

[54] **CYCLOCONVERTER ARRANGEMENTS WHICH PREVENT CIRCULATING CURRENTS**

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[22] Filed: **Mar. 25, 1970**
[21] Appl. No.: **22,600**

[30] **Foreign Application Priority Data**
Apr. 2, 1969 Great Britain.....17,420/69
[52] U.S. Cl.....**318/227, 318/231, 321/7, 321/66**
[51] Int. Cl.....**H02p 5/40, H02m 5/14**
[58] Field of Search.....**321/7, 60, 61, 65, 66, 69; 318/231, 341, 227**

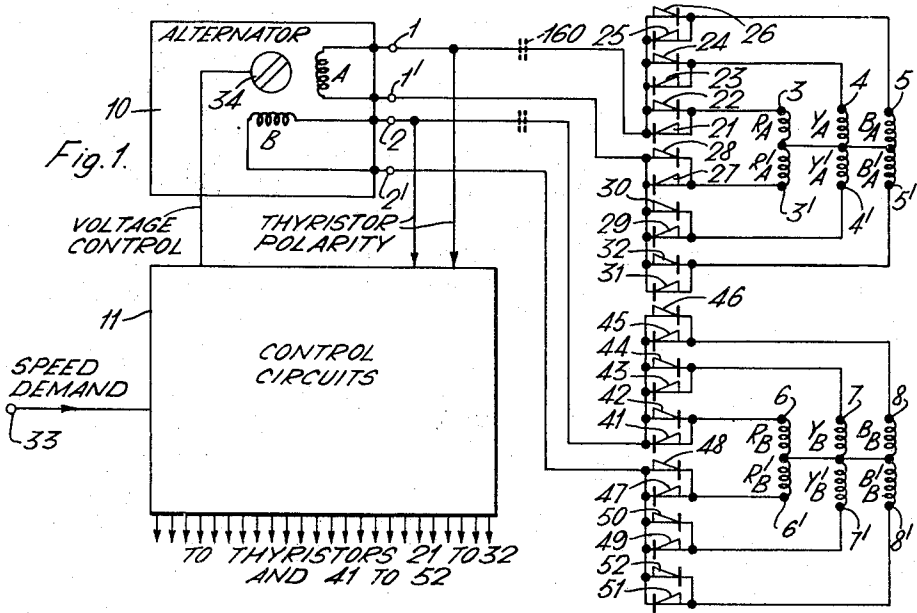
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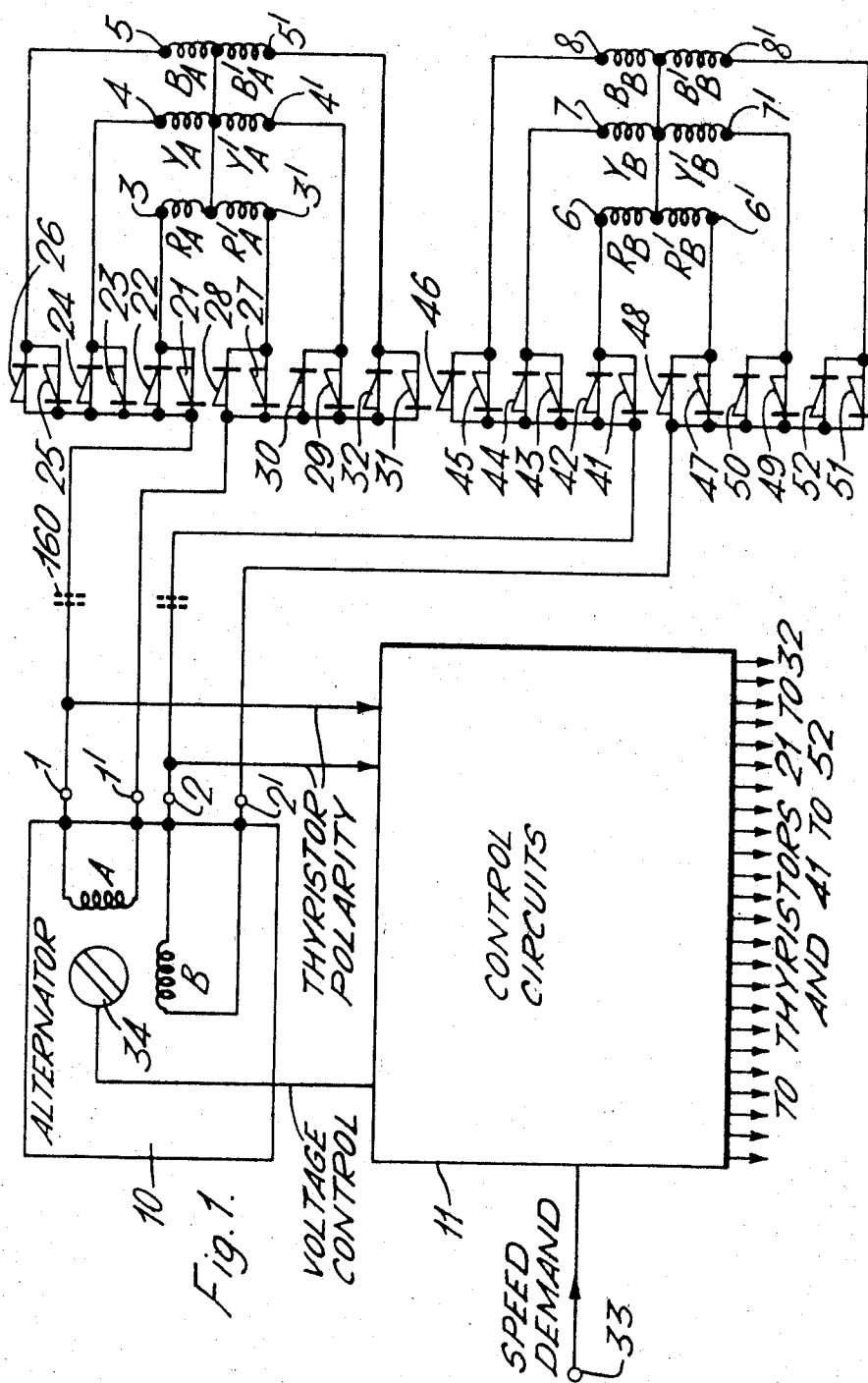
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[57] **ABSTRACT**

A cycloconverter is described in which each supply phase has a separate circuit path to the load, each path having a separate pair of oppositely poled controlled rectifiers. This arrangement prevents circulating currents flowing and thus removes the need for large expensive reactors to limit these currents. Logic circuits for firing the controlled rectifiers both at unitary and at any load power factor are also described.

