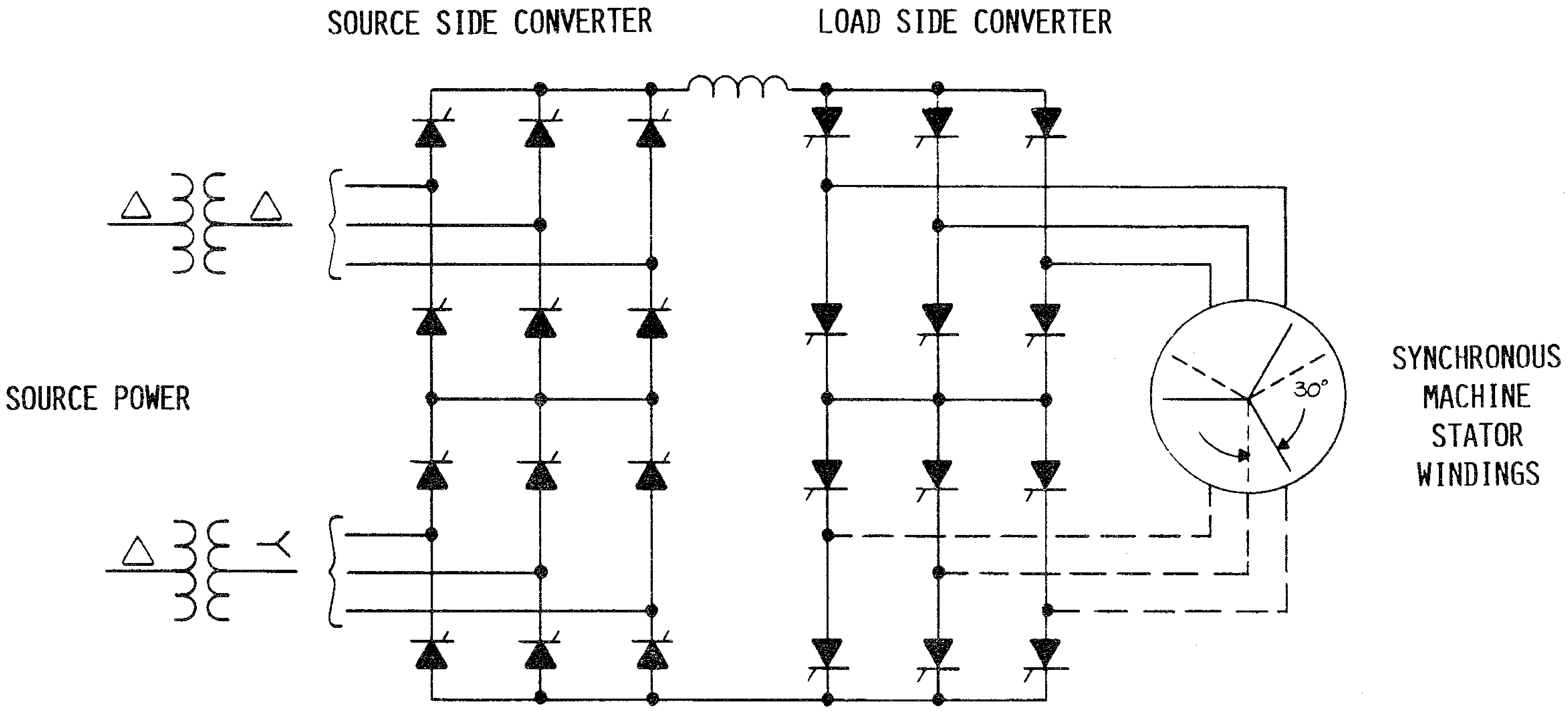

FIG. 4. BASIC CIRCUIT FOR THE SYNCHRONOUS MACHINE VARIABLE SPEED DRIVE SYSTEM. 12-PULSE CONNECTED TO 6-PHASE MACHINE.

