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You will be pleased to know that 525 people attended one or more of the 16 seminars, and over 2700 people attended the Trade Show.

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ADJUSTABLE SPEED DRIVES:
THEIR APPLICATIONS, TYPES AND HARMONICS BEHAVIOUR

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1.0 INTRODUCTION

The use of adjustable speed drive in industry is increasing and this trend is expected to continue because of good economical advantages. This presentation describes the application of adjustable speed drives to centrifugal machines for energy savings, and reviews the main type of electronic adjustable speed drives. It also highlights the harmonic problems encountered when using adjustable speed drives for new or retrofit application and offers some possible solutions. Field results for two large installations are presented and analyzed with particular emphasis on presence of harmonics.

2.0 APPLICATION OF ADJUSTABLE SPEED DRIVES TO CENTRIFUGAL MACHINES

2.1 PUMP BASICS

There are two main reasons for considering centrifugal machines for adjustable speed drive application. First, this type of equipment is used extensively in industrial and commercial establishments; second, the horsepower requirements of centrifugal machines vary at a cubic rate relative to speed, and this offers significant energy saving when operating at reduced speed. In order to understand the application of adjustable speed drive to centrifugal machines, be it a pump, a fans or a compressor, it is necessary to review their basic operating characteristics. The discussion here is concentrated on pumps but equally applies to fan and compressors. Figure 1 shows a pump curve describing the head (or pressure) versus flow characteristic of an actual water pump with given impeller size, specific speed, etc. The rating conditions are: 2800GPM at 122FT head and 1775RPM. The pump brake horsepower (BHP) is given as:

$$\text{BHP} = \frac{\text{HEAD (FT)} \times \text{FLOW (USGPM)} \times \text{SPECIFIC GRAVITY}}{3960 \times \text{PUMP EFFICIENCY}}$$

Substitution the pump rated values in this equation, and with efficiency equal to 0.83, the brake horsepower is 104HP. If pump speed is reduced progressively from rating speed of 1775 RPM, a similarly shaped curve exists to relate the head/flow characteristics of the pump at any particular speed.

Figure 2 shows a family of curves generated for these speeds over the range of 1775 RPM to 1150 RPM. The head/flow curves for any speed can be predicted from the constant speed rating curve by use of "similarity laws",

Let rating speed be n_1 RPM

Let reduced speed be n_2 RPM

THEN SPEED RATIO = n_2/n_1

FLOW IS PROPORTIONAL TO n_2/n_1

HEAD IS PROPORTIONAL TO $(n_2/n_1)^2$

POWER IS PROPORTIONAL TO $(n_2/n_1)^3$

Figure 3 shows the above relationships graphically except that the "power" curve is replaced by "efficiency". This latter curve shows that as speed is reduced, the efficiency change from the design efficiency at rating is negligible over the first 20% of speed reduction and even for a 50% speed change, the efficiency is still about 85% of the design efficiency.

2.2 SYSTEM DEMAND CURVE

For pumping operations, the characteristics of the system into which pumping take place must be considered and the back pressure on the pump consists of two components:

- STATIC LIFT
- FRICTION LOSSES

Figure 4 shows a system demand curve superimposed on the adjustable speed curve of Figure 2. Static Head is seen to be 75 feet and represents the total lift from the pump suction to the elevation of discharge point. Friction losses are a function of pipe size, length, co-efficient of friction, specific gravity of the liquid and the number of fittings and valves. The friction losses are approximately proportional to the square of the flow.

2.3 FLOW CONTROL TECHNIQUES

Historically, adjustable flow has been produced by operating the motor and pump at fixed speed, and modulating flow through the use of flow control valve. The closing of the valve can be represented by a different system curve, as shown in Figure 5. The throttled system curve shows the same static lift but increased friction head due to friction introduced by the throttle valve itself. Note that the desired reduction in flow has been achieved but the head has been increased, relative to 100% flow, by introducing the artificial friction of control valve into the system. If the desired flow could be achieved by modifying the pump curve rather than the system curve, as shown in Figure 5, flow and head could both be reduced together. In fact, the head required across the pump would be reduced rapidly relative to flow reduction. The pump output is proportional to head times flow for any given substance. Hence significant energy saving would result when controlling the flow by varying the pump speed rather than using throttle valve.

In order to understand better the energy savings when controlling the flow using adjustable speed drive versus throttle valve consider the following example.

Assume flow is to be reduced to 50%, i.e. 1500GPM using adjustable speed drive, see Figure 5. The pump speed required to operate at this point on the demand curve has been calculated by the similarity laws and is 1300RPM. The Pump curve for this speed is included on the diagram, system back pressure at this point is 85FT including friction losses of about 10FT.

$$n_2/n_1 = 1300/1775 = 0.732$$

Ratio of efficiency at 50% flow to design efficiency = 0.97 (see Figure 3). So the drop in efficiency is insignificant. From Figure 4, efficiency at 1500GPM is 0.74. Therefore, efficiency at 1500GPM at reduced speed is $0.97 \times 0.74 = 0.72$

$$\text{PUMP BHP} = \frac{1500 \times 85}{3960 \times 0.72} = 44.71\text{HP}$$

Consider now the case when controlling the flow using throttle valve from Fig. 5 the operating condition are: SPEED = 1775RPM, HEAD = 160FT, FLOW = 1500GPM AND PUMP EFFICIENCY = 0.74

$$\text{PUMP PHP} = \frac{1500 \times 160}{3960 \times 0.74} = 81.9\text{HP}$$

The excess head dropped across the valve therefore represents the "throttling energy loss" indicated in Fig. 5 which amount to:

$$81.9 - 44.71 = 37.19 \text{ (45.4\%)}$$

This example clearly demonstrates the power wasted across a throttling valve for a 2 to 1 turndown in flow. In order that overall losses are included, i.e. from electrical input to pump output, the above comparison must also take into account the efficiency of the adjustable speed drive and motor. Adjustable speed drives have relatively high efficiencies, ranging from 85% to 95% or even higher, and this does not change significantly with speed or load.

3.0 PRINCIPLES OF ADJUSTABLE SPEED DRIVES

Most solid state adjustable speed drives used with standard A.C. motors produce variable voltage and frequency to control the motors. Frequency is controlled in order to vary the speed of the motor:

$$\text{SPEED} = \frac{120 \times \text{FREQUENCY}}{\text{NO. OF POLES}}$$

Voltage is varied along the frequency so that the flux density in the air gap between the rotor and stator, and therefore the torque produced by the motor, can be controlled,

TORQUE IS PROPORTIONAL TO AIR GAP FLUX

AIR GAP FLUX IS PROPORTIONAL TO VOLTS/HERTZ

Typically, a constant relationship between voltage and frequency (Volts/Hertz) is maintained. The basic components of an adjustable speed drive are a line converter (rectifier) and load converter (inverter). The rectifier changes constant A.C. input to constant or variable D.C. output. The inverter alters the D.C. to variable voltage/variable frequency A.C. power fed to motors.

3.1 BASIC TYPES OF ADJUSTABLE SPEED DRIVES

The following is an overview of the most popular types of AC drives with brief description. A.C. drives may be broken down into the following two categories:

I. CURRENT SOURCE VARIABLE FREQUENCY DRIVES

Current source inverter (CSI) drives can be identified by the large reactor in the D.C. bus, see Figure 6. Most current source drives require that a motor be connected before the drive has the capability to commute. Motor inductance characteristics, in addition to capacitors in the drive, are part of the commutating circuit. This makes it difficult to retrofit these drives to existing fixed speed motor. The most common designs of current source drive do create high voltage spikes during commutation. This could be a factor in selecting the drive, especially in the higher voltage drives (2300V and above) to assure that the insulation on the motor will not be damaged by the voltage spikes. An alternative design to this approach is one which includes capacitors on the output, which minimizes the voltage spikes.

Another type of current source drive is a load commutation drive which utilizes a separately excited synchronous motor which forces the commutation of the inverter section of the drive. This type of drive is common in the higher horsepower (1500 and above). In most cases they use brushless exciters on the motor for excitation of the rotating fields. Two actual installation examples for load commutated drives are given in section 4.4.

II VOLTAGE SOURCE DRIVES

In the smaller horsepower (1000HP or less), the voltage source drives are the most common types of drives. The power conversion unit of these voltage source drives may be broken down into two types, variable voltage input (VVI) and pulse width modulated (PWM).

The VVI inverter drive, see Figure 7 has the simplest regulation scheme, but it uses the largest amount of D.C. filter components.

The PWM, see Figure 8, utilizes a diode rectifier to provide a constant D.C. Voltage. The inverter section in this type of drive therefore controls both voltage and frequency. This is done by varying the width of the output pulses as well as the frequency in such a way that the effective voltage is approximately sinusoidal. Because a PWM drive presents a closer simulation of sine-wave power to the motor, less power filter components are required. However, the complex switching wave forms in the inverter require the most complex regulator of the drive types being discussed here and losses due to switching can be high.

4.0 HARMONICS AND THEIR EFFECTS ON ADJUSTABLE SPEED DRIVES

All adjustable speed drives, unlike fixed speed, generate harmonics to some degree. Harmonics are currents and voltages that are multiples of the fundamental 60HZ frequency. Any power converter, which converts A.C. to D.C. or D.C to A.C., can be considered a source of harmonics. Harmonics produced by the rectifier may cause harmful effects on equipment connected to the plant or electric utility system or neighbouring industrial plant. On the other hand, harmonics produced by the inverter may cause motor overheating. In the following sections, the presence of harmonics in adjustable speed drives for both 6 pulse and 12 pulse system will be analyzed. The effect of the use of harmonic filters and special transformer arrangement in reducing harmonics is also discussed. Harmonics measurements for two actual large installation using load commutated drives are presented and analyzed.

4.1 SOURCE OF HARMONICS

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

Rectifiers

D.C. motor drives

Adjustable frequency A.C. drives

Uninterruptible power supplies (UPS)

Arc furnace

Static VAR Generator

Cyclo converter

Static Motor Starters

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, a good guideline is that if 20% or more of the plant load consists of harmonic producing sources, a harmonic study should be considered. This will determine the magnitude of harmonic currents and voltages, and will aid in designing special filters to reduce these distortions.

4.2 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 Figure 9 and each harmonic is assumed to be in phase with the fundamental. Figure 10 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 Figure 11 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 Figure 12, 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 levels of harmonic distortion in a power system, the harmonic distortion factor (HDF) is used, and is defined in IEEE Standard 519-1981 as:

$$\text{HDF} = \left(\frac{\text{sum of squares of amplitudes of all harmonics}}{\text{square of amplitude of fundamental}} \right)^{1/2} .100\%$$

Harmonic distortion standards are needed to

1. Ensure users are provided with a suitable voltage supply waveform.
2. Limit distortions to levels that system components can tolerate.
3. Prevent the power system from interfering with the operation of other systems.

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. In Canada, for example, the requirements for harmonic distortion factors vary from utility to utility, but in general they range from 1% to 5% depending on the system voltage level. The higher the voltage level the more stringent become the harmonic limitation requirements. It is therefore necessary to check with the power company as to their requirements in limiting harmonic voltages and currents as this may have substantial impact on the drive and filter design.

4.3 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. Because of 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, an 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:

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

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.

4.4 INSTALLATION EXAMPLES

In order to better understand the presence of harmonics in an adjustable speed drive, harmonics measurement for two installations 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

Figure 13 shows a simplified single line diagram for the first drive installation. It consists of the following:

1. Line filters connected to 4.16 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, 1000V, 1800RPM, 4 poles.

Figures 14 and 15 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 rotor was of solid pole type and designed for an 80°C temperature rise. The measured rotor temperature rise was satisfactory when connected to 60HZ supply, but it was in excess of 150°C when energized from load commutated inverter.

After considerable discussions with the motor manufacturer, it was decided to build a new rotor of laminated type to replace the original solid pole rotor in order to correct the overheating problem. In addition, several design modifications were incorporated for the new rotor to further reduce harmonic losses problem, and these were:

1. Add damper bars in the pole face.
2. Decrease the air gap from 0.5 inch to 0.35 inch.
3. Increase the effective exterior surface area of the field winding to achieve better heat dissipation.
4. Use class F insulation for the field winding and for rotor laminations.
5. Improve airflow circulation by replacing the cooling fans.

The rebuilt motor with the laminated rotor underwent heat run test. The measured rotor temperature rise when connected to load commutated inverter was 72°C, and when connected to 60HZ supply was 48°C. The isolating transformer temperature rise was also measured and found to be above the design value of 115°C. This problem was corrected by providing adequate ventilation. Harmonic currents fed back to the 4.16KV supply were kept within acceptable level by using individual harmonic filters for 5th, 7th, 11th, 13th and 24th as shown in Figure 13.

CASE 2

Figure 16 shows a simplified single line diagram for the second drive installation. It comprises of the following

1. Line filters connected to 25KV incoming power lines. These filters provide a sink for the harmonics and are used for power factor correction. The amount of compensation is such that the power factor is always between 0.95 and 1.0 depending on the load. The filter combination used is the high pass type consisting of an inductance in parallel with a resistance and a series capacitance. There are three filter branches, one for the 5th and 7th harmonics, one for the 11th and 13th, and the last one for 23rd and higher order harmonics. The reactive power requirements of the drive are met by branch one or two, each providing 3.5 MVAR and the last one providing 2MVAR.

2. 3-phase/6-phase converter transformer rated at 21MVA, 25/2 X 7.3KV. The primary winding is connected in delta and the secondary consists of two 3-phase winding, one being connected in star and the other in delta. The line voltage is the same for both secondary winding but with a phase shift of 30°. To each secondary winding an independent six pulse rectifier/inverter system is connected and only the winding combination makes it a 12 pulse system. The reason for the use of the 12 pulse system lies in the reduction of harmonics created by the converter. The transformer was specifically designed for this application as the presence of harmonic currents in the secondaries would require considerable oversizing of regular power transformer.
3. 12-pulse line converter (system rectifier)
4. DC-link smoothing reactor.
5. 12-pulse load converter system (inverter). The converters are cooled by deionized water flowing through the thyristor heat sink. Each branch in the converter consists of 6 thyristors in series, with the sixth one being redundant for additional protection. Each converter is therefore made of 36 thyristors.
6. 6-phase burshless synchronous machine rated at 17MW, 7200V, 6060RPM, 101HZ, 2-poles. The rotor is of the cylindrical solid steel type. Non magnetic wedges were used in the rotor to hold the main field windings in place. Because of the reduced penetration of the current into the steel of the rotor, most harmonic currents will flow in the wedge. Therefore, the wedges were also used in the part of the rotor without a field winding. The choice of motor voltage of 7200 V mainly depends on the thyristor converters configuration and the manufacturer design preference. The motor voltage can accordingly be adjusted through selection of the number of winding slots an the number of conductor per slot.

Figures 17 and 18 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. Under symmetrical and balanced loading conditions, the 5th and 7th harmonic current should be zero in a 12-pulse system but, in reality, they are present.

The effect of the generated harmonic voltages on 6-phase machines is less when compared to 3-phase because of cancellation of certain space harmonics, see Table 3.