16 Claims, 11 Drawing Figures





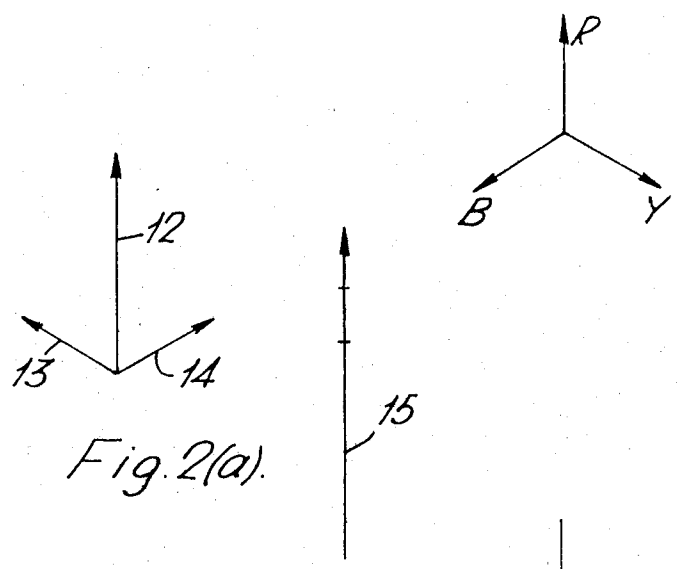


Fig. 2(a).

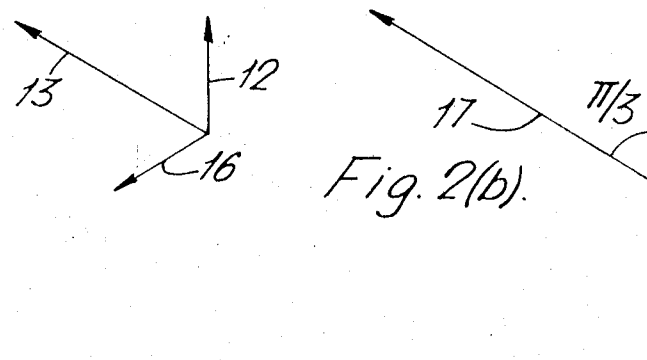


Fig. 2(b).

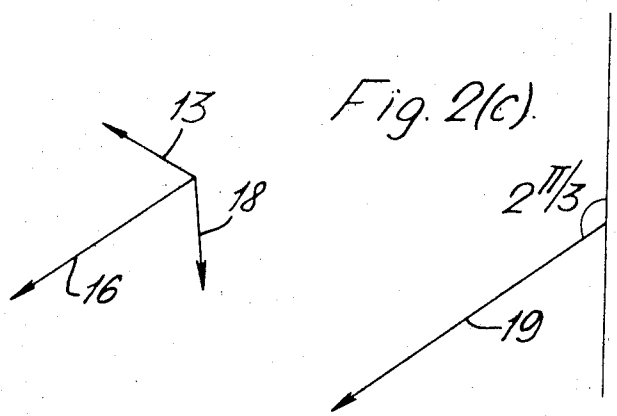


Fig. 2(c).

Fig. 3.