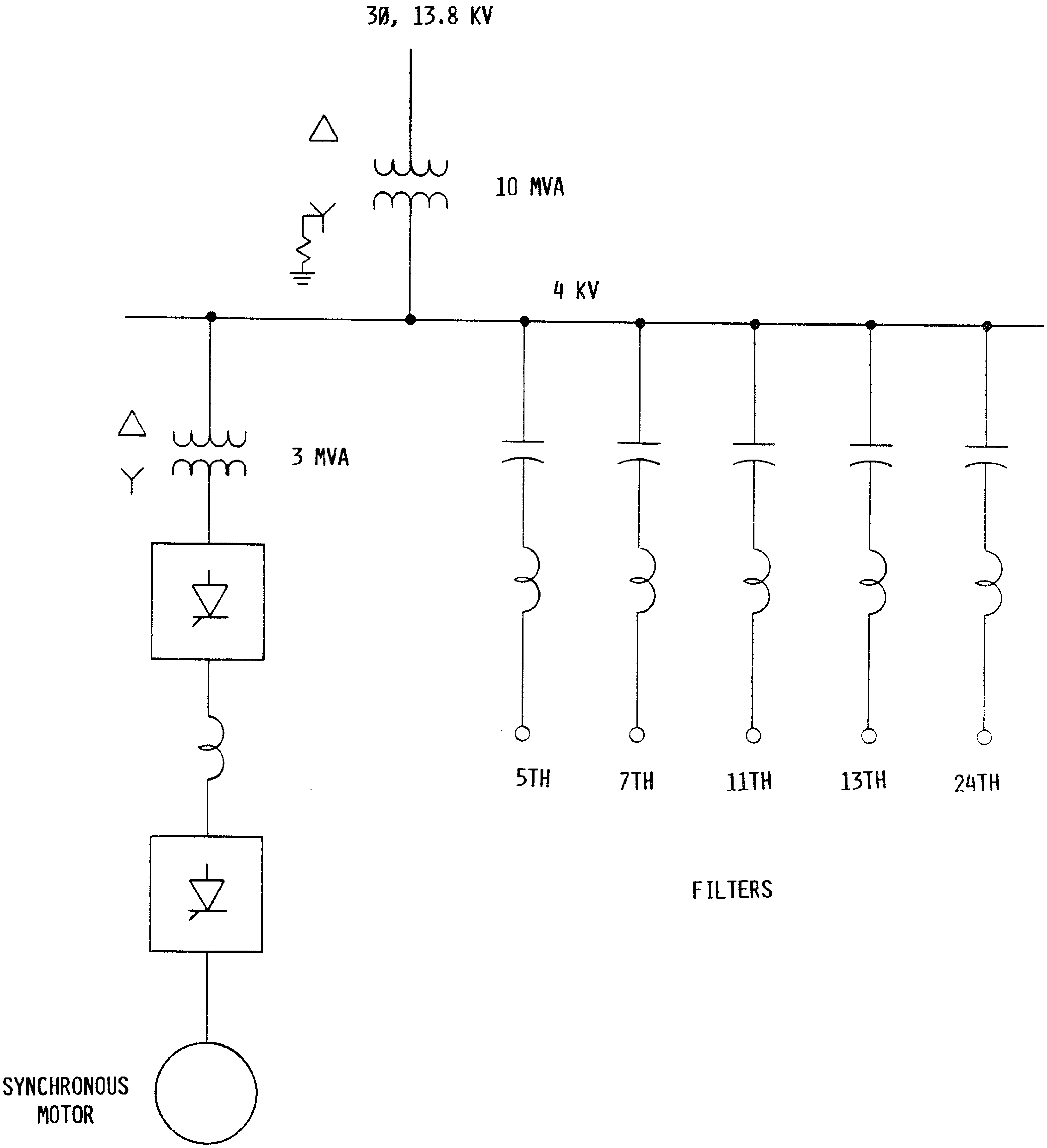

FIG. 5. SIMPLIFIED SINGLE LINE DIAGRAM FOR 2.3 MW VARIABLE SPEED DRIVE HAVING 6-PULSE SYSTEM CONNECTED TO 3-PHASE BRUSHLESS SYNCHRONOUS MOTOR.