Figure 19 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%. Theoretically, a 12-pulse converter does not produce 5th, 7th, 17th and 19th harmonics; but due to unbalances, some will be present. These unbalances might be caused by:

1. Variations in voltage or impedance line - line in three-phase systems (possibly $\pm 2.5\%$).
2. Differences in transformer winding ratios for star and delta winding connections.
3. Differences in thyristor firing pulse angles between multipulse circuits.
4. Variations in thyristor turn-off times.

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 affected 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. For this installation, Hydro Quebec requirements for harmonic distortion factors at 230KV is not to exceed 1%, and this was satisfied. 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 three filter branches were used.

The first filter branch is tuned to 342HZ in order to reduce both the 5th and 7th harmonic voltages at the incoming bus. The second filter branch is tuned to 702HZ to absorb the 11th and 13th together, and the third filter branch is tuned to 1380HZ to absorb the 23RD and 25TH together. These filters are connected to 25KV bus and located outdoor in the substation yard and occupy an area of 94FT. X 41FT. Figs 20 and 21 show the waveforms of the incoming line current and the voltage at 25KV bus. Both waveforms are almost sinusoidal and harmonic levels are within utility requirement. Figure 22 shows the total current in the harmonic filters connected to 25KV.

In the design of the filters, the possible failures of the individual capacitor cans and the corresponding increase in voltage and to be considered. The capacitor cans had to be small enough so that the failure of one or two cans would not jeopardize the function of the filters and lead to drive shutdown. With a selection of 100 KVAR capacitor cans, in a rack mounted arrangement, it was possible to to tolerate the failure of two capacitors per filter branch before the filters had to be disconnected. The use of individual external fuses makes the visual inspection simple and failure easy to detect.

5.0 CONCLUSIONS

Almost all adjustable speed drives save energy. For centrifugal machine application, the adjustable speed drive is very energy conscious because the horsepower varies proportionally to the cube of the speed. An adjustable speed drive is the most effective for saving energy when the operating profile is more evenly distributed over the entire range of flow rates, and when the system resistance curves are steep.

When selecting an adjustable speed drive for a particular application, one must consider the characteristics of the available drives. These include the drive cost, efficiency, power factor, maintenance, reliability, complexity of power circuit and regulator and harmonics.

It is inevitable that harmonics will be generated whenever an adjustable speed drive is used. The order and magnitude of these harmonics greatly depend on the drive configuration and system impedance. The principle effect of harmonics on motors is over heating and this might require motor derating from 5 to 15 percent depending on type of insulation class and load characteristic.

There is a great need for a coordination of decisions regarding acceptable harmonic levels between users, drive manufacturer, electric utilities and standards group. There are no current CSA standards specifically relating to adjustable speed drive. However, IEEE standard 519 which specify limits of harmonics is widely used and accepted.

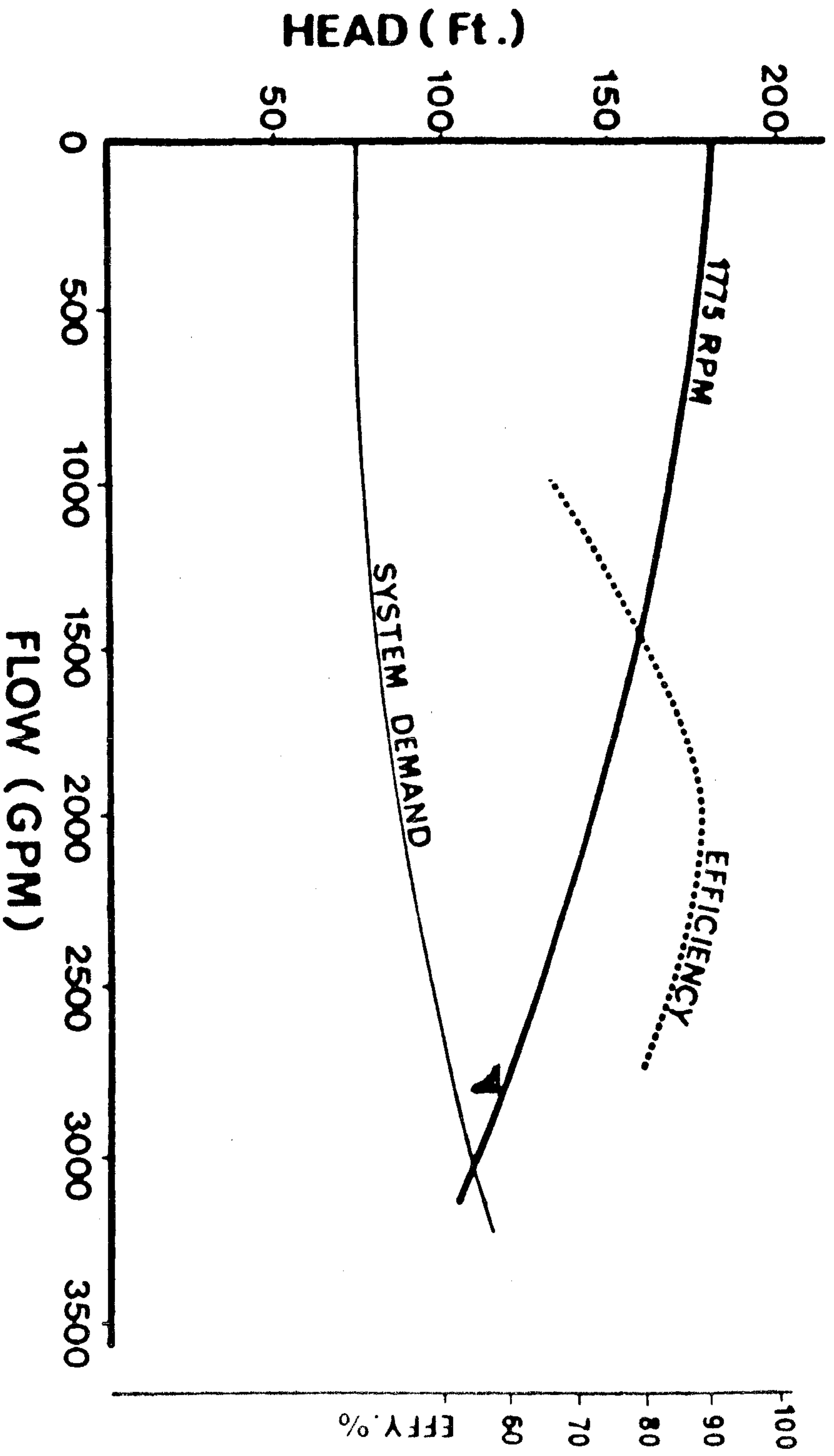


FIG. 1

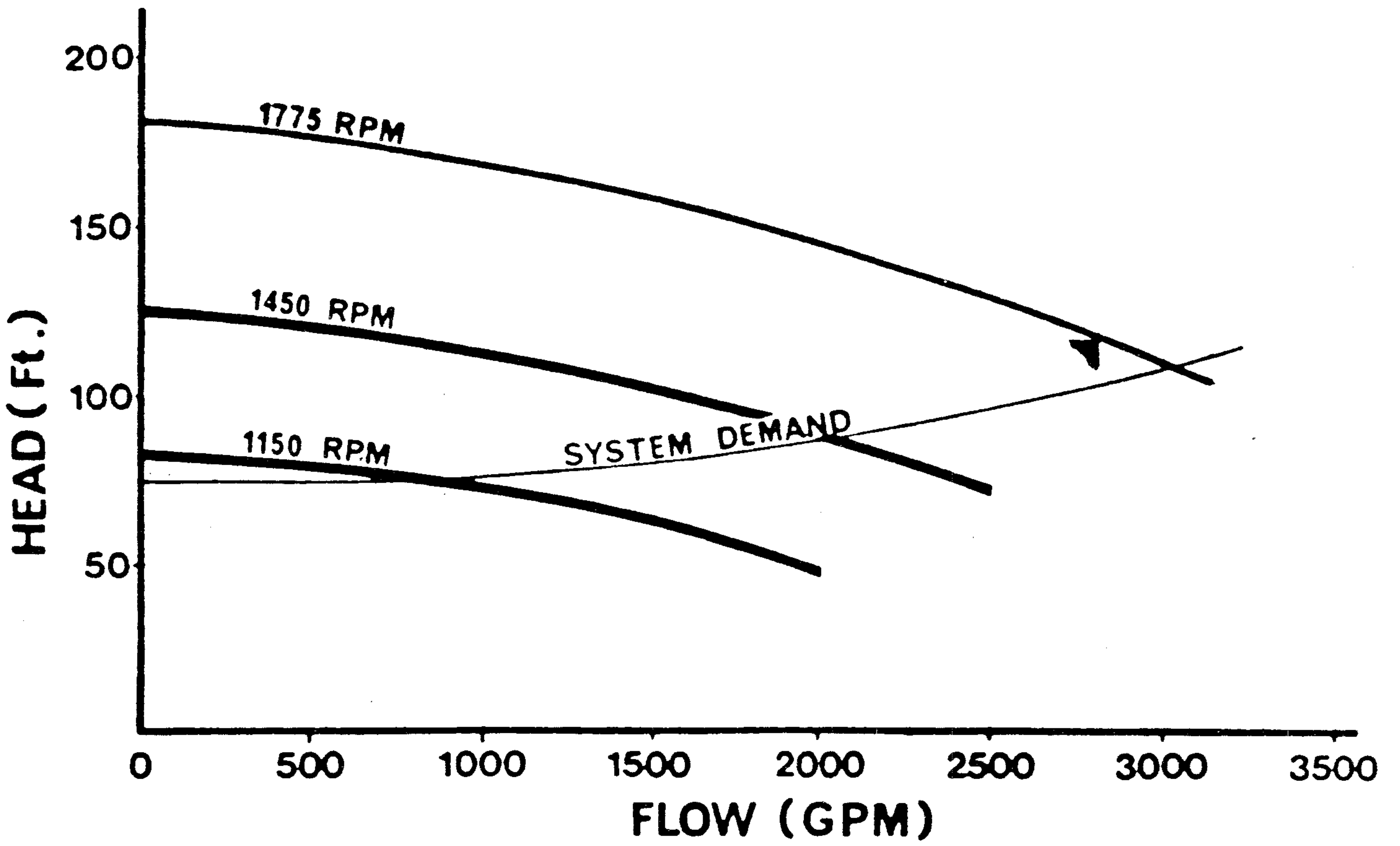
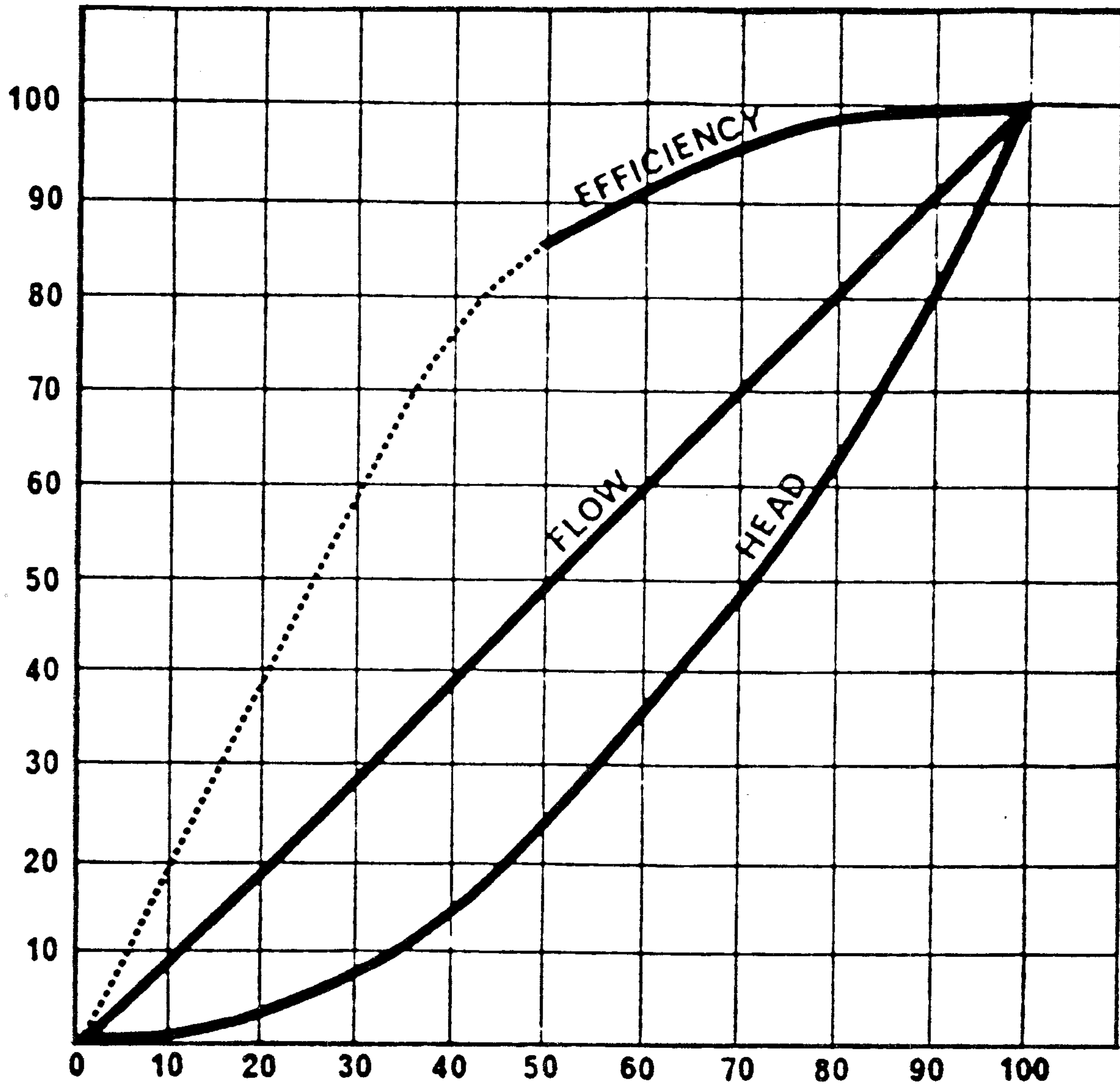