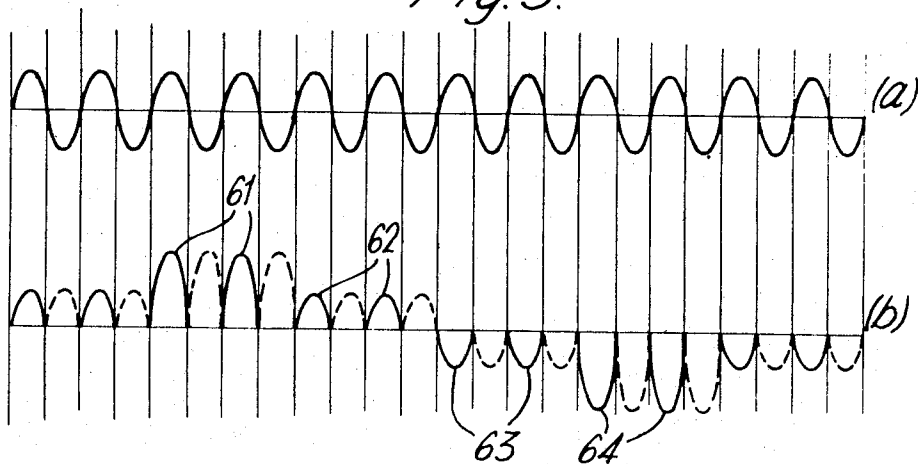
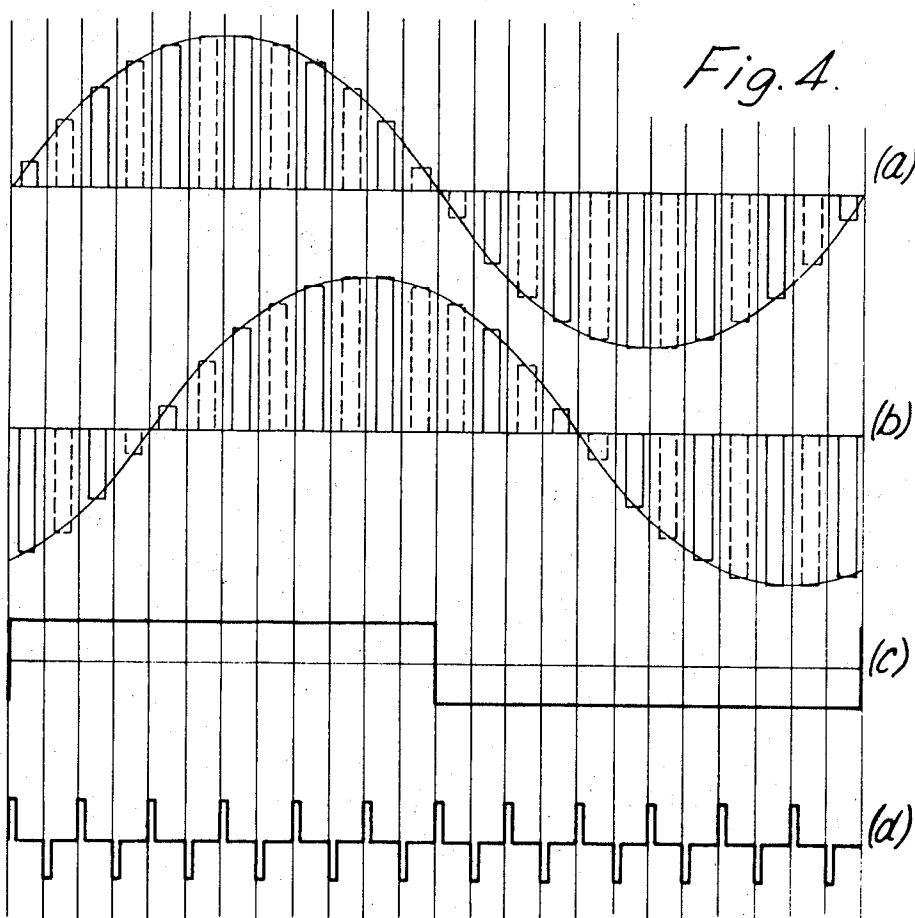