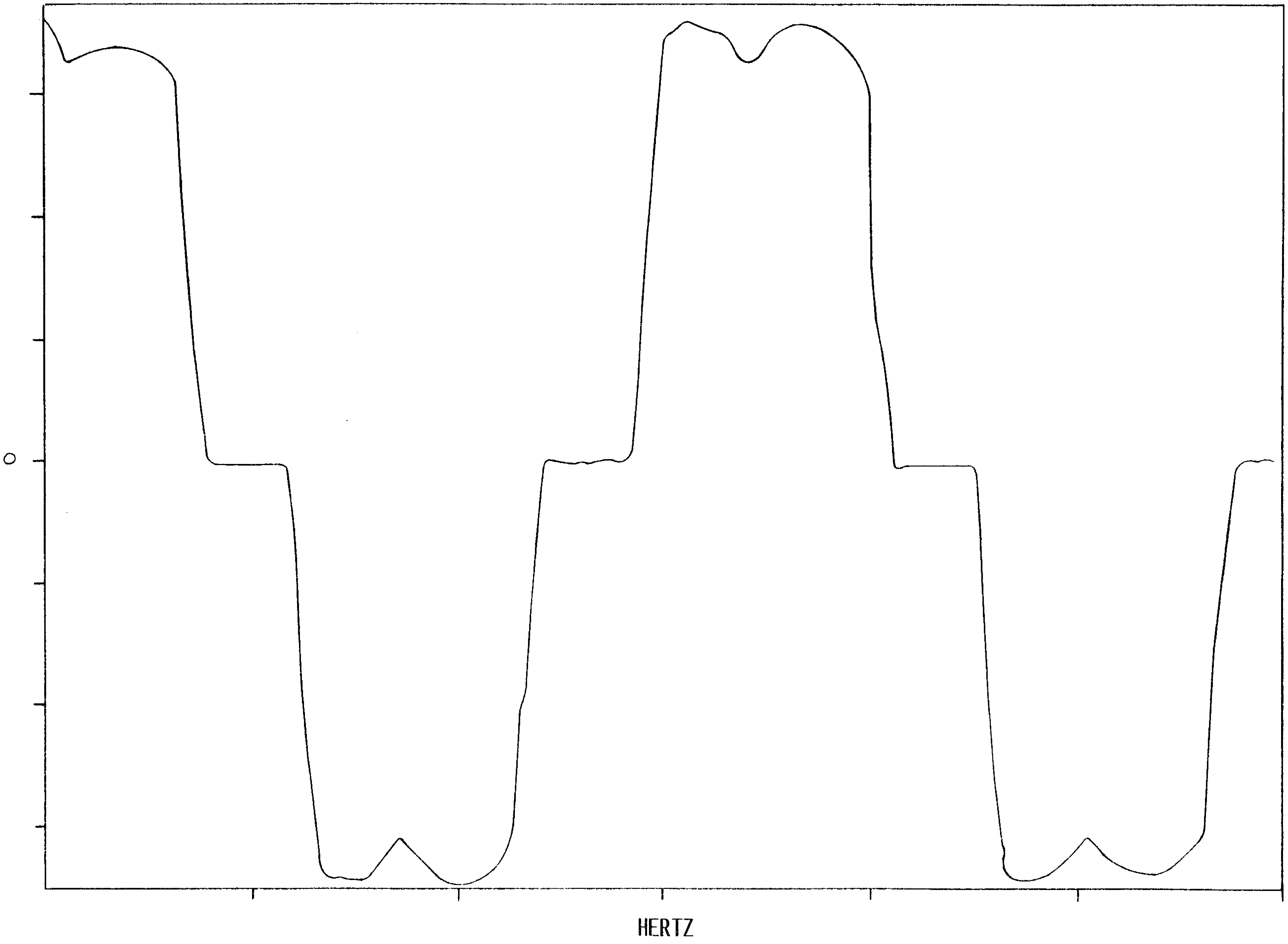

FIG. 6. CURRENT WAVEFORM FOR 3-PHASE SYNCHRONOUS MOTOR RATED AT 2.3 MW, 1000 V, 1800 RPM.

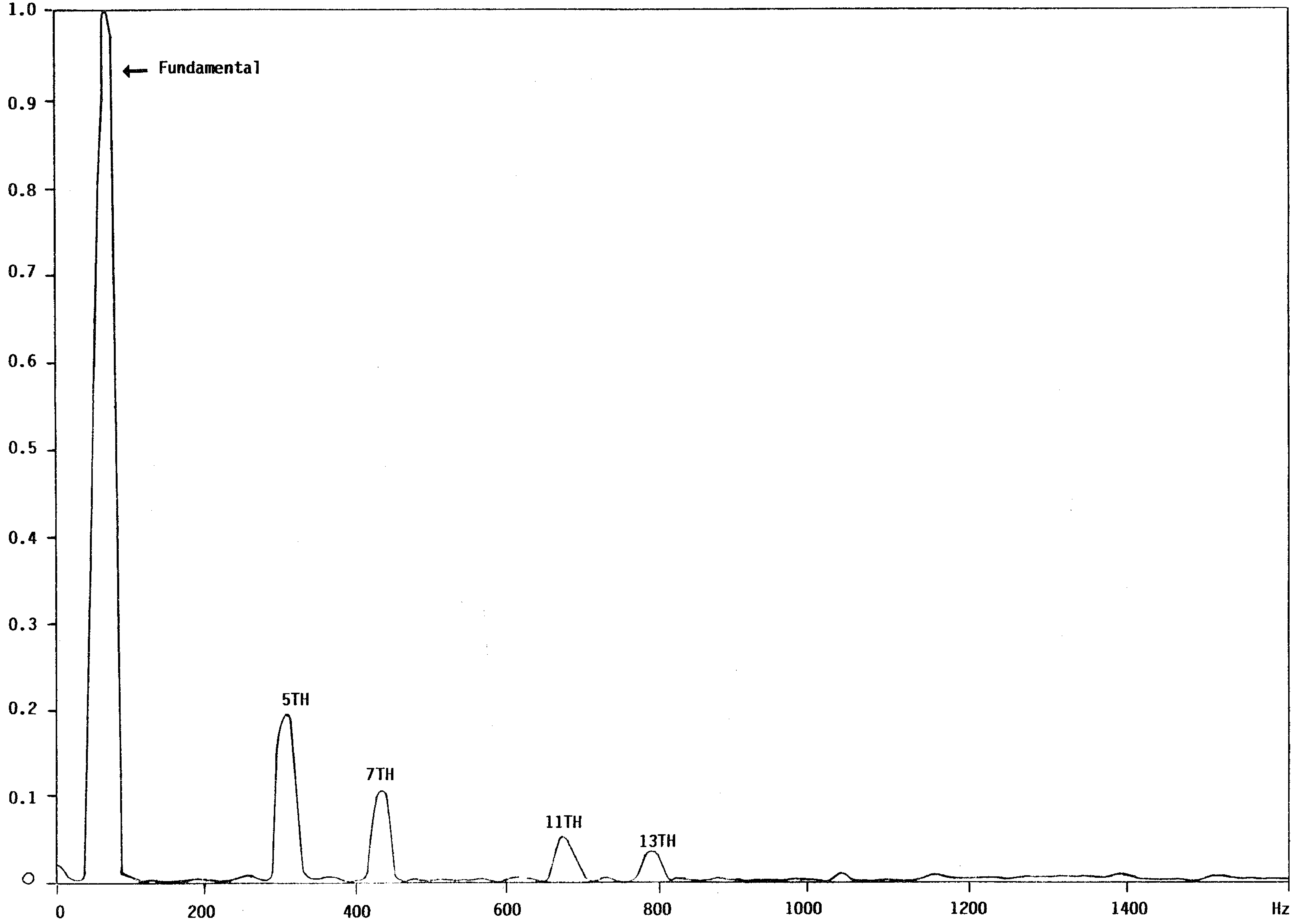

FIG. 7. HARMONIC COMPONENTS FOR CURRENT WAVEFORM IN FIGURE 6.