FIG. 2



% SPEED

FIG. 3

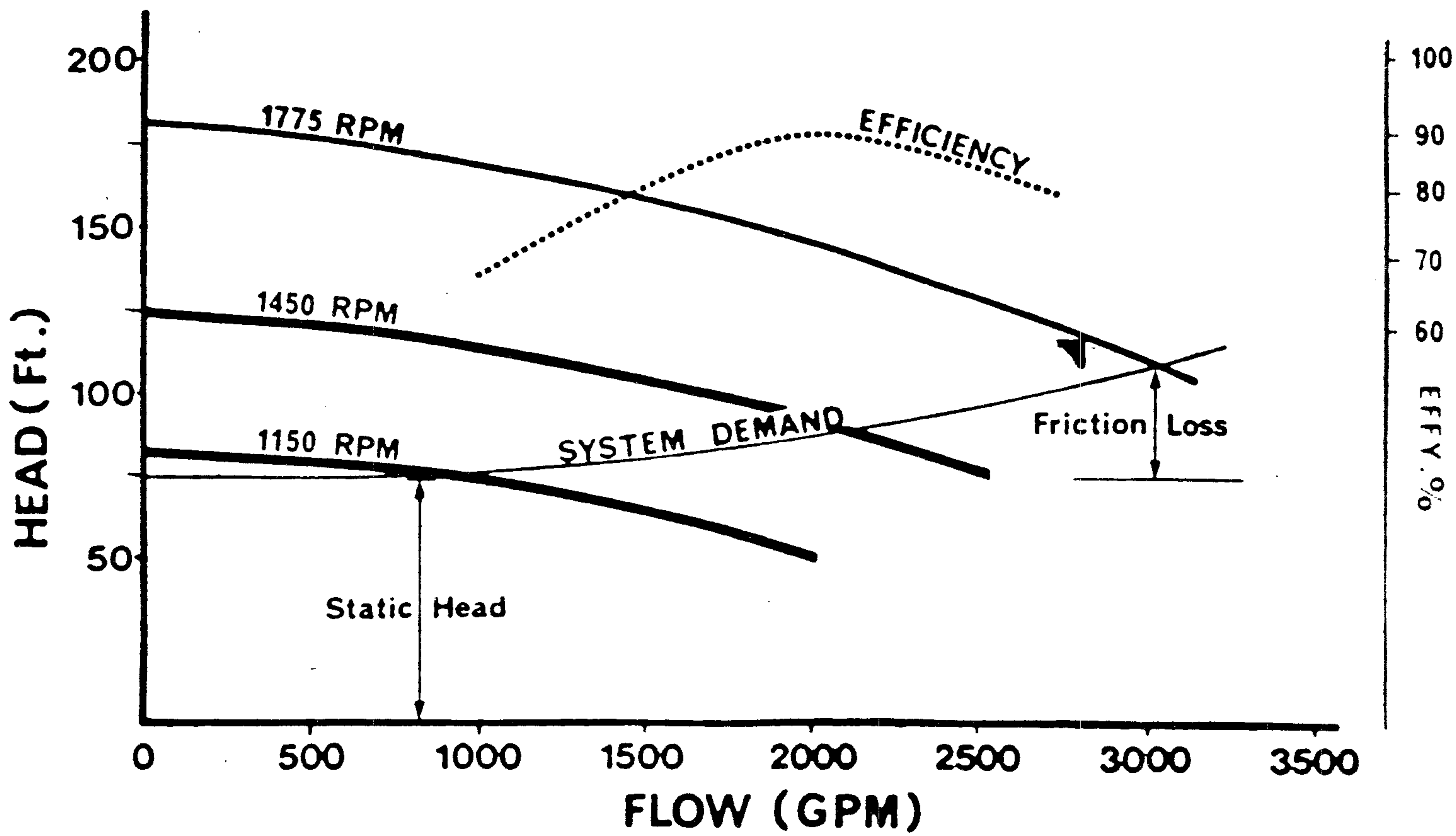


FIG. 4

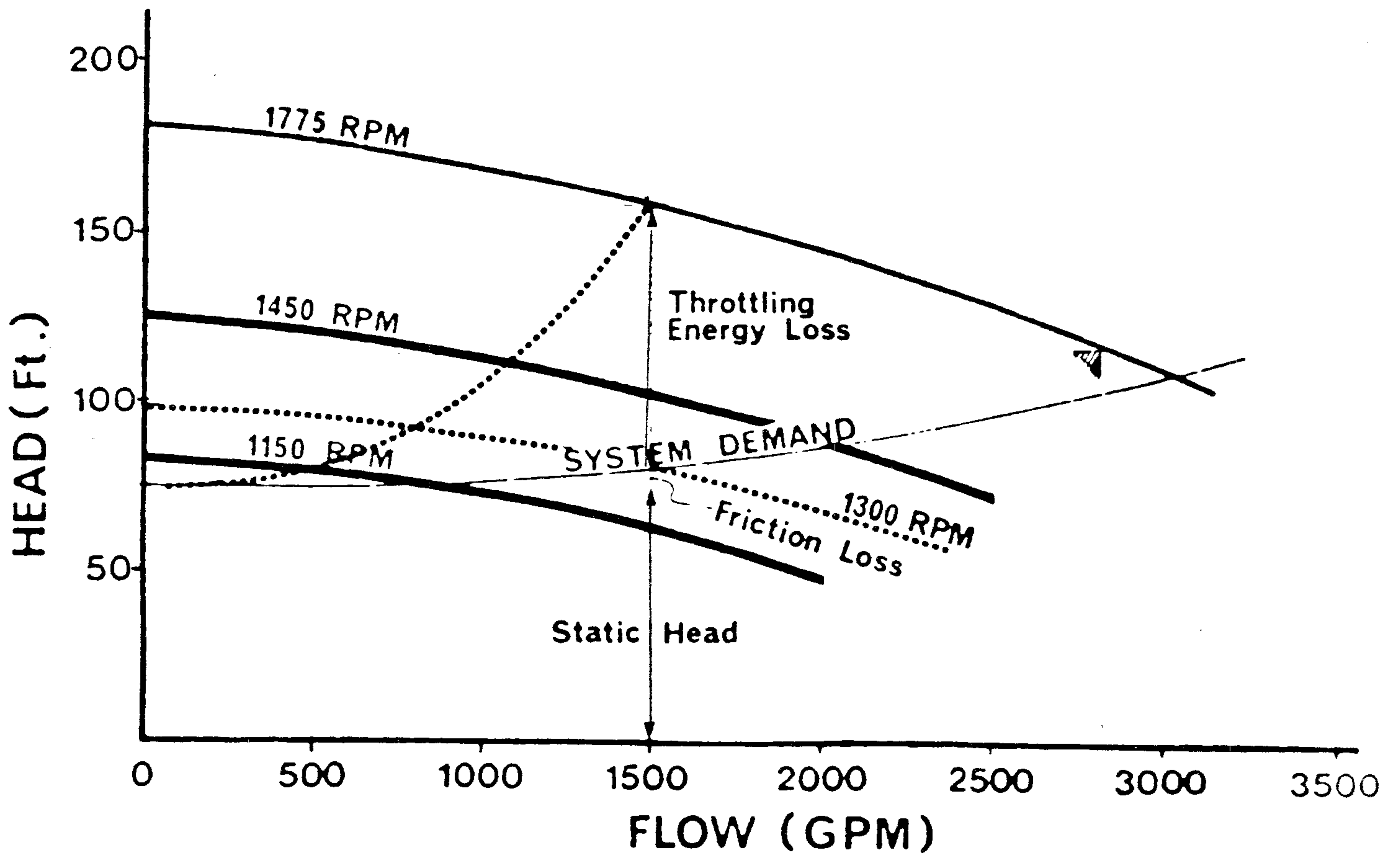


FIG. 5

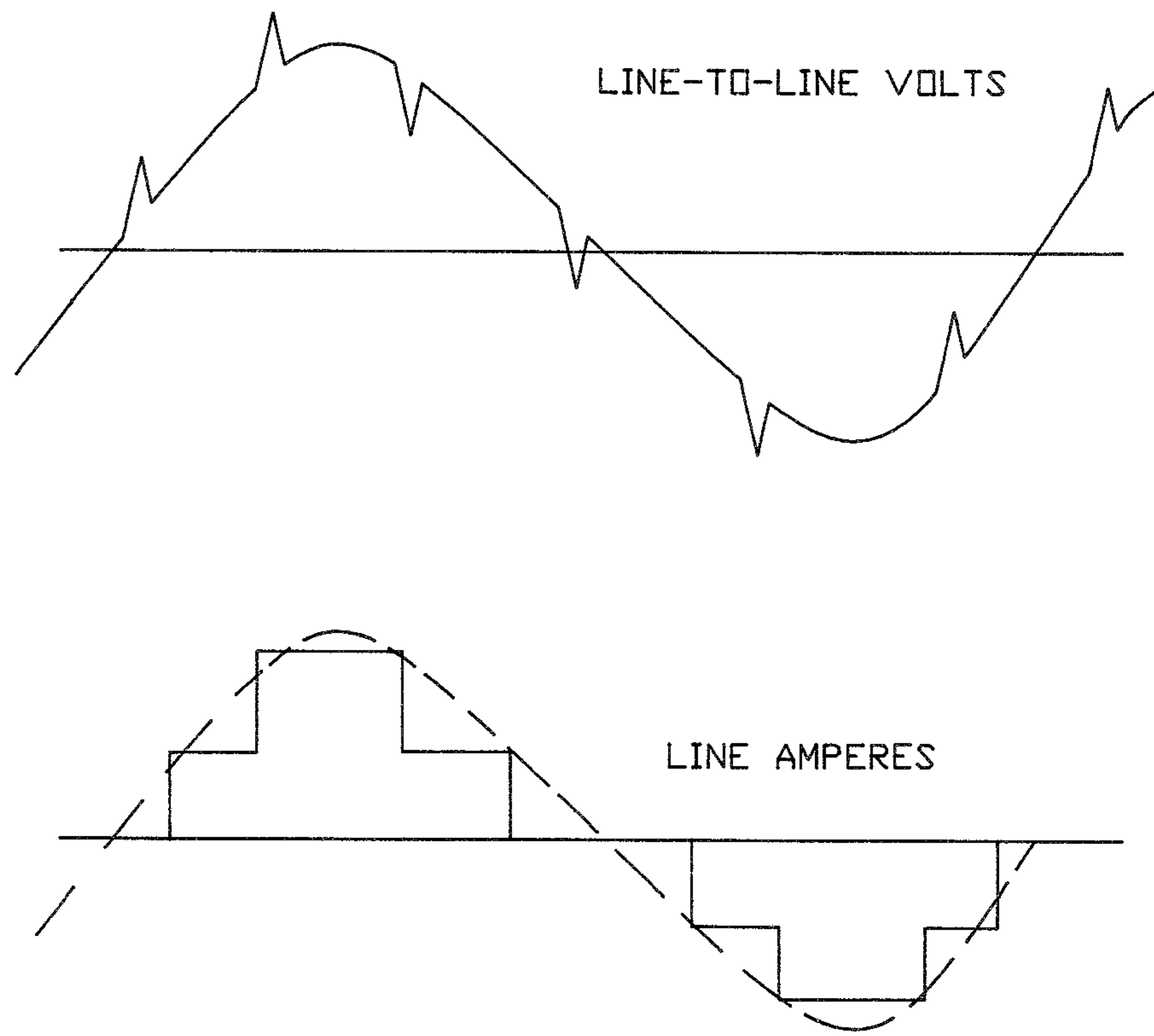
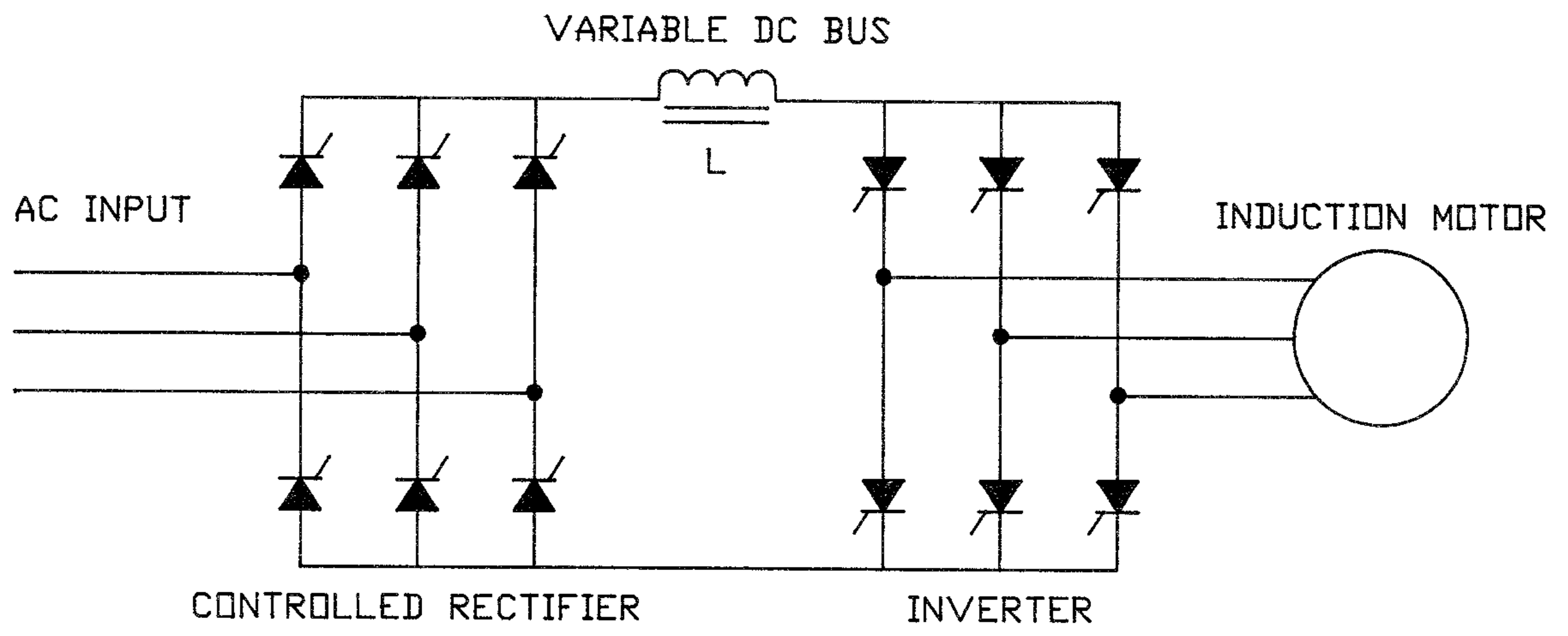