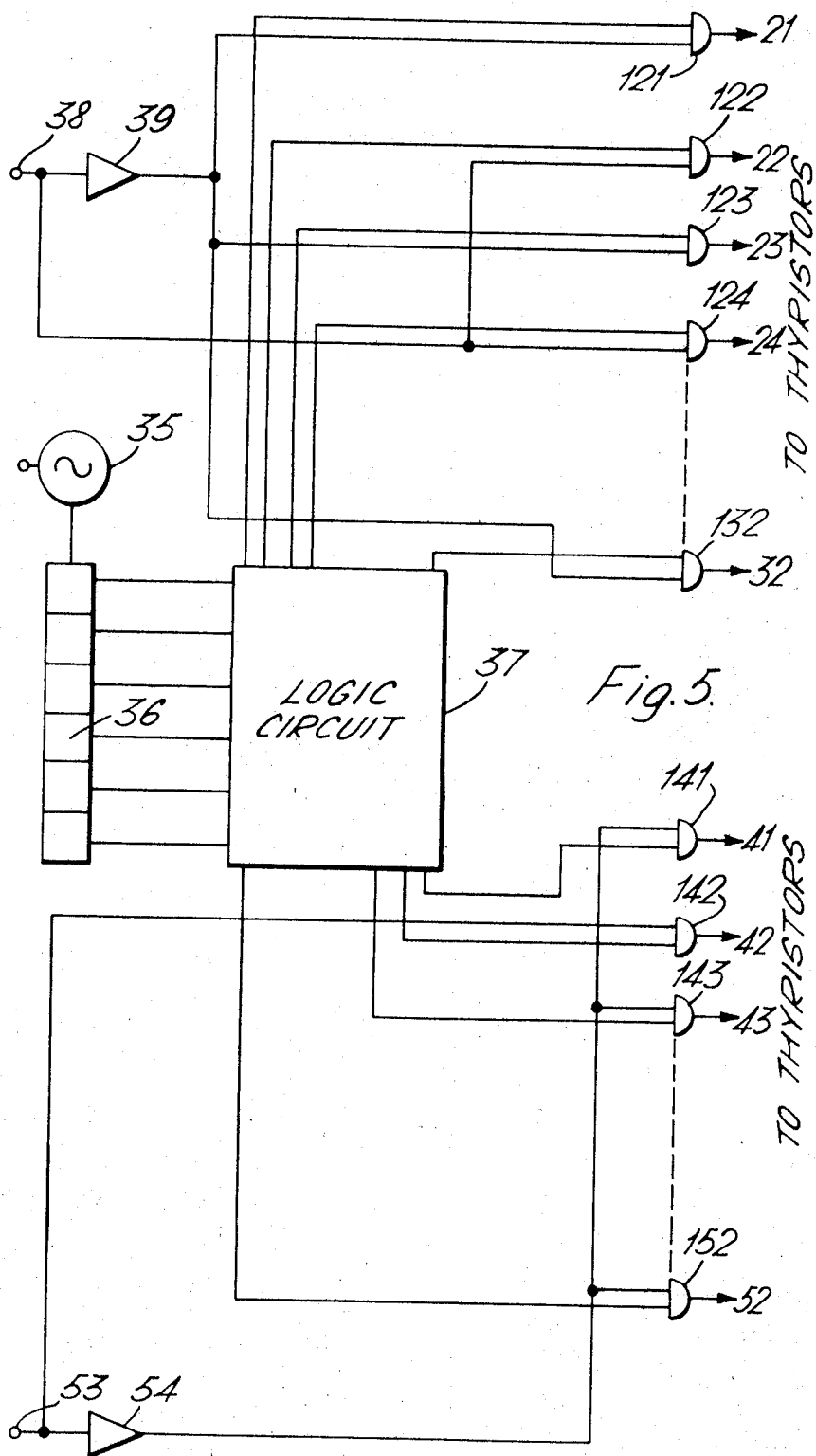
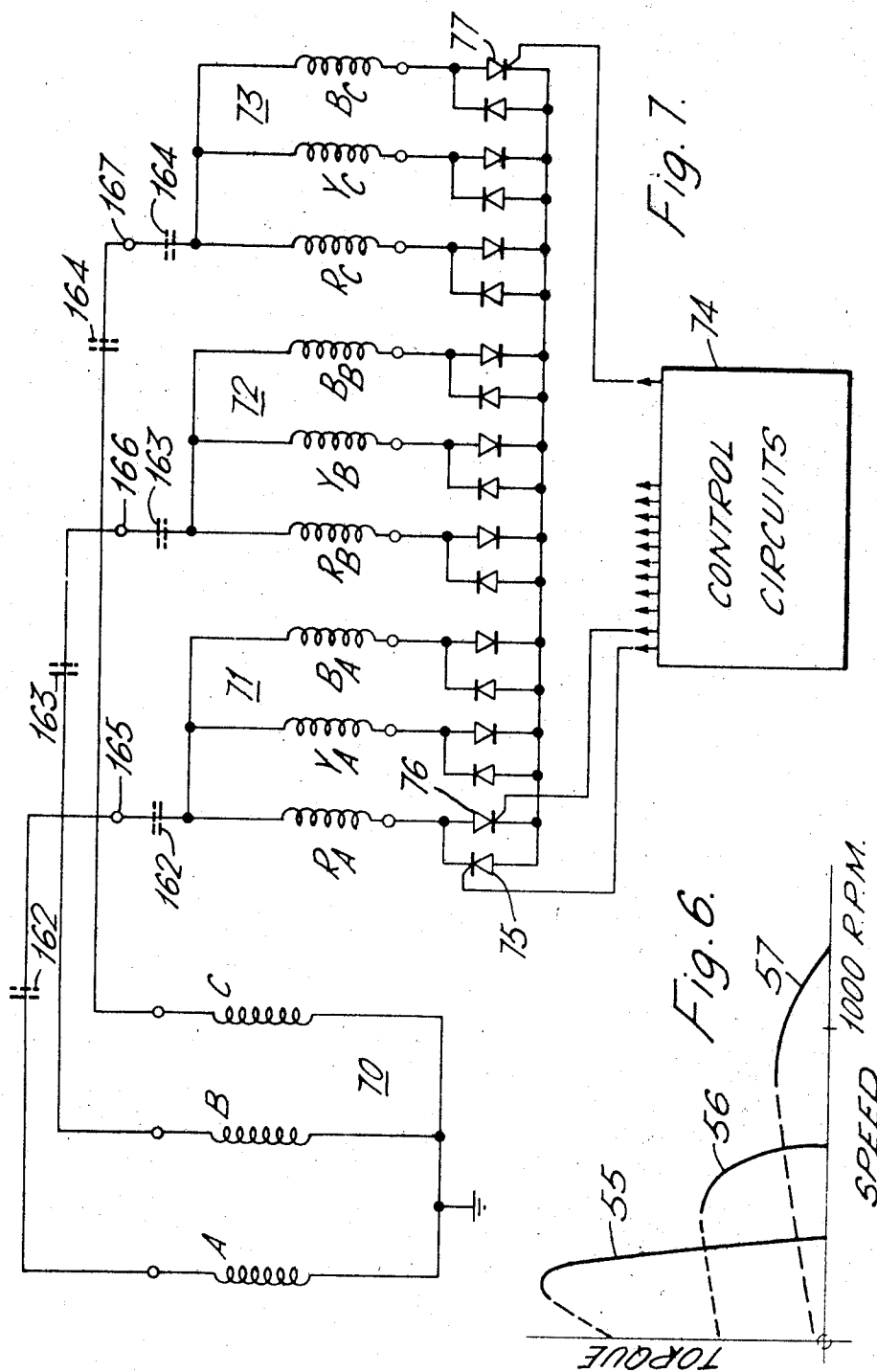