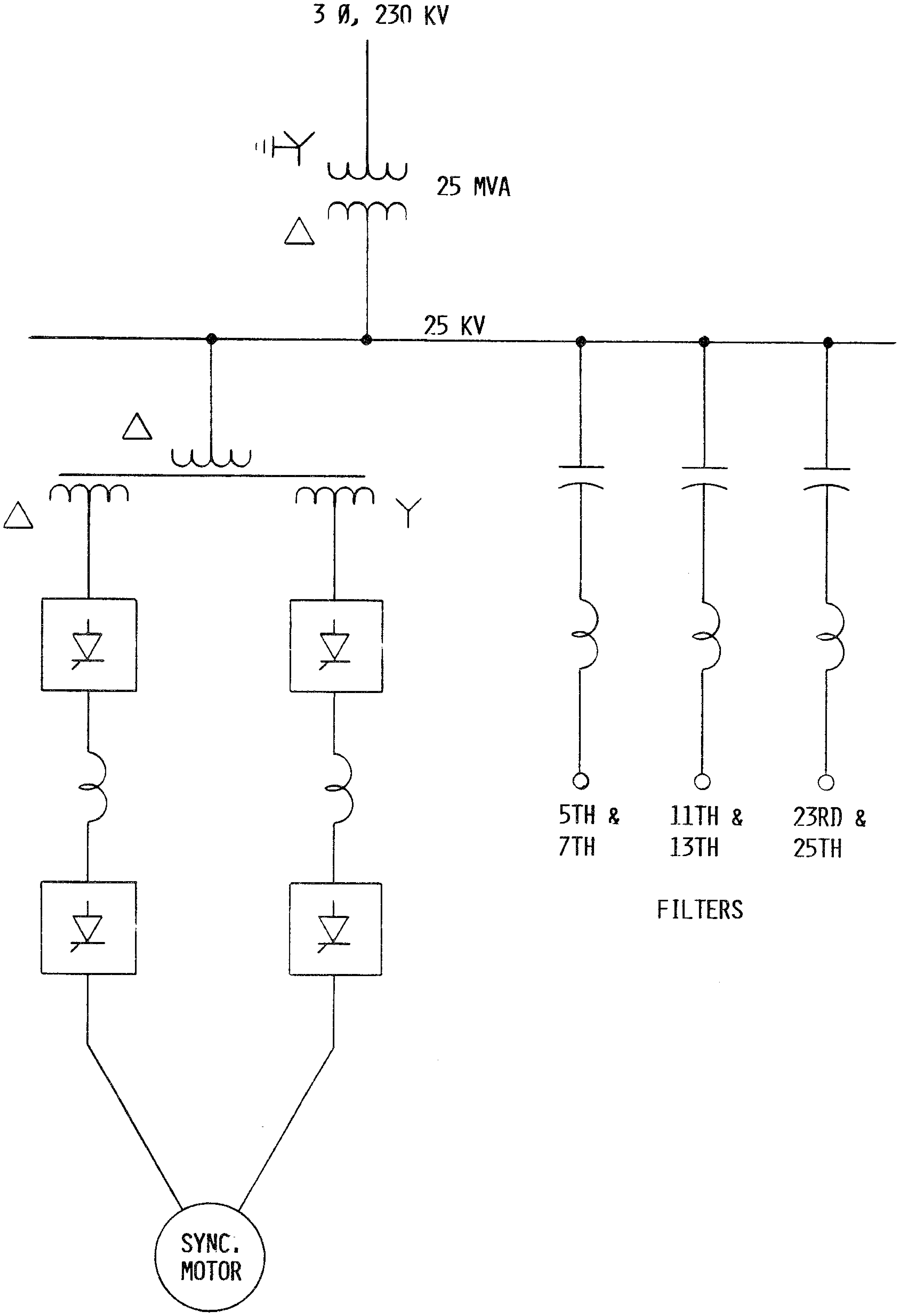

FIG. 8. SIMPLIFIED SINGLE LINE DIAGRAM FOR 17 MW VARIABLE SPEED DRIVE HAVING 12-PULSE SYSTEM CONNECTED TO 6-PHASE BRUSHLESS SYNCHRONOUS MOTOR.