FIG. 6. CURRENT-SOURCE INVERTER

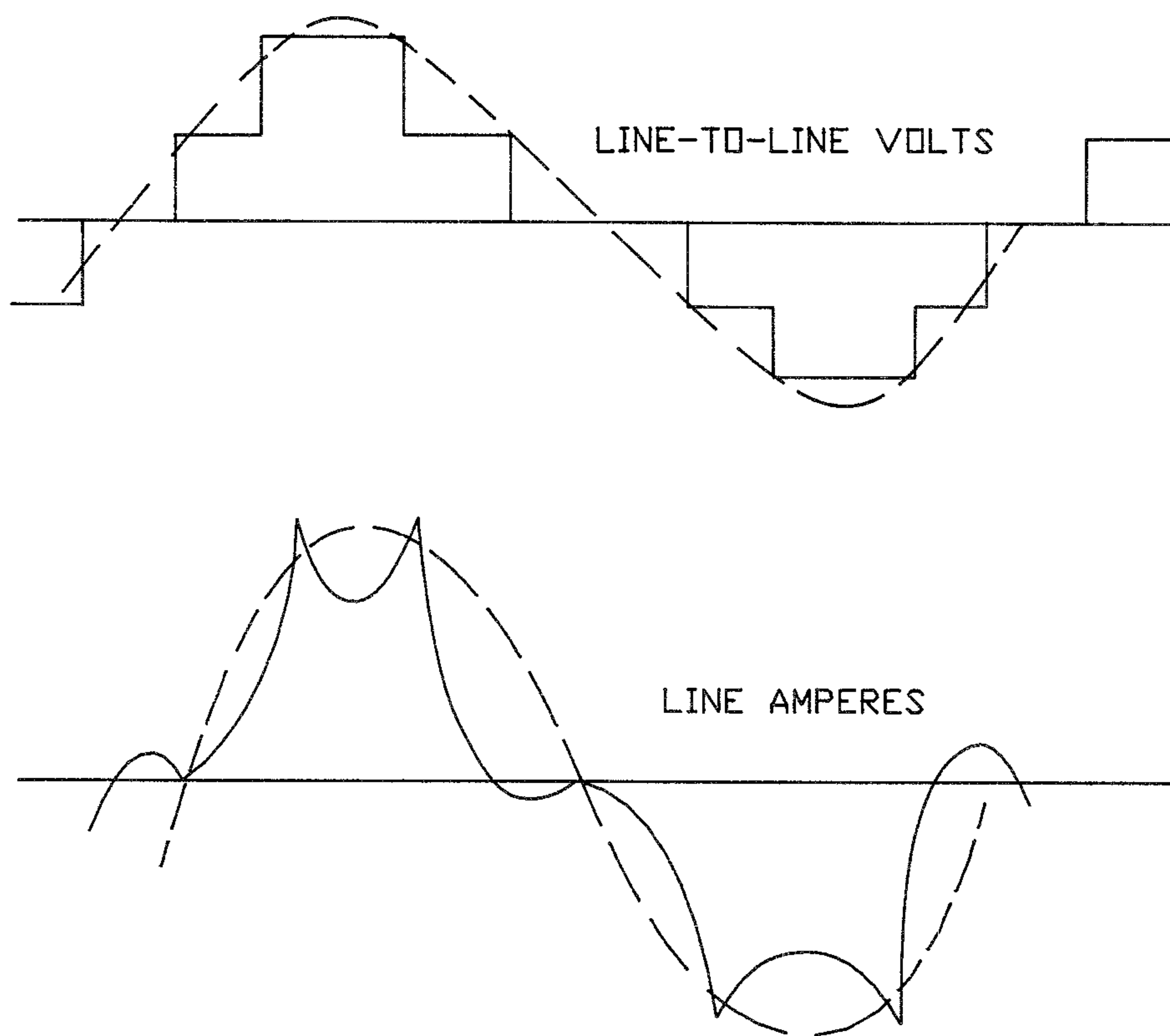
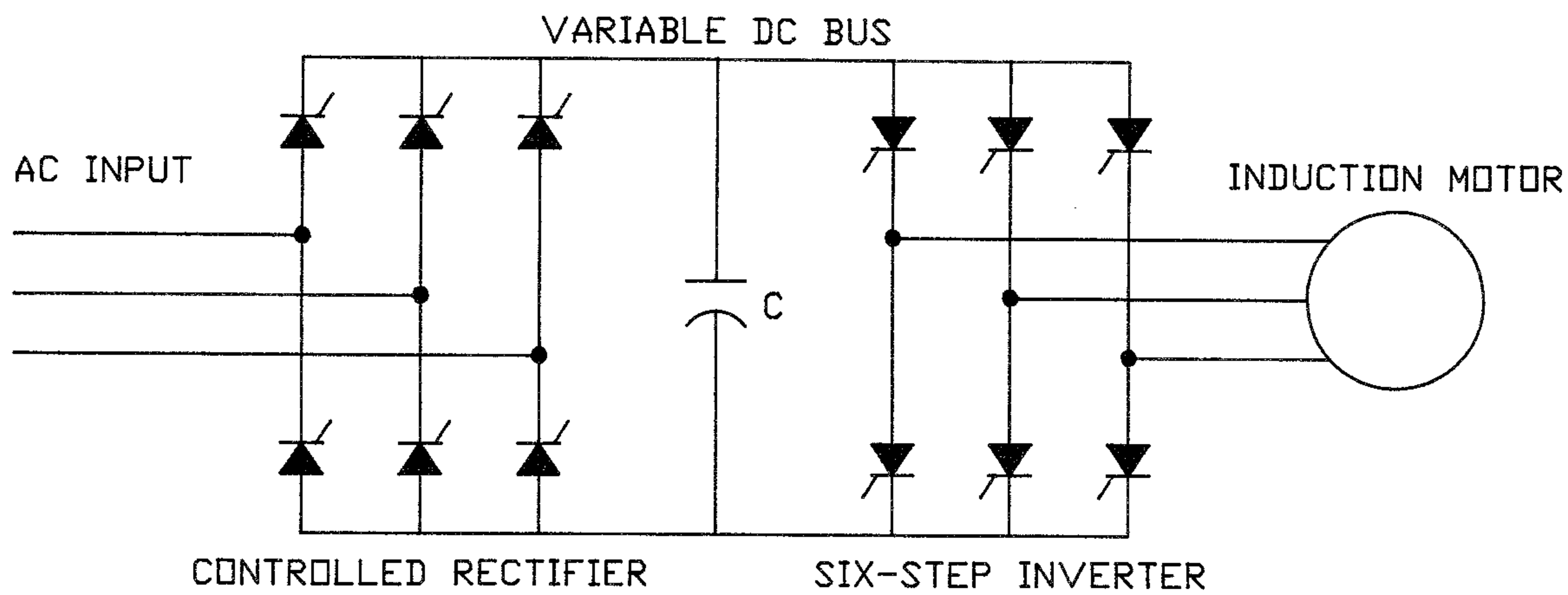


FIG. 7. VOLTAGE-SOURCE SIX-STEP INVERTER

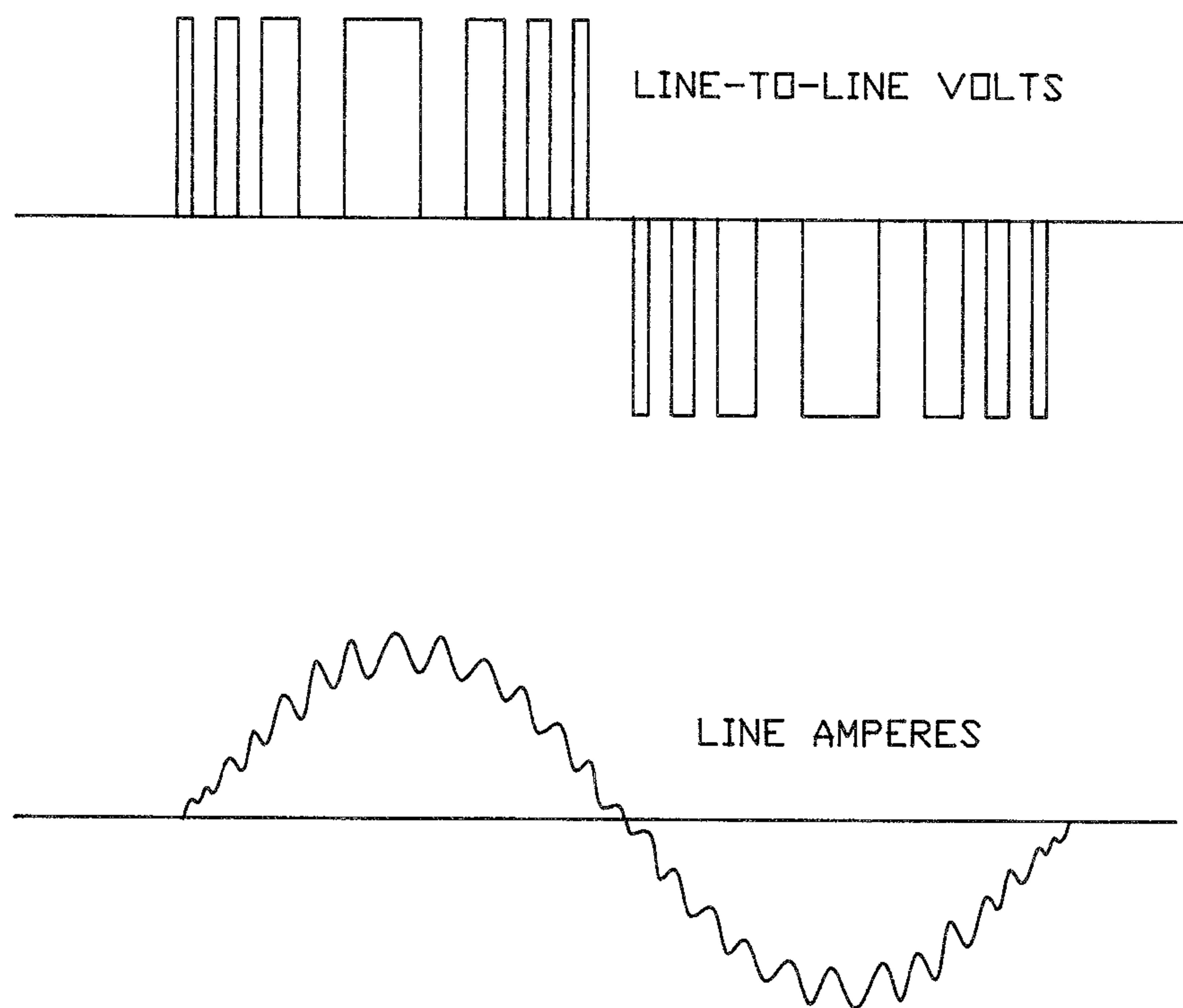
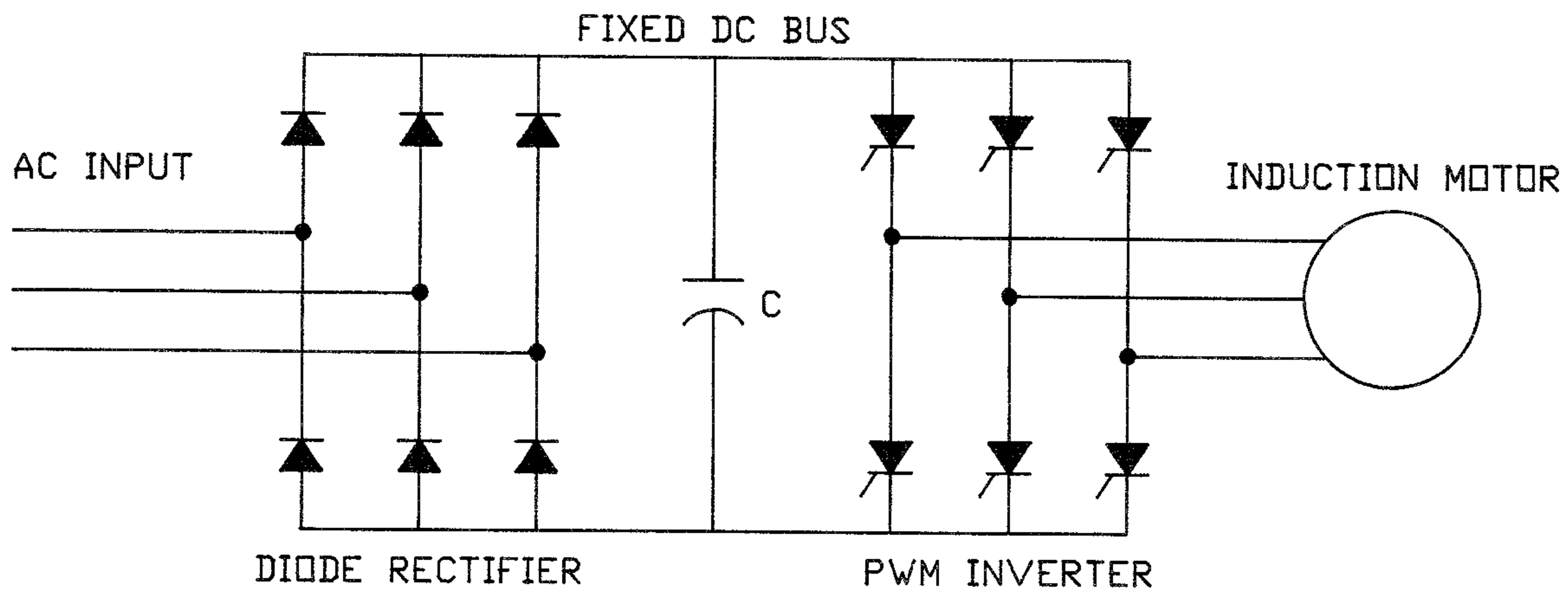


FIG. 8. PULSE-WIDTH MODULATED INVERTER

TABLE 1

HARMONIC VOLTAGE DISTORTION LIMITS

Power System Voltage Level	Dedicated System Converter	General Power Systems
460 V	10%	5%
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

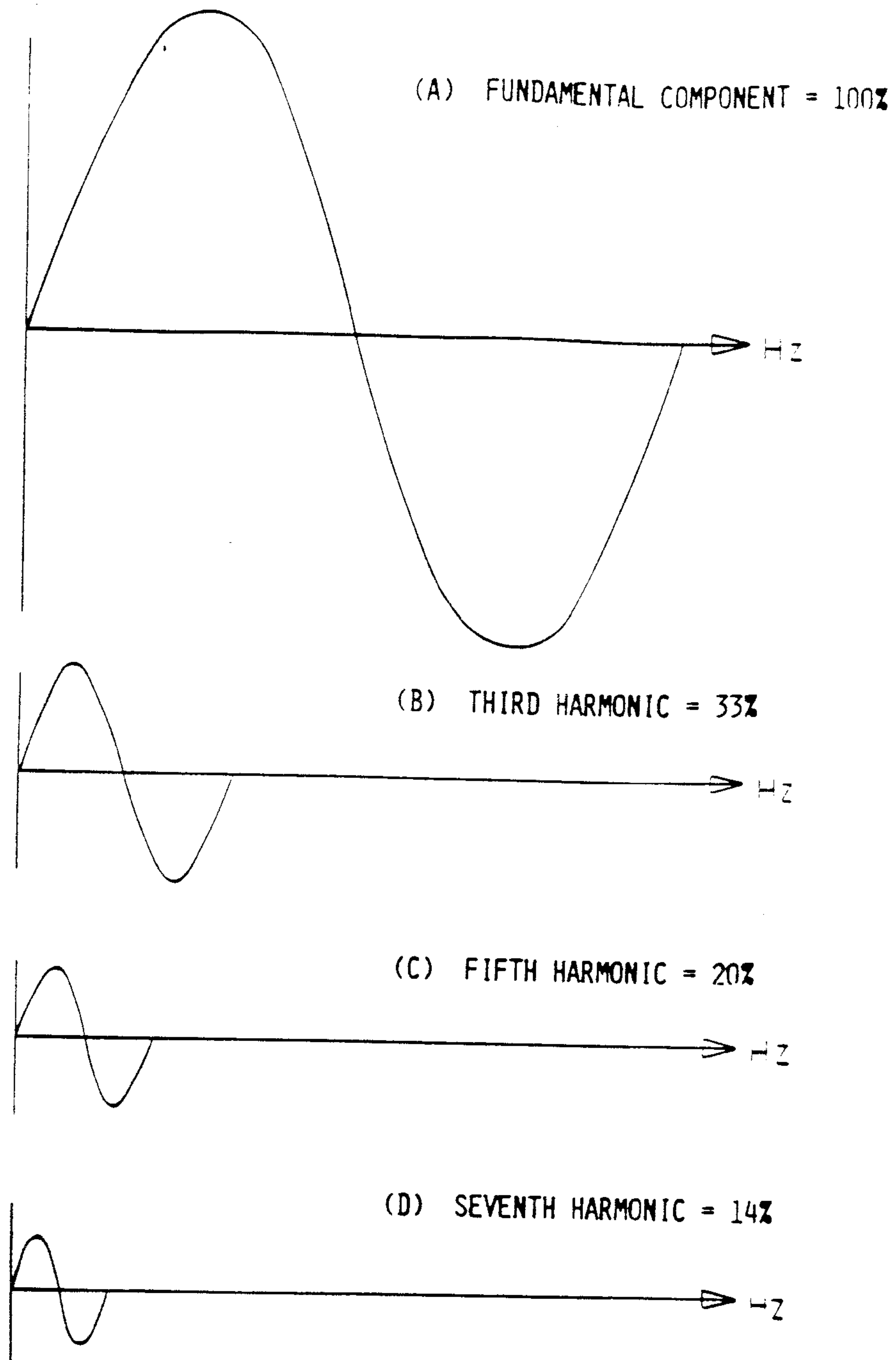


FIG. 9. COMPONENTS OF SQUARE WAVE:

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

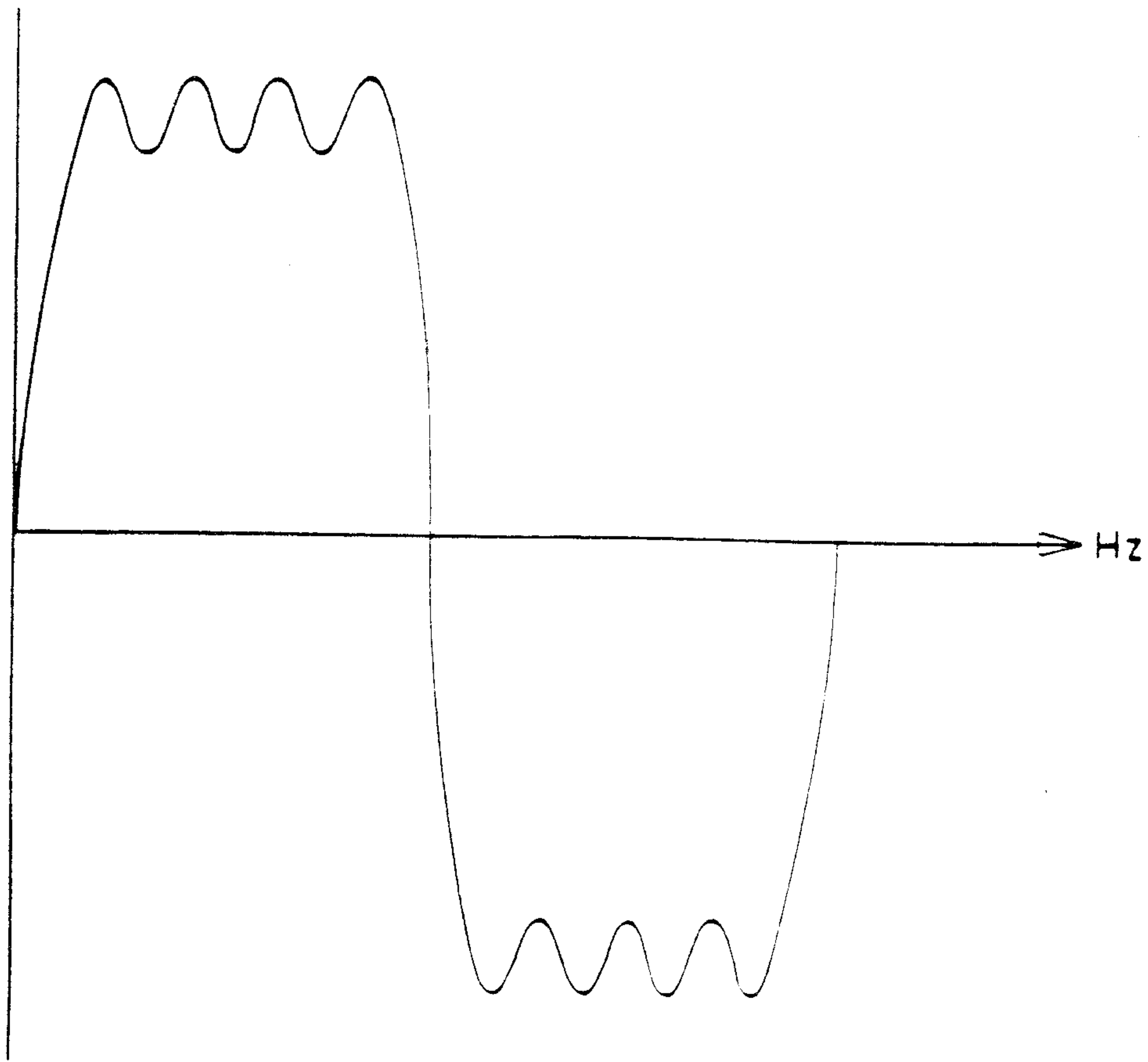


FIG. 10. WAVEFORM RESULTING FROM ADDING FUNDAMENTAL + 3RD + 5TH + 7TH HARMONIC COMPONENTS ALL BEING IN PHASE AND EACH HARMONIC OF A MAGNITUDE INVERSE TO ITS ORDER.

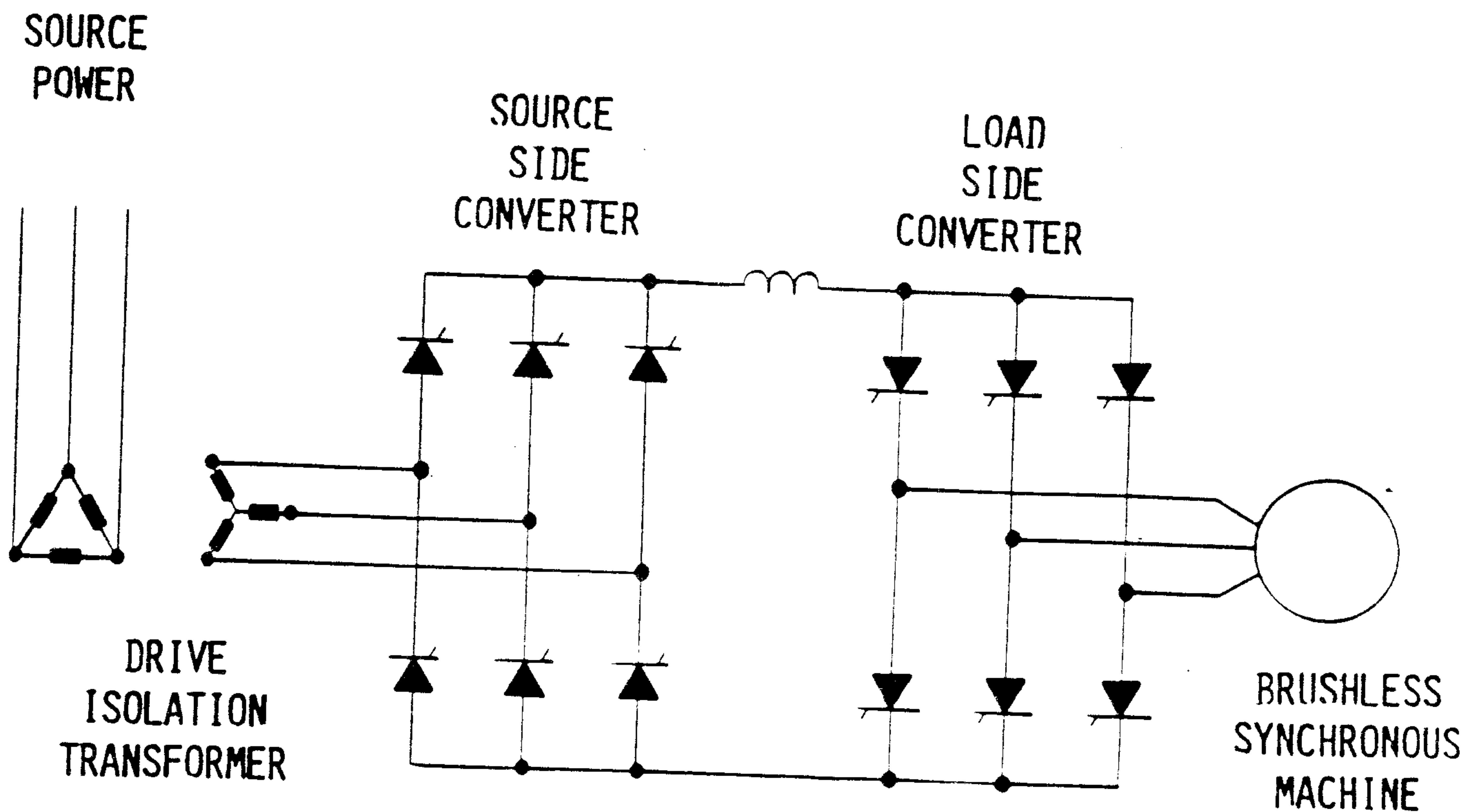


FIG. 11. BASIC CIRCUIT FOR THE SYNCHRONOUS MACHINE ADJUSTABLE SPEED DRIVE SYSTEM. 6-PULSE CONNECTED TO 3-PHASE MACHINE.

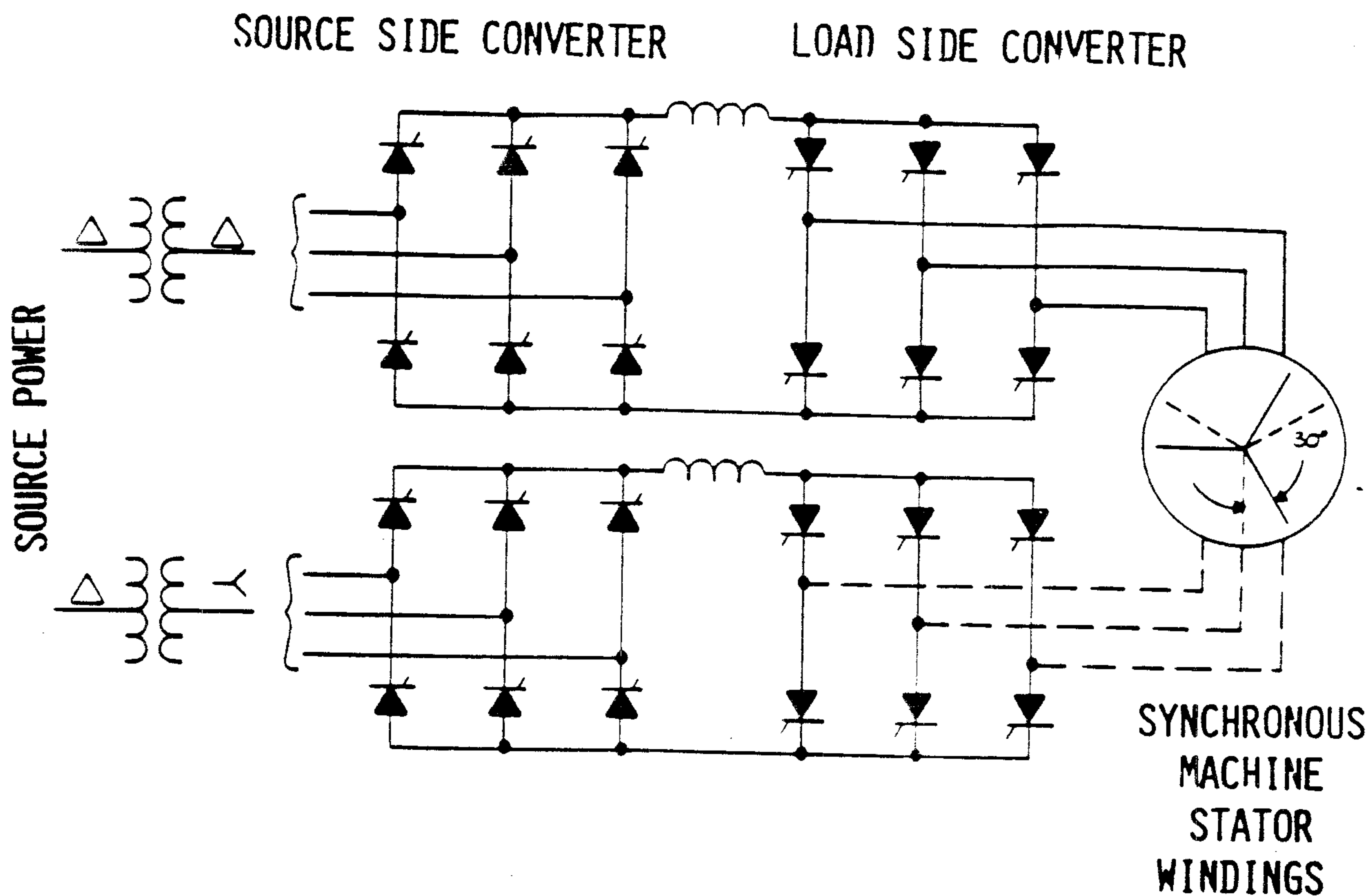


FIG. 12. BASIC CIRCUIT FOR THE SYNCHRONOUS MACHINE ADJUSTABLE SPEED DRIVE SYSTEM. 12-PULSE CONNECTED TO 6-PHASE MACHINE.