Fig. 4.







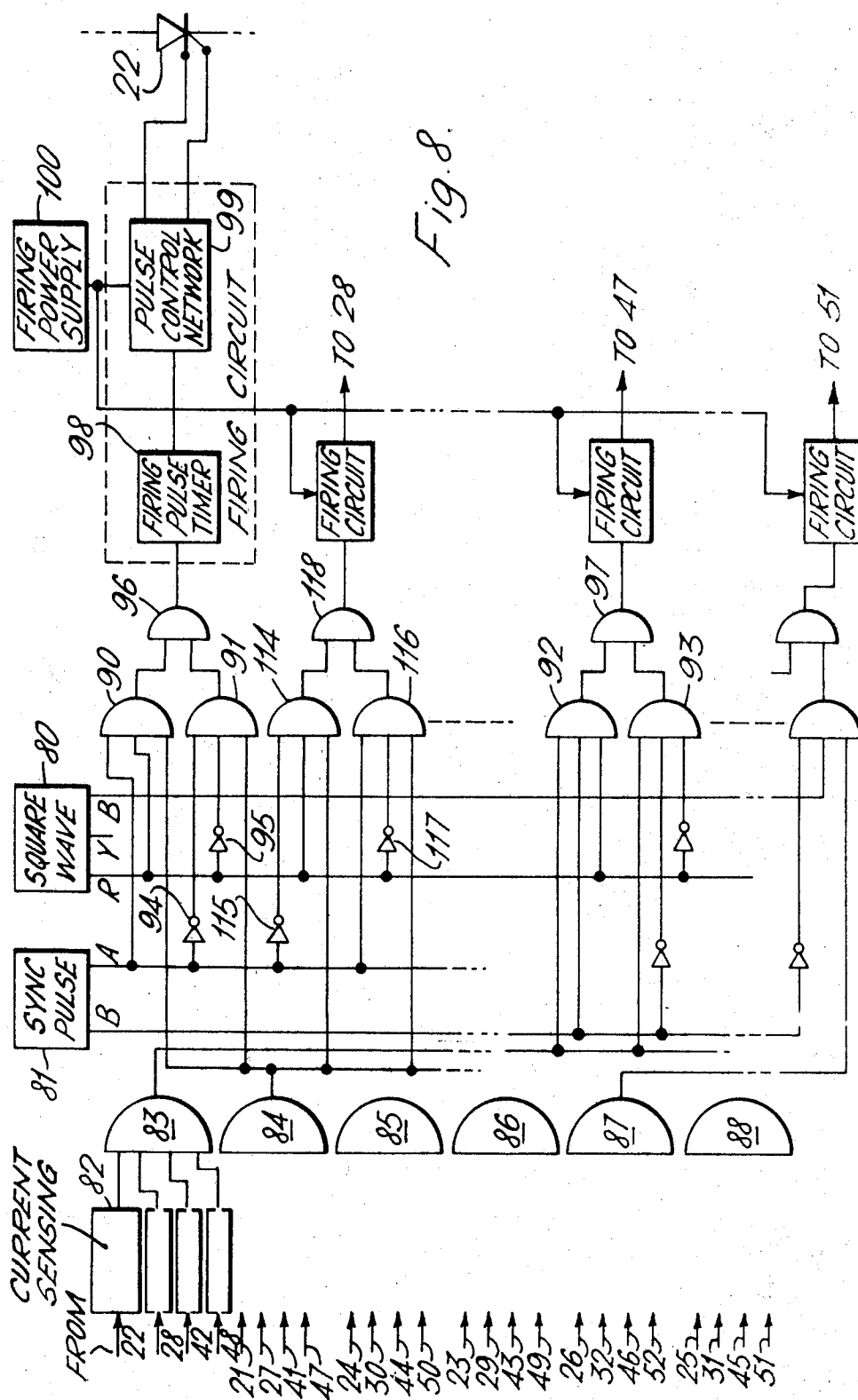
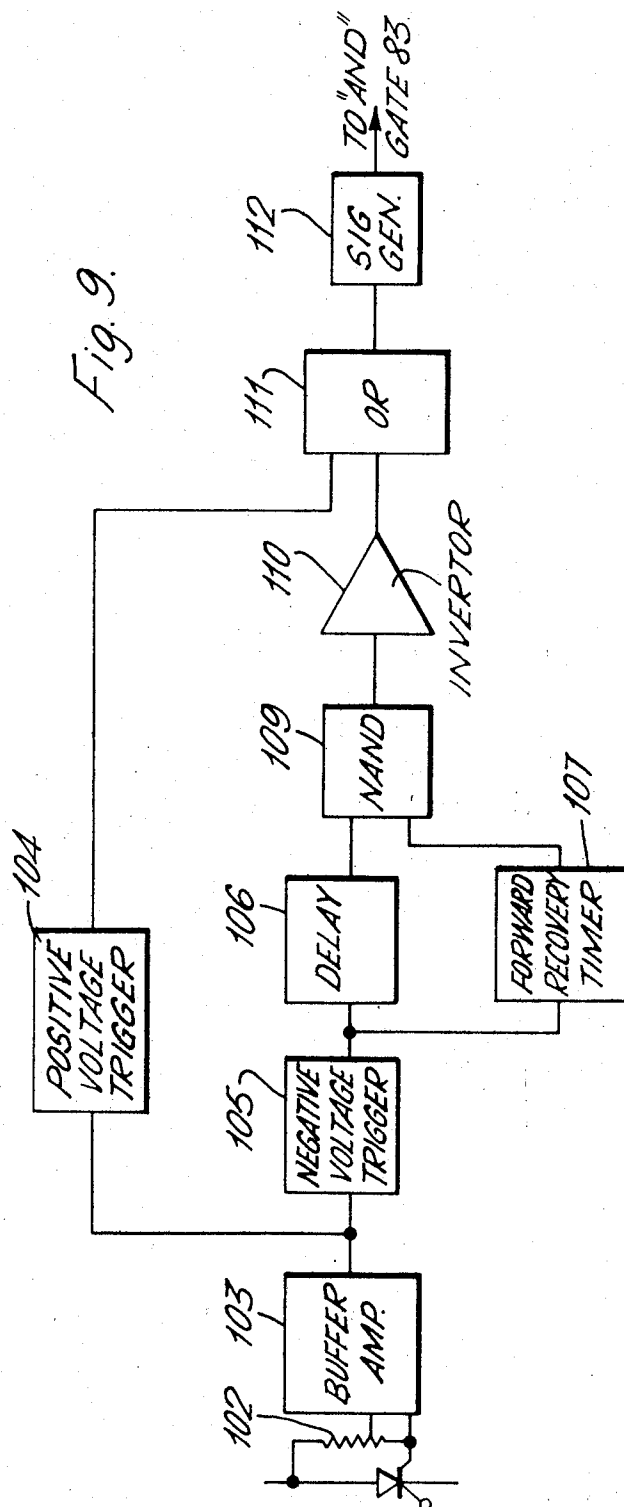


Fig. 9.



CYCLOCONVERTER ARRANGEMENTS WHICH PREVENT CIRCULATING CURRENTS

The present invention relates to cycloconverters for providing a variable low-frequency electrical supply from a high-frequency supply. Such converters are particularly, but not exclusively, useful for controlling the speed of induction motors. For example, drives for off-highway vehicles require a high power-to-weight ratio with control at each wheel. The combination of gas-turbine driven alternator and AC motor wheel drive is attractive for this application. Other applications of cycloconverters include: the generation of travelling magnetic fields for metallurgical uses where alternating magnetic fields in molten metal produce currents which heat and stir the metal; the control of closely controlled variable low-speed drives for use for example in steel mills; and the excitation of the linear induction drive of linear motors for traction systems.

The direct-driven multiphase alternator runs at a high, relatively fixed frequency since the single shaft gas turbine must operate within a narrow speed range. A solid-state converter can be used to shape the high-frequency wave into a variable-frequency, variable-voltage motor input.

The converter may be a rectifier-inverter assembly or a cycloconverter. The rectifier-inverter is a two-stage converter which requires auxiliary commutating components. The cycloconverter is a one-stage converter without commutation component requirements. It is, potentially, lighter and more efficient.

The operation of a cycloconverter is briefly described by stating that a high-frequency supply is rectified for variable intervals to give successive positive and negative output voltages, and the output voltages are used to synthesize a low-frequency output, whose frequency depends on the duration of the intervals.

Conventional phase-controlled cycloconverters have several disadvantages such as relatively heavy reactors are required to limit circulating currents; motor control is difficult at low-current values; voltage transients are impressed on the system when the firing delay of controlled rectifiers in the cycloconverter is large; and firing delays reduce the power factor of the cycloconverter operation.

Cycloconverters have been developed which eliminate some of these difficulties. For example, the "practical cycloconverter" prevents intergroup circulating currents by blanking off groups of thyristors. However, control of motor speed may be lost during blanking. The "practical cycloconverter" is described by L. J. Lawson, in I.E.E.E. Transactions on Industry and General Applications, Vol. IGA-4, No. 2, March/April 1968.

According to the present invention there is provided cycloconverter apparatus for converting a high-frequency electrical supply having a first predetermined number of phases to a low-frequency supply having a second predetermined number of phases, including a number of controlled-rectifier means at least equal to the larger of the said predetermined numbers, each controlled-rectifier means being capable of passing current selectively in either direction and control means for providing control signals for the controlled-rectifier means to synthesize a low-frequency output having the same number of phases as the load, the controlled-rectifier means being connected to provide a number of bidirectional current paths, one path for currents flowing in each combination of load phase and supply phase and particular to that combination, and the only paths for substantial currents from the supply, when the load and supply are connected to the cycloconverter apparatus, being by way of the load, even if all the rectifier means were to receive control signals enabling them to conduct.