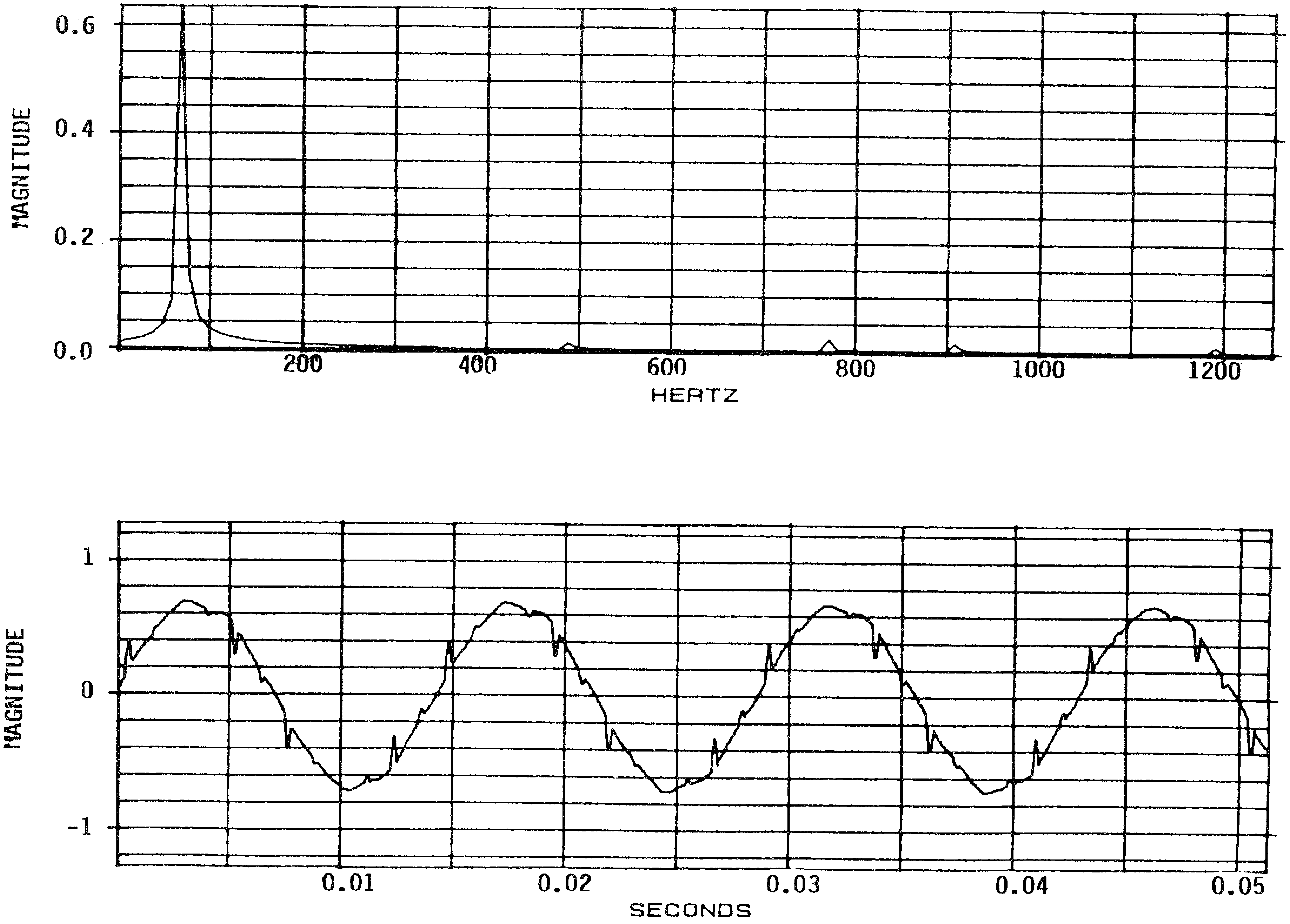

FIG. 9. VOLTAGE WAVEFORM AND ITS HARMONIC SPECTRUM FOR 6-PHASE SYNCHRONOUS MOTOR RATED AT 17 MW, 7200 V, 6000 RPM.

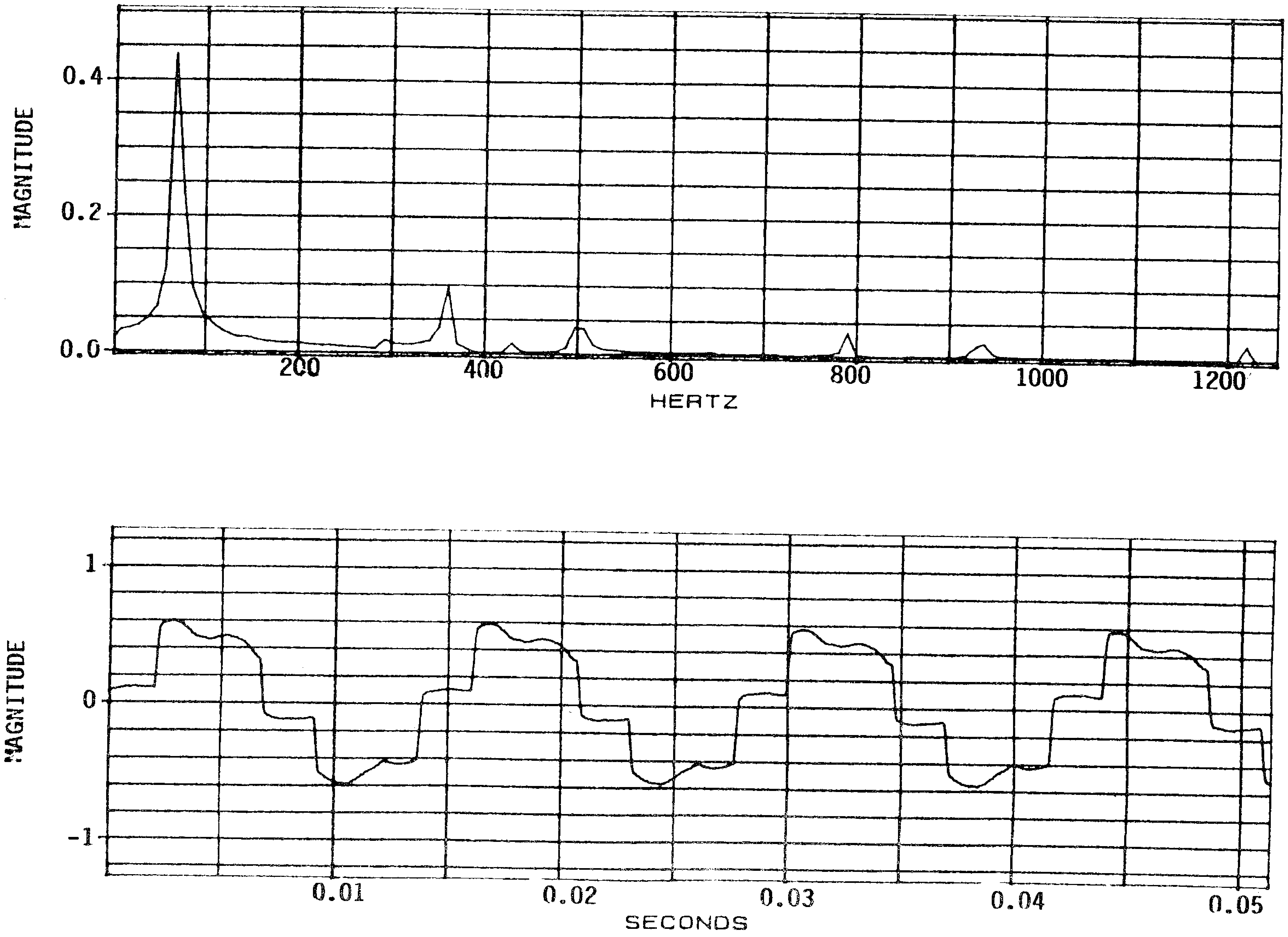

FIG. 10. CURRENT WAVEFORM AND ITS HARMONIC SPECTRUM FOR 6-PHASE SYNCHRONOUS MOTOR RATED AT 17 MW, 7200 V, 6000 RPM.