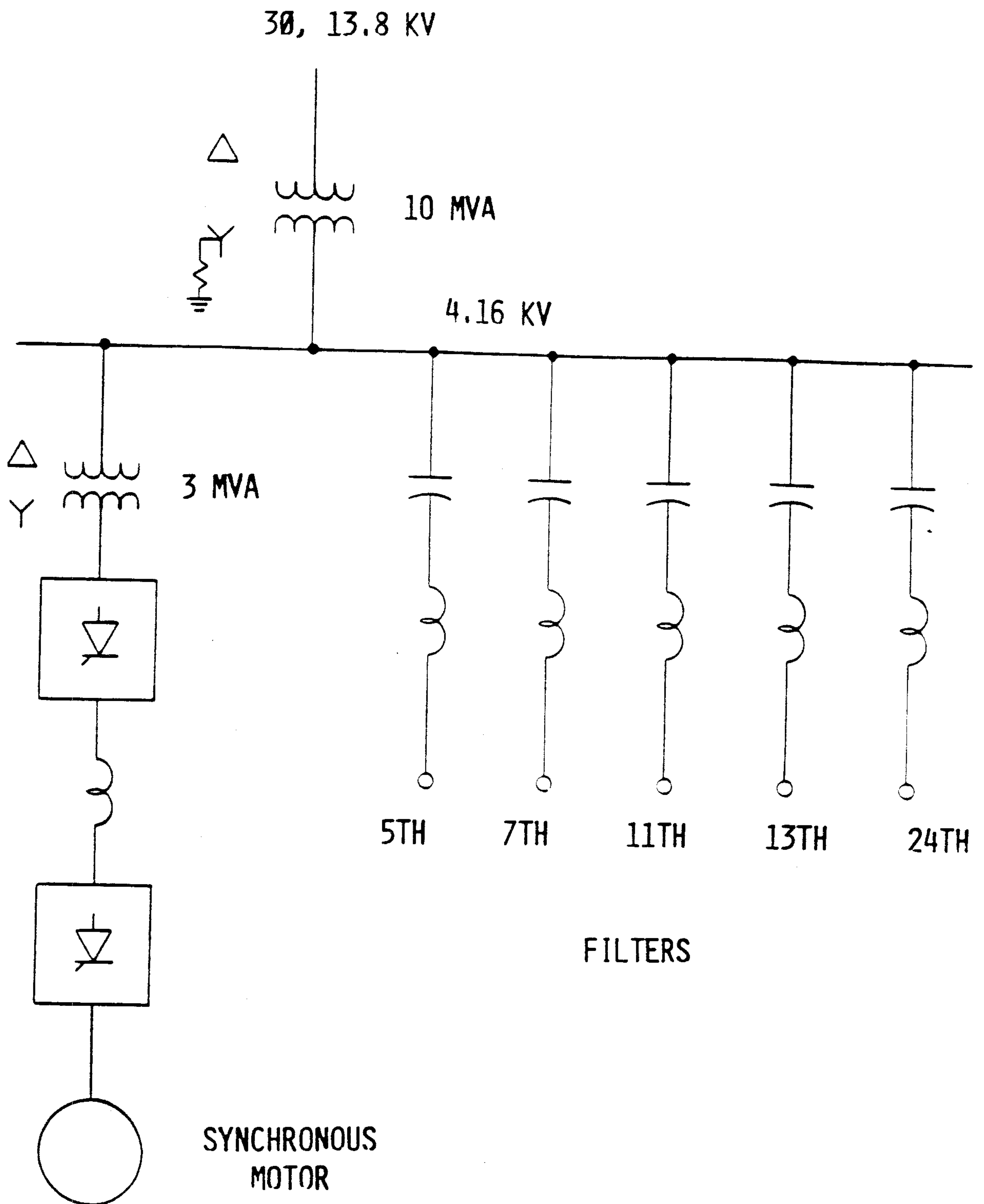


FIG. 13. SIMPLIFIED SINGLE LINE DIAGRAM FOR 2.3 MW ADJUSTABLE SPEED DRIVE HAVING 6-PULSE SYSTEM CONNECTED TO 3-PHASE BRUSHLESS SYNCHRONOUS MOTOR.

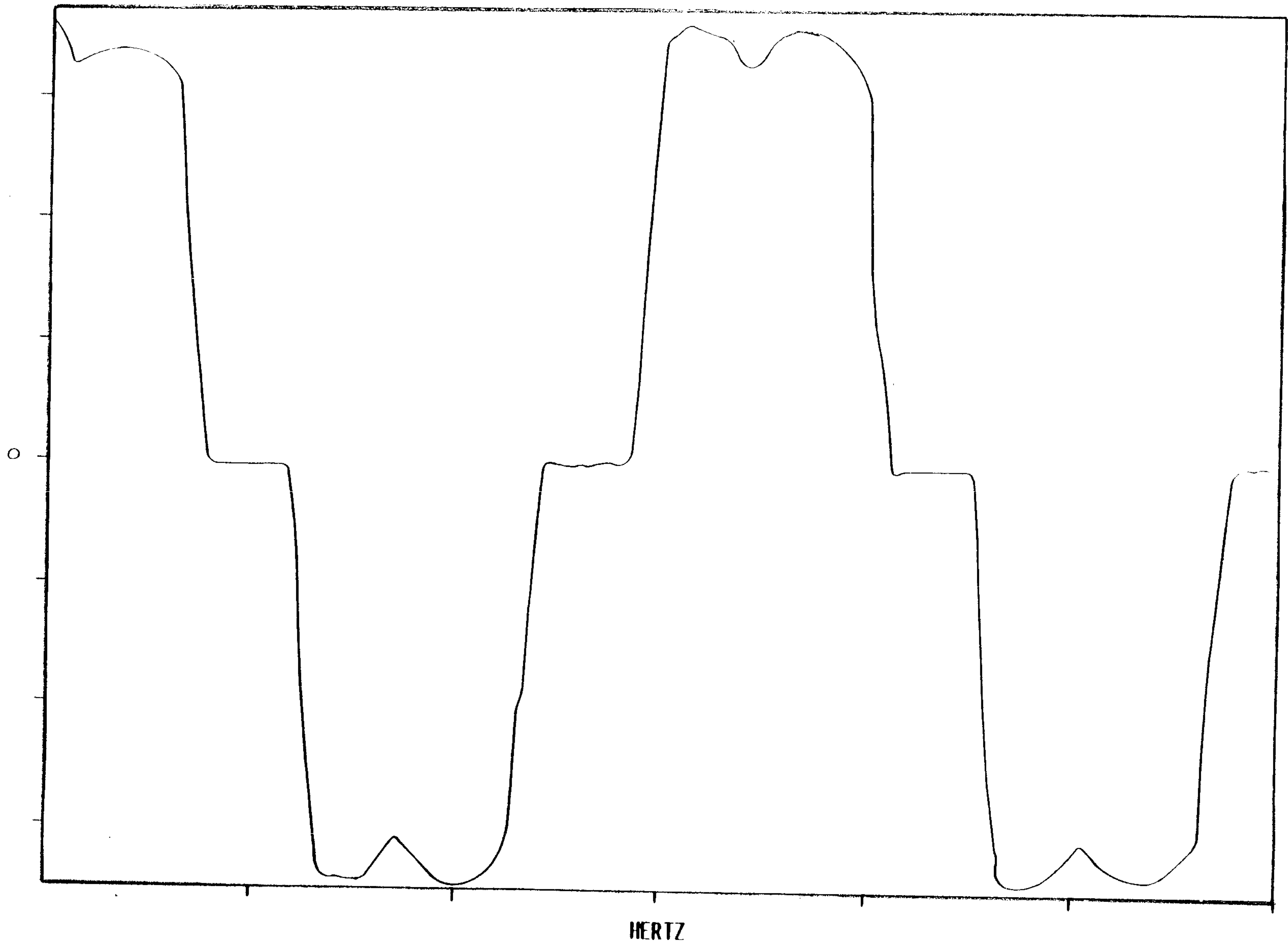


FIG. 14. CURRENT WAVEFORM FOR 3-PHASE SYNCHRONOUS MOTOR RATED AT 2.3 MW,
1000 V, 1800 RPM.

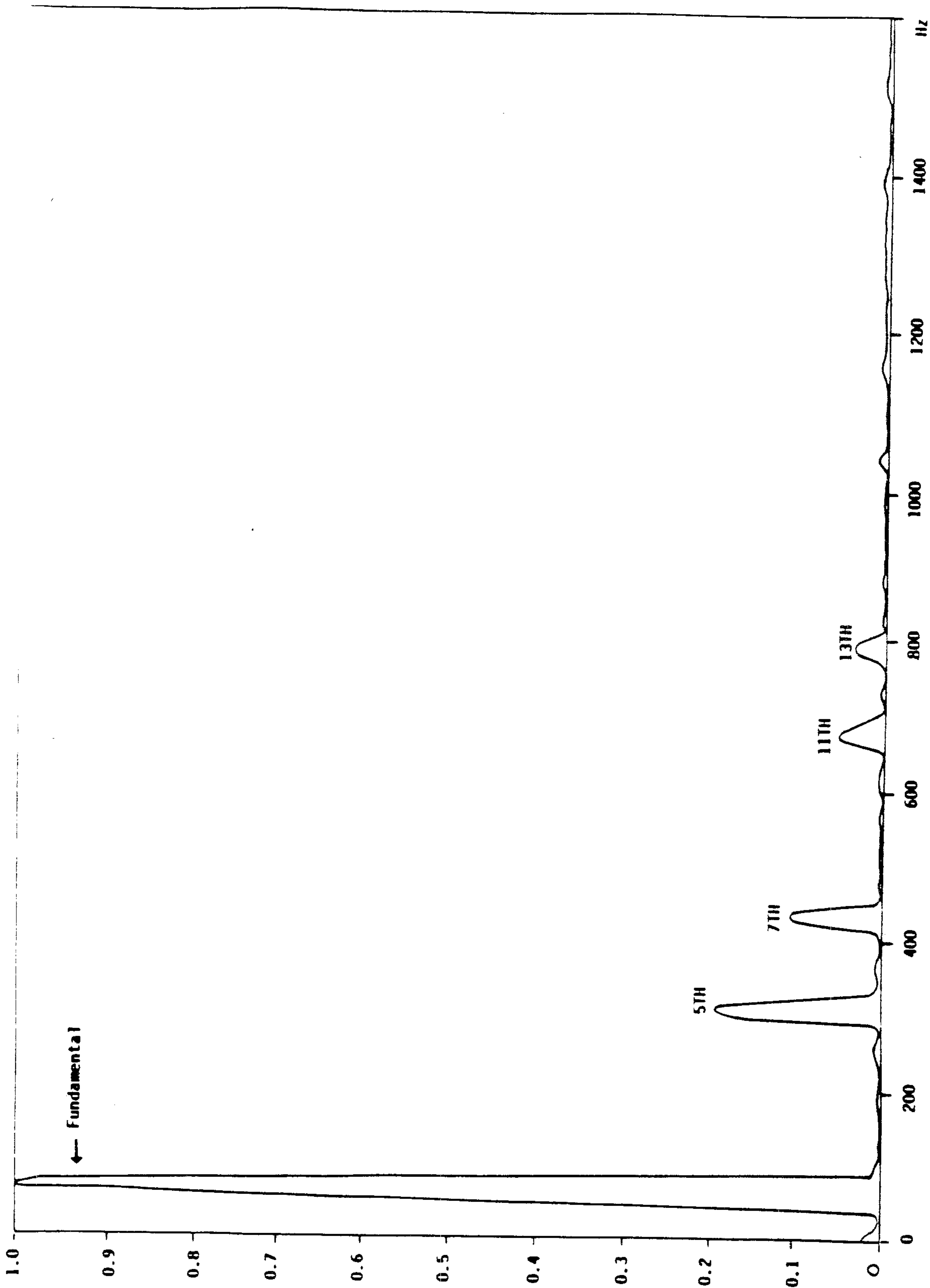


FIG. 15. HARMONIC COMPONENTS FOR CURRENT WAVEFORM IN FIGURE 6. 14.

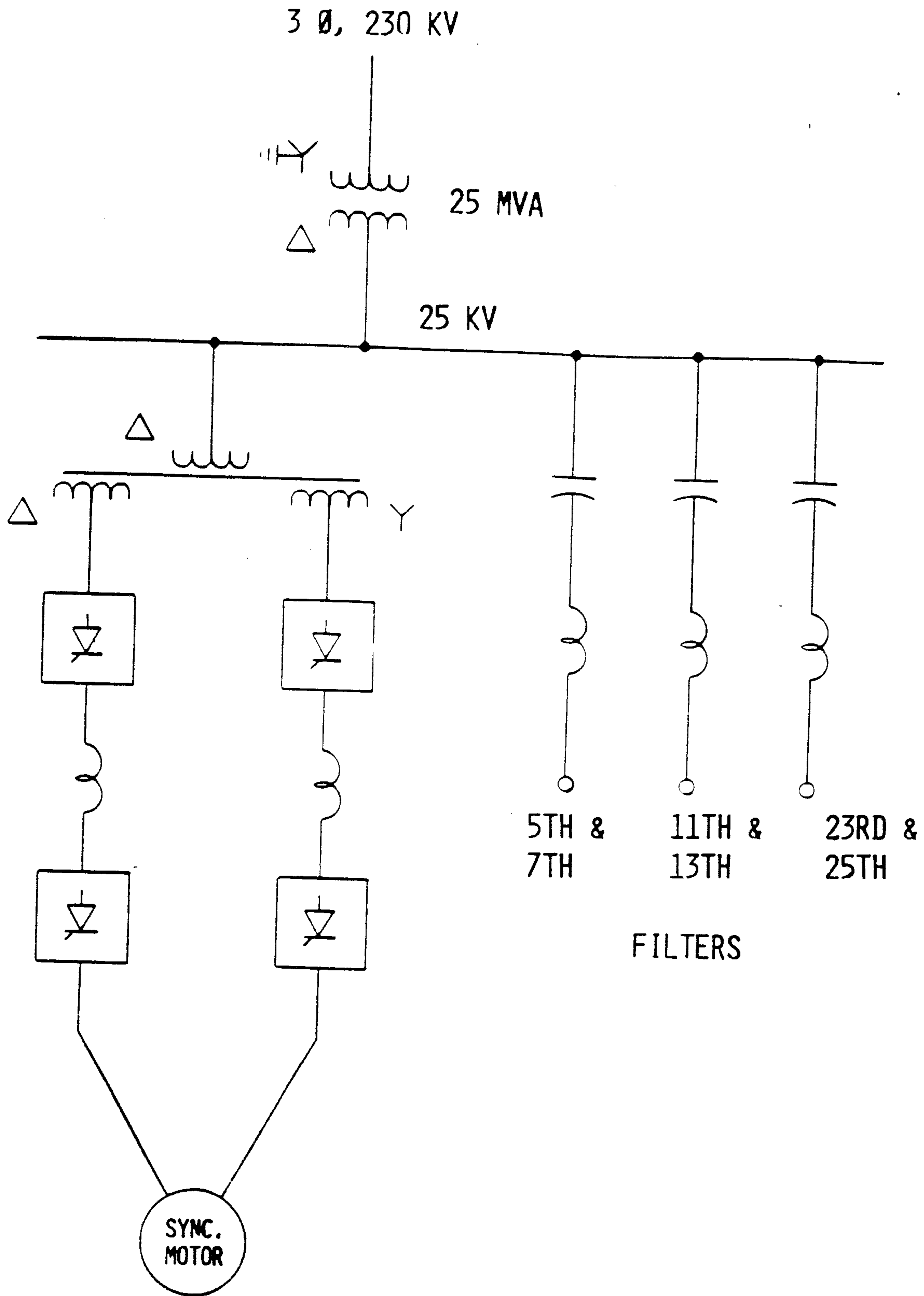


FIG. 16. SIMPLIFIED SINGLE LINE DIAGRAM FOR 17 MW ADJUSTABLE SPEED DRIVE HAVING 12-PULSE SYSTEM CONNECTED TO 6-PHASE BRUSHLESS SYNCHRONOUS MOTOR.