The term "bidirectional current path" means either a single path in which current can flow in either direction or a path in which there are parallel parts for currents in opposite directions; for example, where oppositely poled thyristors are connected in parallel. These parallel parts may extend over the whole of the path.

Since in the cycloconverter according to the invention there is no path for supply currents except by way of the load the circulating currents mentioned above do not flow.

The cycloconverter usually feeds an induction motor although in some applications the load could be a synchronous motor, a transformer, or a travelling-field magnet.

Where the cycloconverter is to supply and control an induction motor, the motor may have two pairs of windings for each phase. Each pair is connected in star, together with one pair from each other phase, to the output terminals of one group. The windings of each pair are wound to give fluxes of equal magnitude and in the same direction when equal currents flow in the windings towards the star point. A vector representing the maneto-motive force in the rotor of the motor has constant magnitude. A similar winding arrangement can be used for the primary windings of a transformer forming the load.

The rectifier means may conveniently comprise pairs of oppositely poled controlled rectifiers such as thyristors connected in parallel with each other between one input and one output terminal.

The control means may then include a logic circuit, and one AND gate for each thyristor, connected to fire the thyristor if it is not conducting and the logic circuit provides an input signal for the gate.

In order to avoid the voltage transients mentioned above the logic circuit should fire each thyristor for half-cycles of the high-frequency supply. However, in other circumstances delayed angle firing may be used for wave-shaping or voltage reduction.

When the load has windings connected in star, as described above, the logic circuit preferably fires one thyristor in selected rectifier circuits to provide a resultant magnetic flux in a given direction. Another selection of thyristors is then fired during the next half-cycle of the supply frequency to provide flux in the same direction. This process is continued for alternate supply cycles for an interval determined by the output frequency, and the further thyristors in the rectifier circuits are fired for alternate supply cycles to provide a resultant magnetic flux at an angle to the given direction. After a similar interval other rectifiers are again fired to increase the angle, and in this way the resultant magnetic flux is made to resolve.

The logic circuit may include a shift register having a number of stages equal to the number of intervals required to rotate the resultant magnetic flux by 2π radians. Thus when the register contains a binary "one" and clock pulses are applied thereto, the "one" progresses round the register, and the position of the "one" determines which AND gates receive an enabling signal from the logic circuit.

Certain embodiments of the invention will now be described by way of example, with reference to the accompanying drawings, in which:

FIG. 1 is a block diagram of a first embodiment of a cycloconverter according to the invention.

FIGS. 2(a), (b) and (c) are vector diagrams used in explaining the operation of the cycloconverter of FIG. 1.

FIG. 3(a) shows the waveform of one phase voltage of an alternator of FIG. 1.

FIG. 3(b) shows the voltage applied to each coil of a motor of FIG. 1.

FIG. 4(a) shows the waveform of currents applied in a phase belt of the motor when the load power factor is unity.

FIG. 4(b) shows the waveform of currents applied in the red phase belt of the motor when the load power factor is 0.5 lagging.

FIG. 4(c) shows a waveform from a square wave generator used in controlling the firing of thyristors.

FIG. 4(d) shows a waveform from a synchronizing pulse generator used in controlling the firing of the thyristors.

FIG. 5 is a block diagram of the control circuit of FIG. 1.

FIG. 6 shows the torque-speed characteristics of the motor controlled by the cycloconverter of FIG. 1.

FIG. 7 is a block diagram of a second embodiment of cycloconverter according to the invention.

FIG. 8 is a block diagram of another control circuit which can be used in FIG. 1, and

FIG. 9 is a block diagram of a circuit for sensing the currents in a thyristor.

In FIG. 1 a two-phase high-frequency alternator 10 supplies a three-phase induction motor, the field windings of which are grouped into red, yellow and blue phases and designated R_A , R'_A , Y_A , Y'_A , B_A , B'_A , R_B , R'_B , Y_B , Y'_B , B_B and B'_B .

The speed of the motor is controlled by a cycloconverter comprising 24 thyristors 21 to 32 and 41 to 52, and a control circuit 11. The cycloconverter has input terminals 1, 1', 2 and 2', and output terminals 3 to 8 and 3' to 8'. The thyristors are fired selectively by the control circuit to rectify variable duration blocks of output cycles of the supply provided by the alternator 10 and also to reverse the polarity of the rectified output periodically. Thus the high frequency of the alternator 10 is reduced by a controllable amount before application to the induction motor.

The induction motor has three phases, but in order to prevent the above-mentioned circulating currents flowing, the motor windings are divided into two groups. One of these groups, whose windings have the suffix A, is coupled to a phase A of the alternator but not to a phase B thereof; and the other group, whose windings have the suffix B, is connected to the phase B of the alternator 10 and not to the phase A.

Each phase winding in each group is further divided into a pair of windings, these windings being those already mentioned as R_A to B'_B . In each pair one winding is designated by a prime, and one by the absence of a prime, for example, Y_B and Y'_B . The pairs of windings in each group are connected in six-phase star and each winding is connected to the appropriate alternator winding by way of parallel oppositely poled thyristors. For example, the winding B_B is connected to phase B of the alternator 10 by way of thyristors 45 and 46.

In order to obtain a more nearly constant magneto-motive force (mmf) that is to reduce fluctuations in the mmf due to switching the thyristors it is necessary to have two groups of motor windings as is shown in FIG. 1.