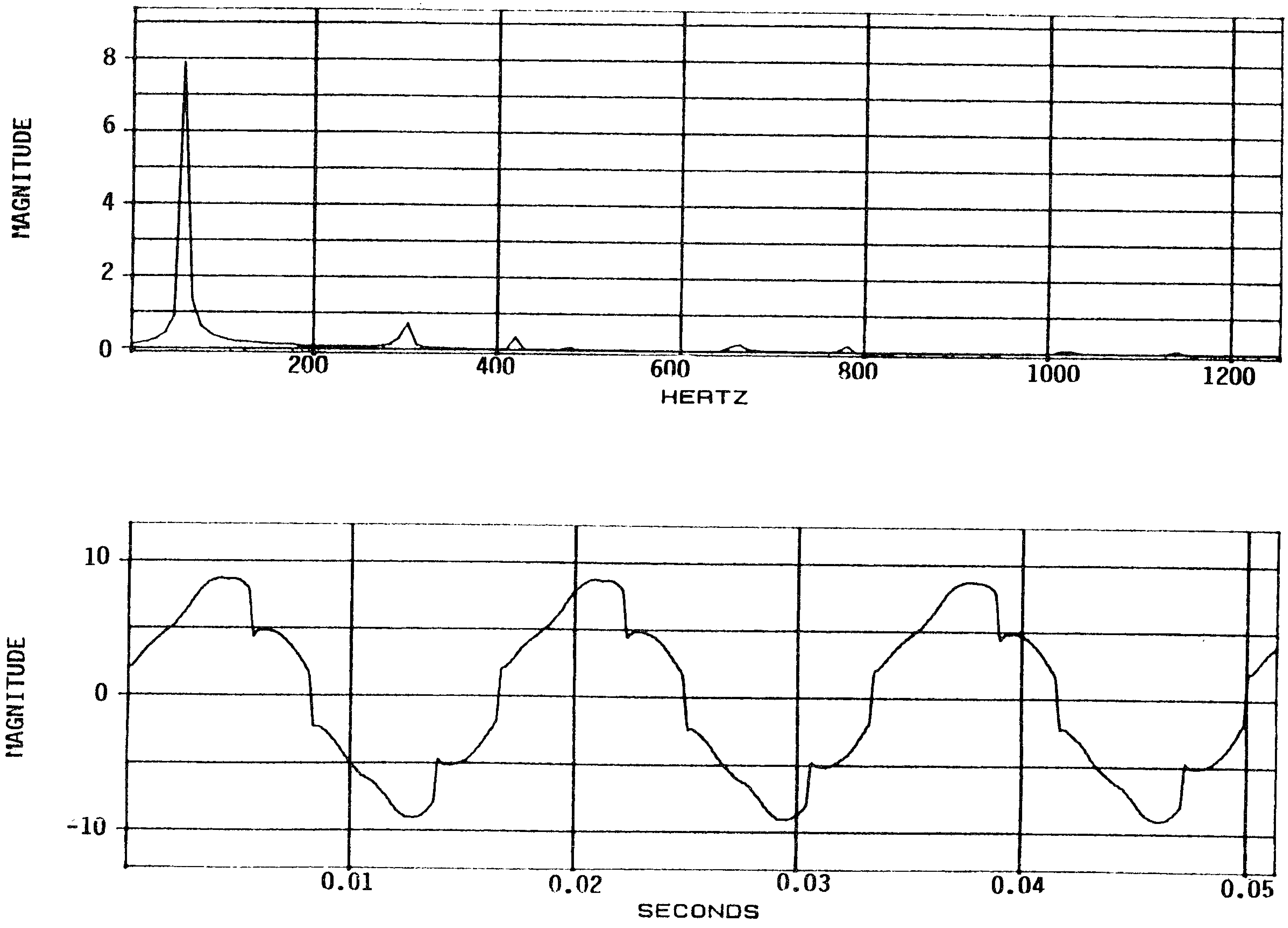

FIG. 11. CONVERTER TRANSFORMER SECONDARY CURRENT IN 12-PULSE SYSTEM.