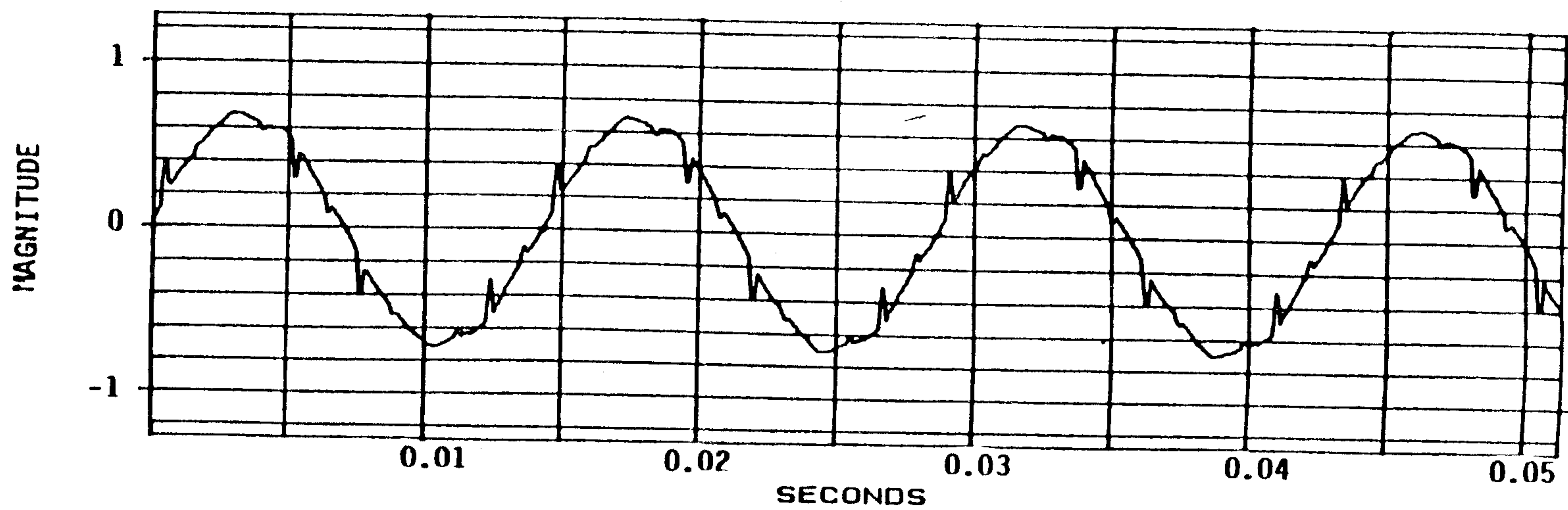
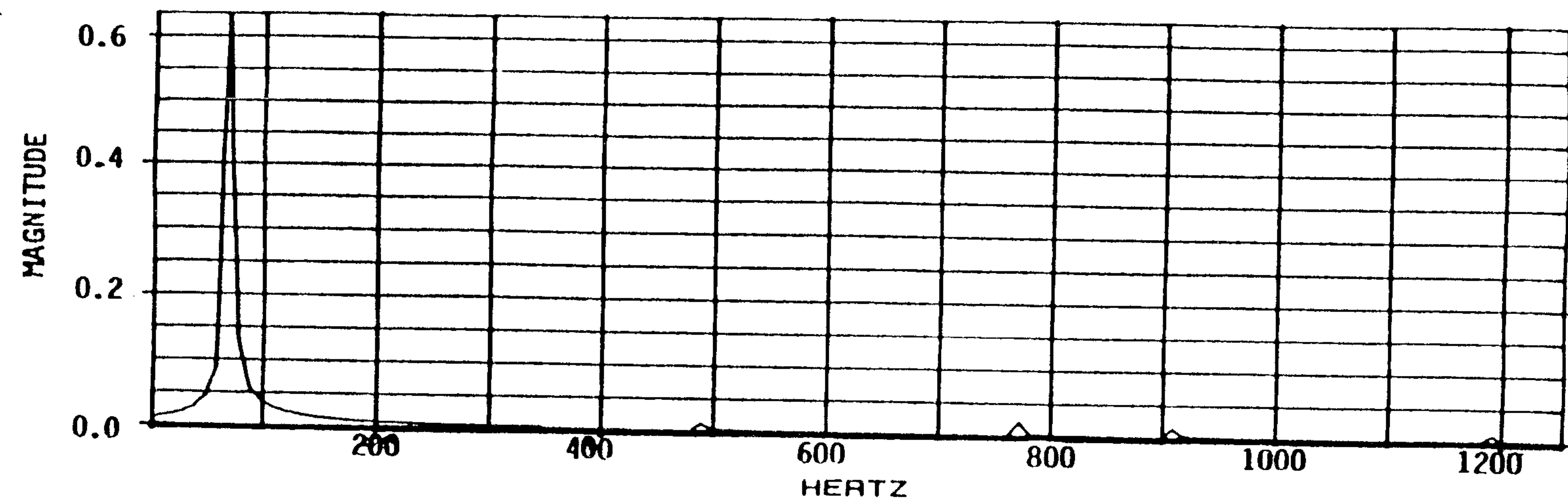
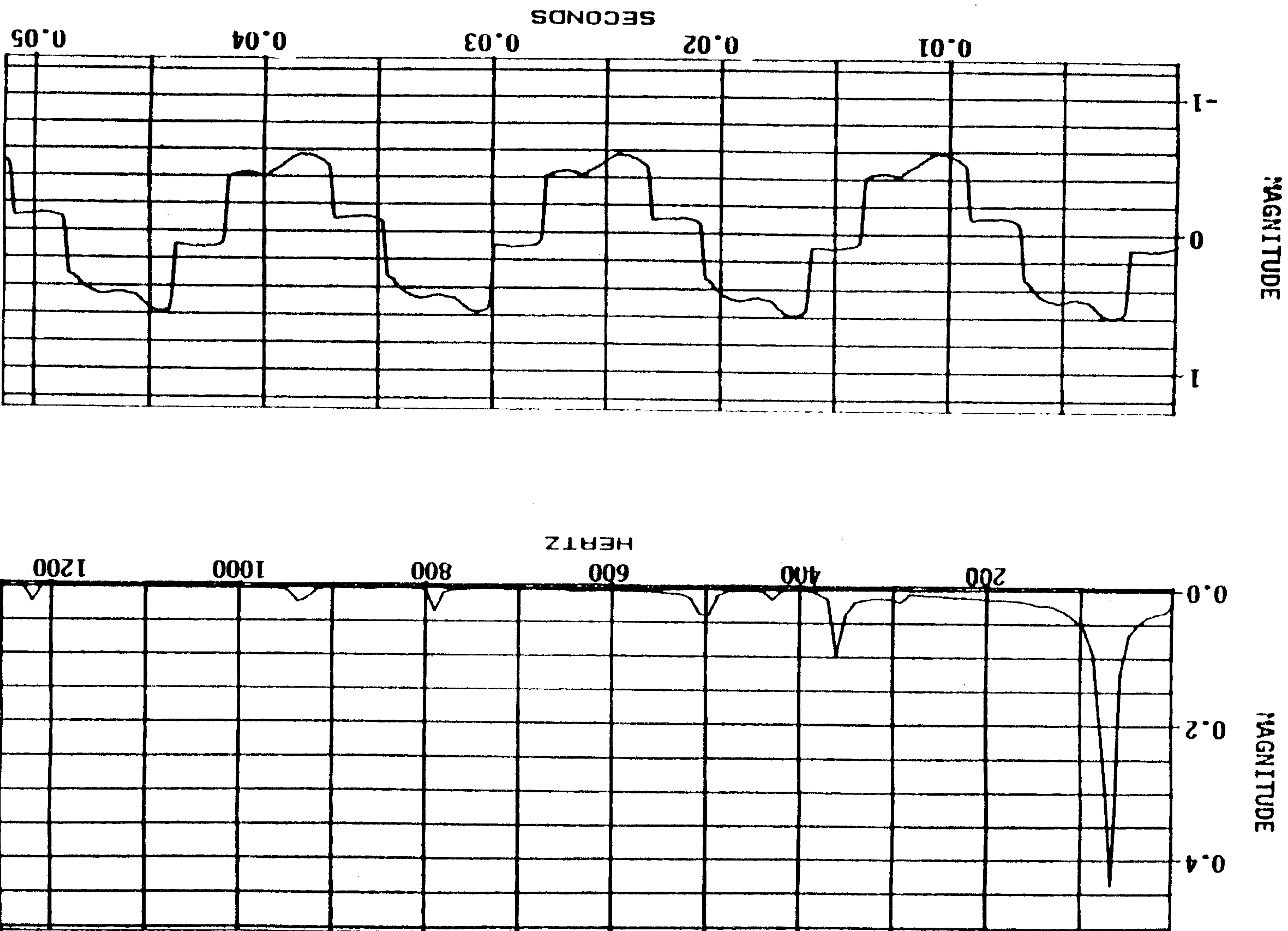


FIG. 17. VOLTAGE WAVEFORM AND ITS HARMONIC SPECTRUM FOR 6-PHASE SYNCHRONOUS MOTOR RATED AT 17 MW, 7200 V, 6000 RPM.

FIG. 18. CURRENT WAVEFORM AND ITS HARMONIC SPECTRUM FOR 6-PHASE SYNCHRONOUS MOTOR RATED AT 17 MW, 7200 V, 6000 RPM.



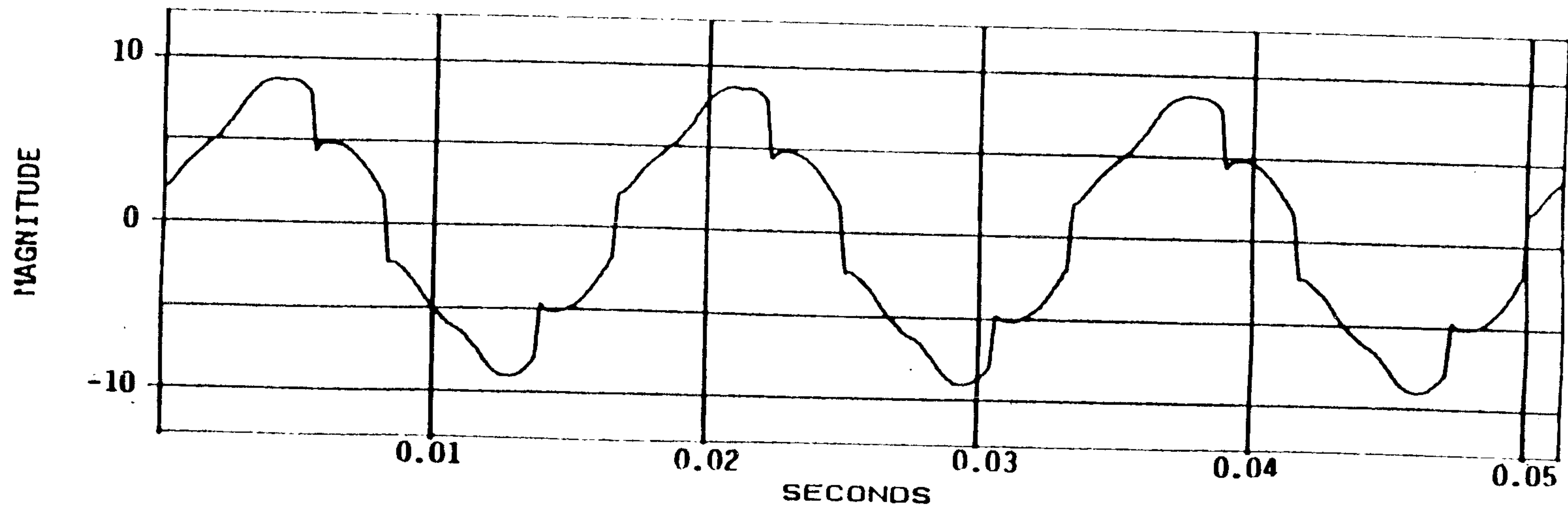
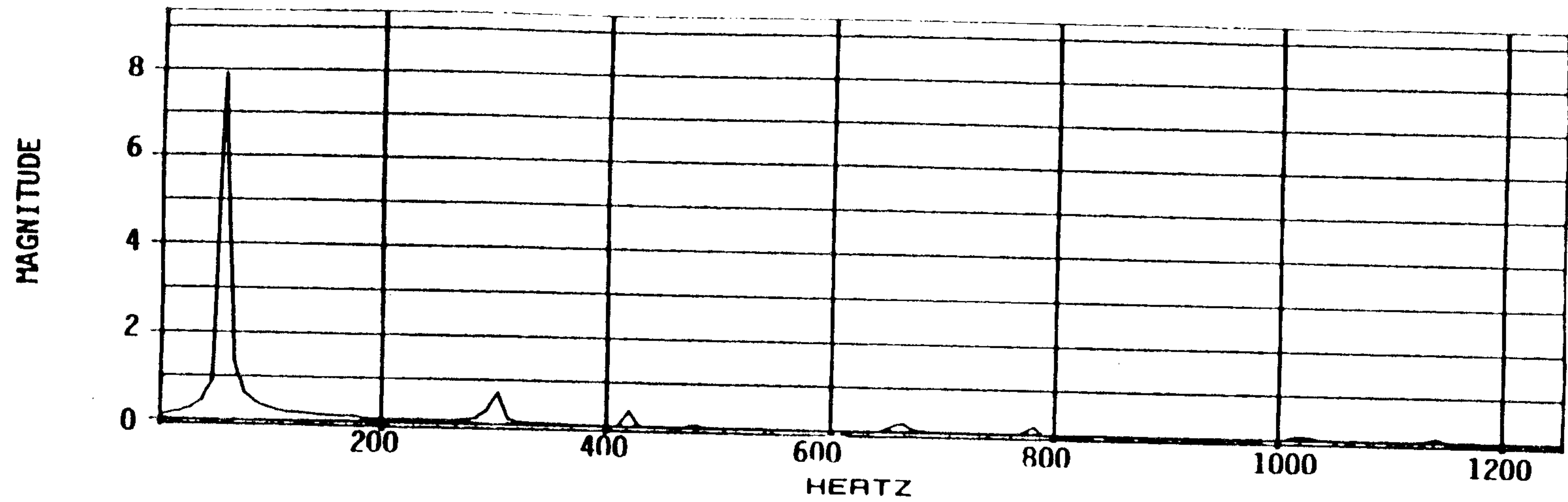
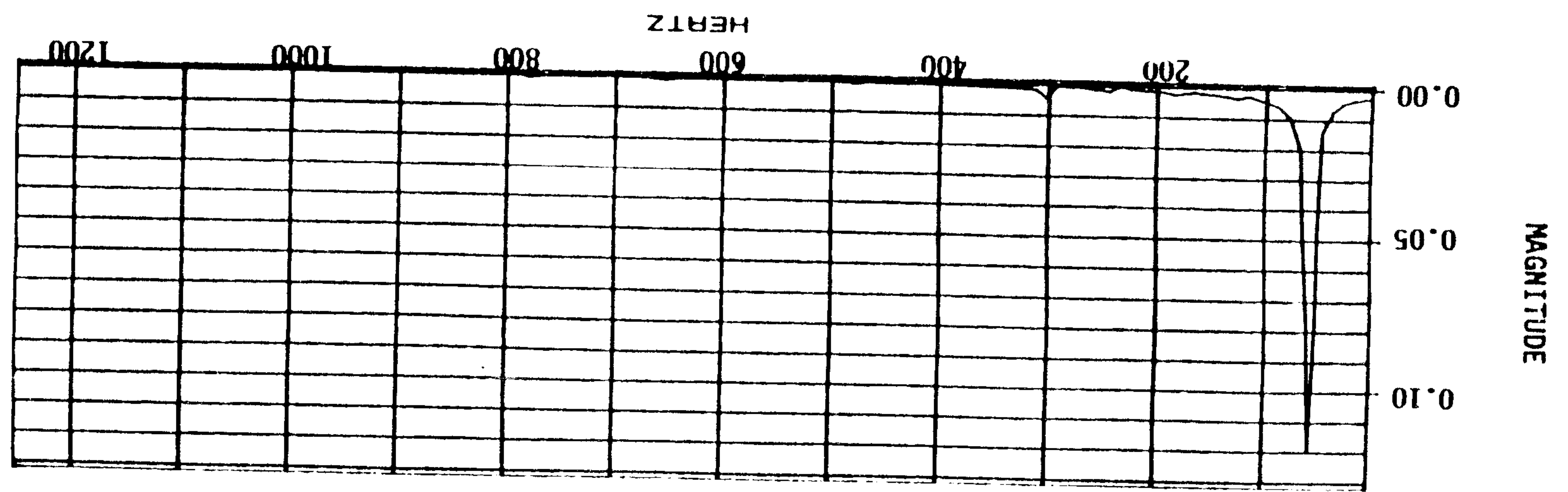
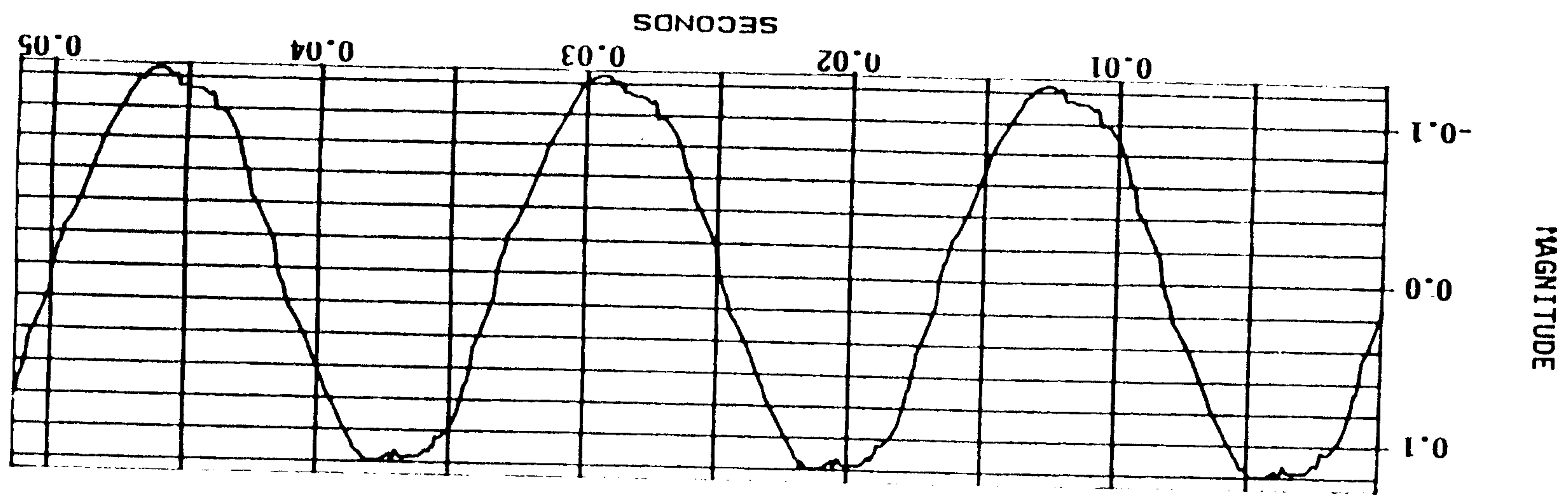