The control circuits 11 fire selected ones of thyristors 21 to 32 and 41 to 52 in a sequence which causes the resultant mmf to rotate at a desired speed. For unitary load power factor, this rotation is achieved by firing the thyristors in the group 21 to 32 in the sequence given in the following table, table 1:

TABLE 1.—THYRISTOR FIRING SEQUENCE

	Polarity of alternator voltage	Alternator half cycle number	Thyristors firing (see Figure 1)	Direction of net MMF ¹
Firing order:				
1st.....	+	1	27, 24, 26	
	+	2	21, 30, 32	
	+	3	27, 24, 26	
	+	4	21, 30, 32	
	+	5	27, 24, 31	
2nd.....	+	6	21, 30, 25	$\frac{\pi}{3}$
	+	7	27, 24, 31	
	+	8	21, 30, 25	
	+	9	22, 24, 31	
3rd.....	+	10	28, 30, 25	$\frac{2\pi}{3}$
	+	11	22, 24, 31	
	+	12	28, 30, 25	
	+	13	22, 29, 31	
4th.....	+	14	28, 23, 25	π
	+	15	22, 29, 31	
	+	16	28, 23, 25	
	+	17	22, 29, 26	
5th.....	+	18	28, 23, 32	$\frac{4\pi}{3}$
	+	19	22, 29, 26	
	+	20	28, 23, 32	
	+	21	27, 29, 26	
6th.....	+	22	21, 28, 32	$\frac{5\pi}{3}$
	+	23	27, 29, 26	
	+	24	21, 23, 32	

¹ With respect to R axis (radians).

The sequence of firing the thyristors 41 to 52 can be obtained from the table by adding 20 to each thyristor designation shown in the table.

The operation of the motor windings in the group having the suffix A will now be considered. Each winding is wound so that flux in the motor core is in the same direction when current flows towards the star point. If this direction is considered to be positive, the vector diagrams of FIG. 2 may be drawn. From the table it can be seen that thyristors 27, 24 and 26 are

first fired together. If the mmf produced by the R phase along is vertical in FIG. 2 when current is negative, then the current through the thyristor 27 and therefore through the winding R'_A will induce a positive flux represented by the vector 12 in FIG. 2(a), since this current flows away from the star point. The currents in the thyristors 24 and 26 are positive and will, therefore, induce magnetic fluxes in the directions of the vectors 13 and 14 respectively, but since the current in the thyristors 24 and 26 combines to provide that in the thyristor 27, the vectors 13 and 14 are half the magnitude of the vector 12. Adding the vectors 12, 13 and 14 together gives a resultant mmf vector in the direction of the R axis as shown at 15. The magnitude of the vector 15 is three halves that of the vector 12 alone. The thyristors 27, 24 and 26 conduct only when the voltage from phase A of the alternator forward biases them, but when they are reverse biased the thyristors 21, 30 and 32 are fired and an mmf in the same direction as the vector 15 is provided since current in the winding R_A is in the negative direction and that in the windings Y'_A and B'_A is positive.

In the table in order to distinguish between those thyristors which fire on positive half-cycles and negative half-cycles, each firing step is divided into two rows, which refer to thyristors, and are designated + and -, respectively.

For a number of cycles of the alternator output frequency, the thyristors 27, 24 and 26, and the thyristors 21, 30 and 32 are fired alternatively. This number, depends on the required speed of the motor, and in table 1 the number is two. When this number of cycles has elapsed a further group of thyristors are fired. This group is the second group in table 1, and it can be seen that for positive half-cycles of the alternator voltage thyristors 27 and 24 are fired, but the thyristor 26 is replaced by the thyristor 31. Thus the vector diagram of FIG. 2(b) retains vectors 12 and 13, but vector 14 is replaced by vector 16. On addition the vectors 12, 13 and 16 a resultant mmf vector 17 is obtained at an angle $\pi/3$; that is the resultant mmf has been rotated by the angle $\pi/3$. On negative half-cycles of alternator phase A thyristors 21, 30 and 25 are fired to give the same vector diagram as given in the diagram in FIG. 2(b).

After a further interval a third group of thyristors is fired. These are the thyristors 22, 24 and 31 for positive half-cycles, and 28, 30 and 25 for negative half-cycles. In FIG. 2(c) the vector 12 is replaced by a vector 18, and the resultant vector 19 of these vectors is at an angle $2\pi/3$ with the R axis. Further groups of thyristors are later fired to rotate the resultant vector by the angles given in the right-hand column of the table. It is clear that the intervals for which these groups of thyristors are fired will govern the frequency applied to the induction motor and hence will control its speed.

While the thyristors connected to the motor windings suffixed A are being fired in the above sequence, the thyristors 41 to 52 connected to the motor windings suffixed B are being fired in an identical sequence with the thyristors 41 to 52, taking the place of the thyristors 21 to 32 respectively. However, since the alternator phases A and B are 90° out of phase the rotation of the resultant mmf from both groups of motor windings is made more uniform. Similarly the load placed on the alternator is more uniform.

The alternator voltage for one phase is shown in FIG. 3(a) and the voltage applied to each winding of each pair of windings in the groups of the induction motor windings is shown in FIG. 3(b). Considering the coil R_A in relation to FIG. 3(b), when the thyristor 21 conducts but none of the thyristors 22 to 26 conduct, the voltage applied will be as shown in solid line at 61. When the thyristor 21 is still conducting but one of the thyristors 23 or 25 conduct, the voltage will be shown at 62. Similarly when the thyristor 22 and either of the thyristors 24 or 26 conducts, the voltage will be as at 63, but when the thyristor 22 conducts alone the voltage will be as shown at 64. Corresponding voltages for the coil R'_A are shown in dotted lines with their polarity reversed since as has been mentioned, the windings suffixed ' are bound to give the same phase direction for currents flowing towards the neutral point as winding without the suffix.

The windings R_A , R'_A , R_B and R'_B are arranged in the stator of the motor in what is known as a phase belt, that is the part of the stator which would, in a conventional induction motor, be occupied by the single winding of one phase. The windings Y_A , Y'_A , Y_B and Y'_B occupy a similar phase belt as do the windings B_A , B'_A , B_B and B'_B .

The currents in the red phase windings R_A and R'_A for unitary load power factor are shown in FIG. 4(a) in full and dotted lines, respectively, the polarity of the currents in the R'_A winding being reversed. In drawing this figure it has been assumed that the load draws a sinusoidal current and that each thyristor conducts for a quarter of an alternator cycle.

Voltages and currents for the yellow and blue phases have the same waveforms displaced by 120° and 240° respectively.