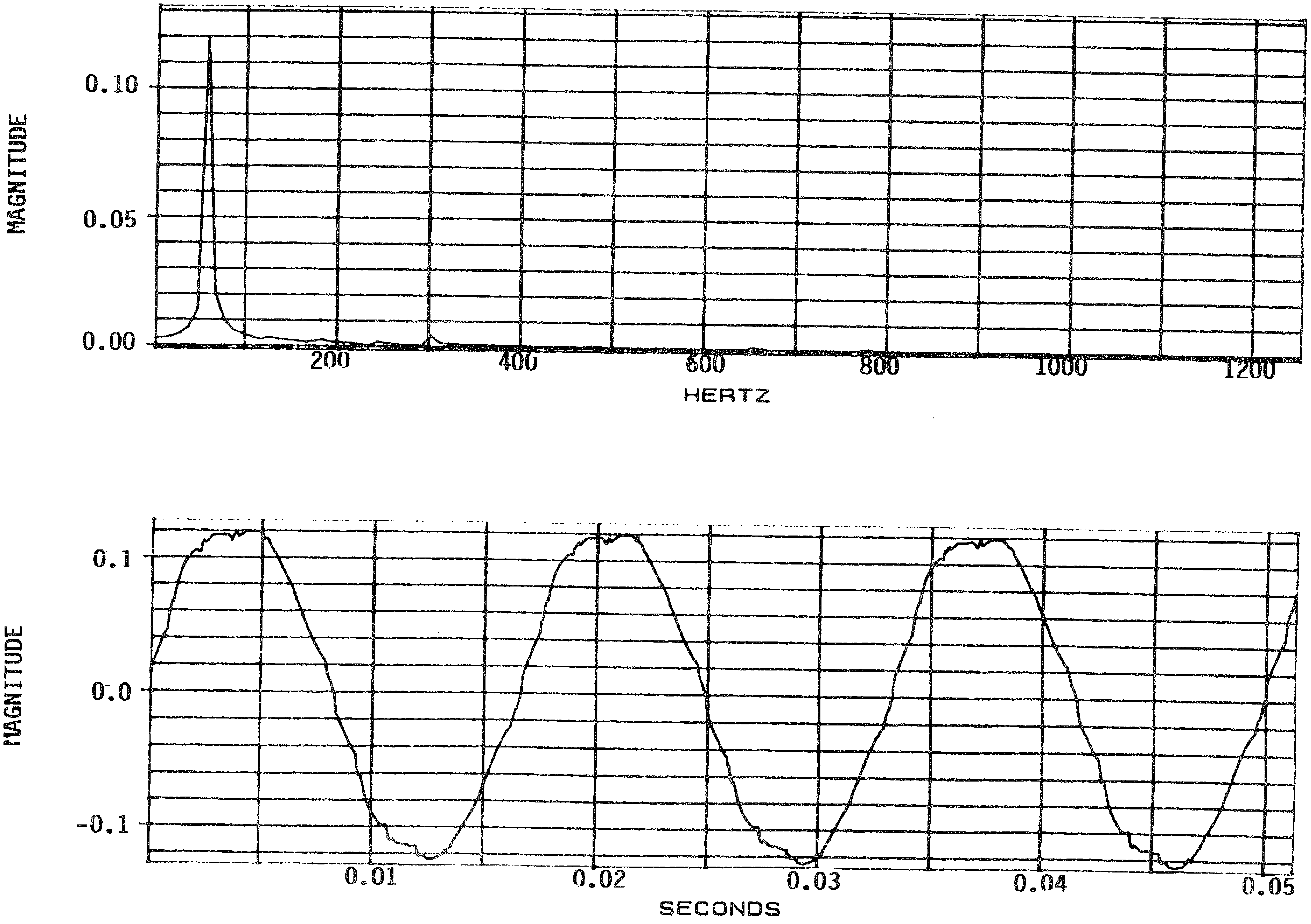

FIG. 12. INCOMING LINE CURRENT TO 25 KV BUS.