FIG. 19. CONVERTER TRANSFORMER SECONDARY CURRENT IN 12-PULSE SYSTEM.

FIG. 20. INCOMING LINE CURRENT TO 25 KV BUS.



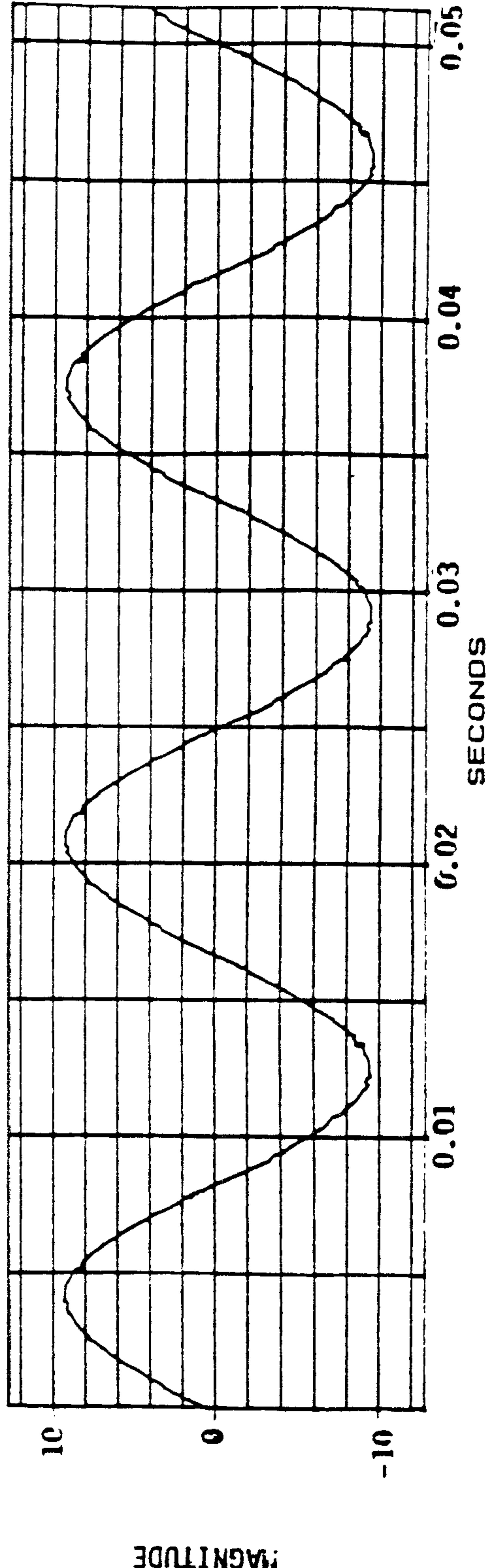
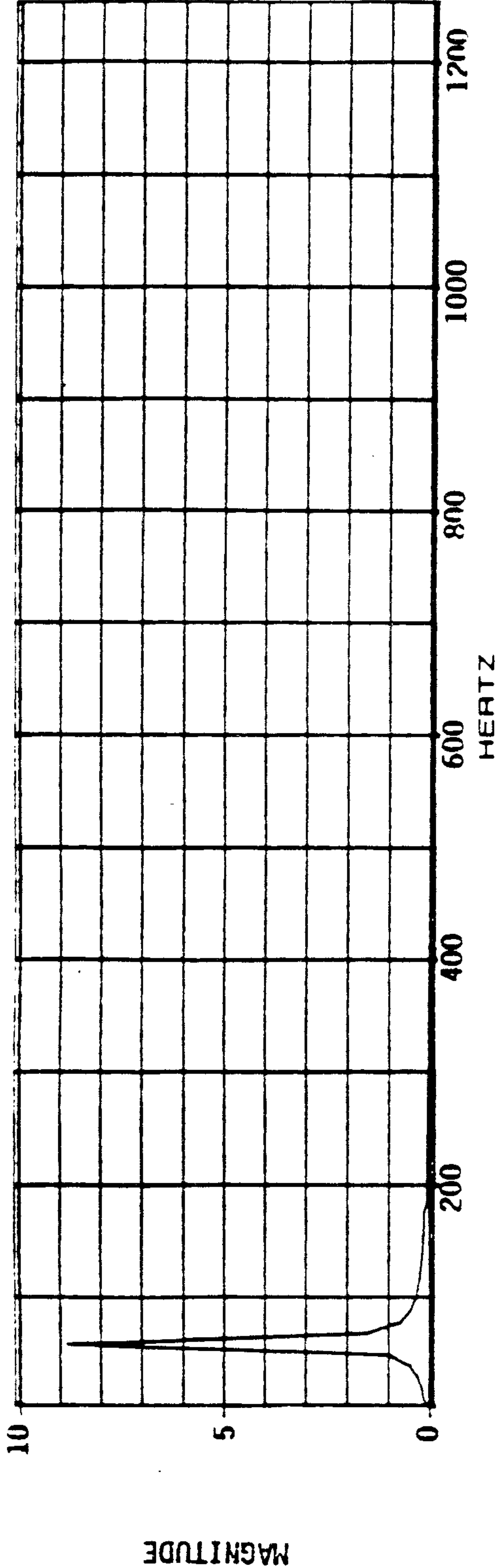


FIG. 21. VOLTAGE AT 25 KV BUS WITH FILTERS CONNECTED.

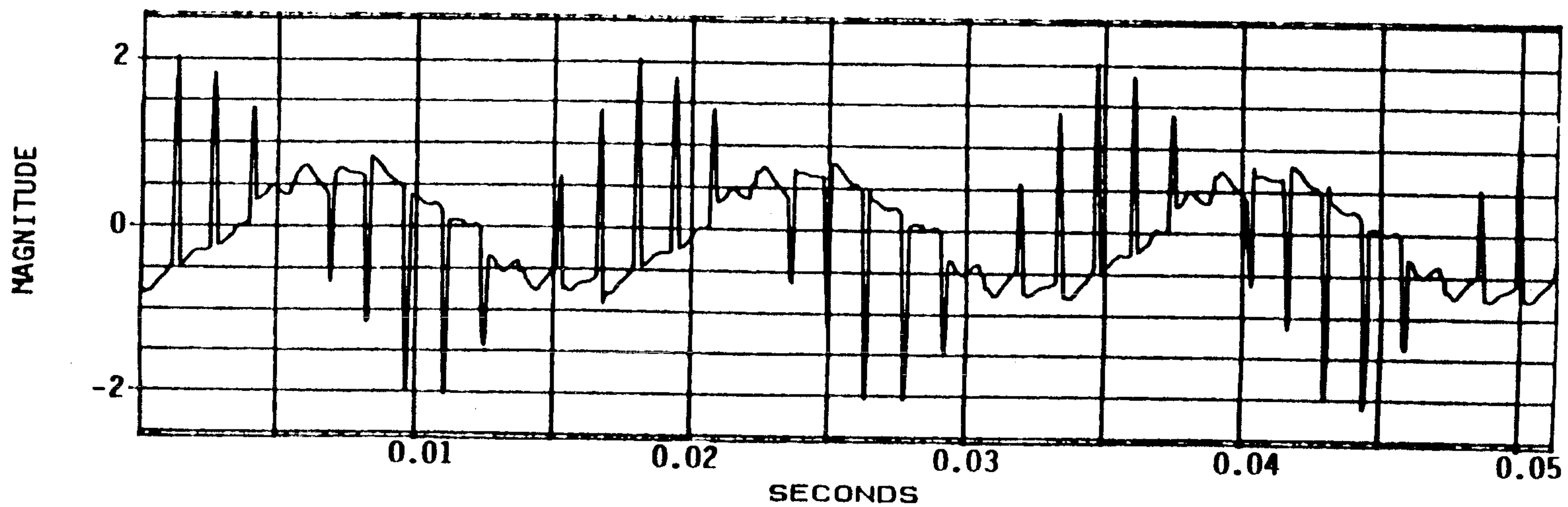
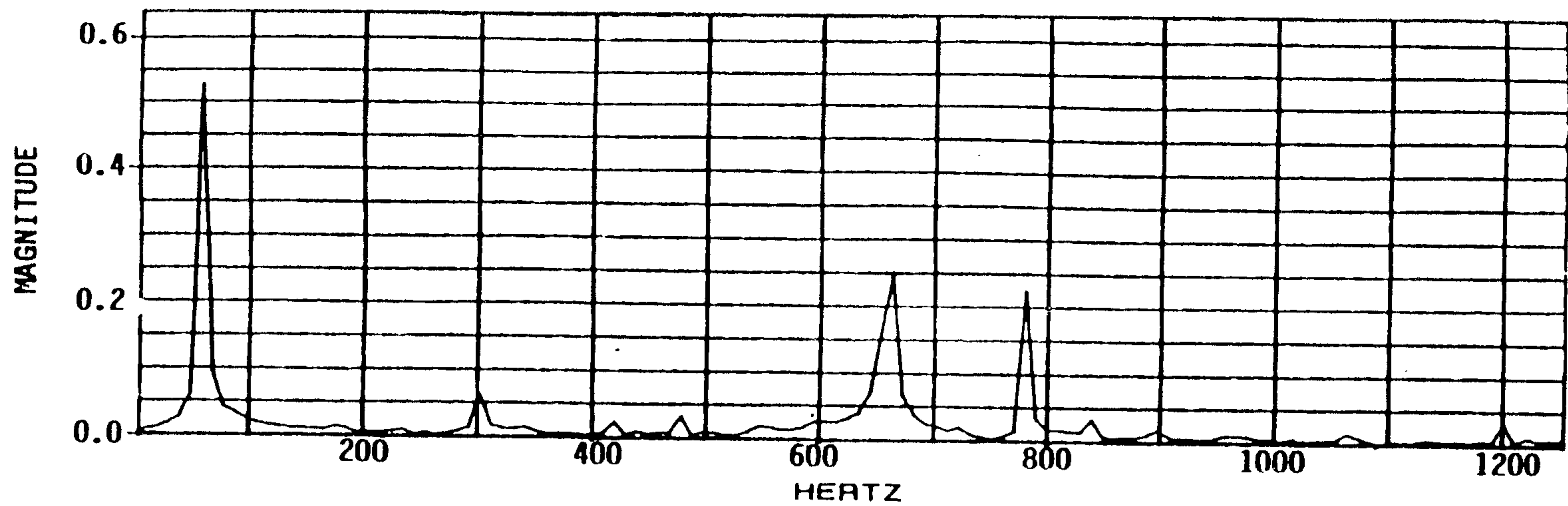


FIG. 22. TOTAL CURRENT IN HARMONIC FILTERS CONNECTED TO 25 KV BUS.