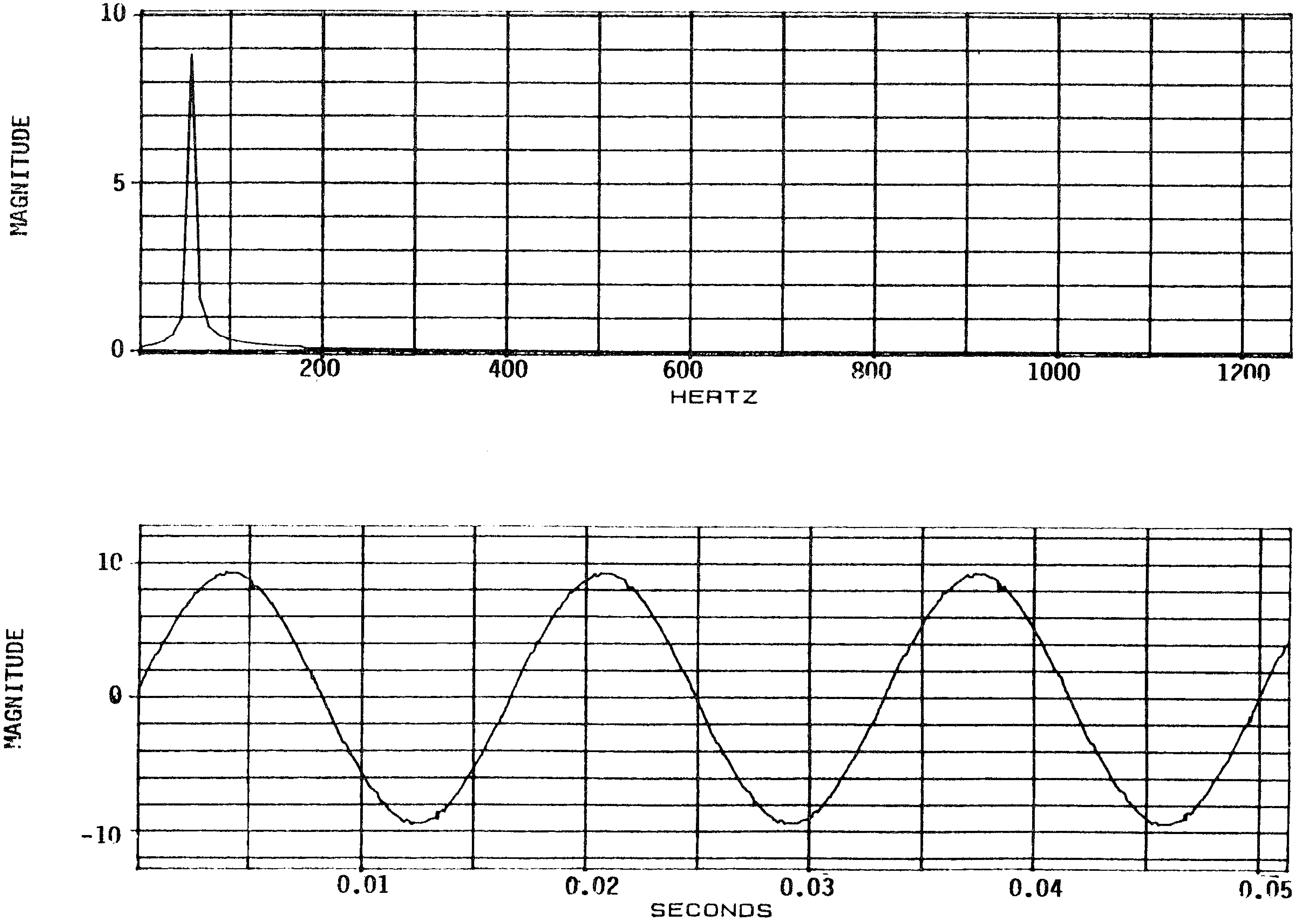

FIG. 13. VOLTAGE AT 25 KV BUS WITH FILTERS CONNECTED.

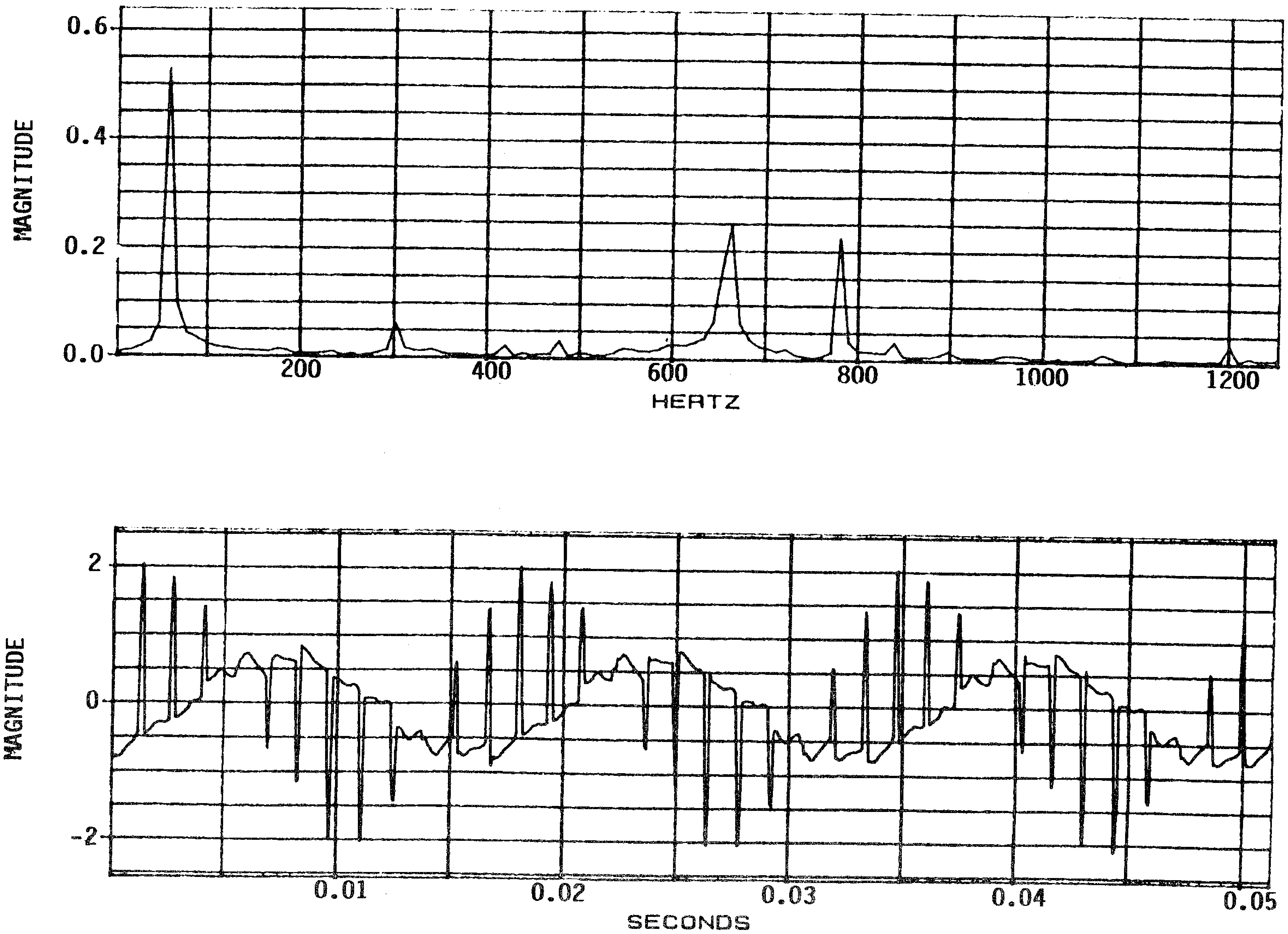

FIG. 14. TOTAL CURRENT IN HARMONIC FILTERS CONNECTED TO 25 KV BUS.