The control circuits for unitary power factor loads will now be described in more detail. A speed demand signal in the form of a unidirectional voltage of varying magnitude is applied at a terminal 33 (see FIG. 1). This signal may, for example, be derived from a tachogenerator coupled to the induction motor or to the error signal output of a servomechanism controlling the speed of the induction motor. The speed demand voltage is applied directly to the field winding of the alternator 34 to control the voltage output thereof, and also to a clock pulse oscillator 35 (see FIG. 5) to control the clock frequency. The oscillator 35 is connected to ring counter 36 having six stages corresponding to the six steps in the sequence of firing the thyristors shown in the table. A binary "one" circulates round the ring counter 36 under the control of clock pulses. When the "one" is in any given position in the ring counter 36 a unique output is applied to a logic circuit 37 which then applies an input to six selected AND gates of AND-gates 121 to 132 and 141 to 152. These AND gates are connected to trigger terminals of the thyristors 21 to 32 and 41 to 52, respectively. For clarity only the gates 121 to 124, 132, 141 to 143 and 152 are shown in FIG. 5. Hence in any one state of the counter 36, six of the AND gates receive an input from the logic circuits 37, these six gates being connected to the six thyristors of one sequence step in the table. In order to prevent losses which occur when a thyristor is back biased but fired, each AND gate also receives a further input indicating whether its associated thyristor is forward or reverse biased. This further input may not be necessary with some types of thyristor. The further inputs are obtained from a terminal 38 or an inverter 39 for phase A, or from a terminal 53 or an inverter 54 for phase B. The terminals 38 and 53 are coupled to phase A and phase B of the alternator 10 respectively. Thus, for example, when the output from phase A is positive and AND-gates 122 and 124 receive inputs while the AND-gates 121 and 123 receive no inputs. When the output from phase A is negative the gates 121 and 123 receive inputs while the gates 122 and 124 do not receive inputs. In this way the appropriate selection is made between the six gates enabled at any one time by the logic circuit 37.

Where other than unity load power factors are required, control circuits which are able to adjust the times and sequence of firing thyristors are required. One form of such control circuits will now be described.

The phase relationship between the load voltage and the load current in any phase is determined by the nature of the load. Four possibilities for current and voltage polarities exist at any time: voltage and current positive; voltage negative, current positive; voltage and current negative; and voltage positive current negative. For example where the current lags the voltage, the current and voltage take the polarities in the sequence given in the preceding sentence.

The thyristors must be fired in a sequence which allows the appropriate current and voltage polarities to be applied to the load. The voltage polarity is determined by a three-phase square wave generator 80 (see FIG. 8) which provides one

square wave for each load phase, the square wave for the red phase being shown in FIG. 4(c). The polarity of the current is then determined by the load and is sensed by determining the directions of current flow in the thyristors, and the moment when current ceases to flow in a group of thyristors.

In each phase there are four thyristors which pass positive current towards the neutral point and four thyristors which pass negative current. For example in the red phase the positive current thyristors are the thyristors 22, 28, 42 and 48, and those passing negative current are the thyristors 21, 27, 41 and 47. Thus in order to provide signals indicating when currents have ceased flowing each thyristor has a current-sensing circuit of a type which is described below, one of these sensing circuits, that for the thyristor 22 being shown at 82. The output of the sensing circuits for each group of four positive or four negative current thyristors in each phase are connected to one of six AND-gates 83 to 88.

Having determined the required load phase voltage and the resulting current direction at any time, it is necessary to arrange to fire the appropriate thyristors to provide this voltage and current, but which thyristor is to be fired also depends on the polarity of the alternator voltages at any time. A synchronous pulse generator 81 is therefore provided, which generates pulses by zero crossing detection, indicating by their polarity whether the next alternator half cycle is positive or negative. The pulse train for the phase A of the alternator is shown in FIG. 4(d).

When the load phase voltage and current are to be positive the appropriate thyristor must be fired, that is for the red phase the thyristor 22 or 28. Thus an AND-gate 90 is provided which receives enabling signals from the square wave generator 80 and the AND-gate 84 enabled by the absence of negative current flow in the red phase. The thyristor 22 conducts for positive half-cycles of the alternator waveform, and hence the gate 90 also receives signals from the synchronizing pulse generator 81, while the thyristor 28 conducts during negative half-cycles. A similar AND-gate 114 is provided for the thyristor 28 which receives enabling signals from the square wave generator 80, and AND-gate 84, and synchronizing pulses by way of an inverter 115.

When the load voltage becomes negative but the current remains positive a change in the sequence of firing thyristors becomes necessary. The current has not changed direction so the same thyristors (that is thyristors 22 and 28) are fired but to provide the negative voltage the alternator must be connected to the winding R_A during negative half-cycles, and to the winding R'_A during positive half-cycles. Two more AND-gates 91 and 116 are therefore provided, both receiving enabling signals from the AND-gate 84, and the generator 80 (by way of inverters 95 and 117, respectively). The AND-gate 91 also receives an enabling signal from the generator 71 by way of an inverter 95, as does the AND-gate 116 except that no inverter is required.

OR-gates 96 and 118 are coupled to the AND-gates 90 and 91, and 114 and 116, respectively, to activate firing circuits for the thyristors 22 and 28. These firing circuits are described in detail below.

When the load phase currents and voltages are negative the thyristors 21 and 27 are fired, as is also the case when the voltage is positive and the current is negative, although the sequence of firing with respect to the alternator waveform is changed in a similar way to that described in connection with the thyristors 22 and 28. Further AND gates, two for each thyristor, together with further OR gates, one for each thyristor, are provided, making a total of 48 AND gates and 24 OR gates. For clarity only the AND-gates 92 and 93 and the OR-gate 97 for the thyristor 47 are shown in FIG. 8, but the connectors for the other gates are apparent from the description of those for the gates 90, 91, 114 and 116 and the following table, table 2:

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TABLE 2

AND gates for initative firing of thyristor			Current- Sensing AND Gate
22	A+	+	84
	A-	-	84
28	A+	-	84
	A-	+	84
21	A+	+	83
	A-	-	83
27	A+	-	83
	A-	+	83
42	B+	+	84
	B-	-	84
48	B+	-	84
	B-	+	84
41	B+	+	83
	B-	-	83
83	B-	-	83
	B-	+	83

In the above table each thyristor has two AND gates represented by the two rows opposite its designation. Each row gives the conditions which are to open the gate and hence specifies the required connection for the gate. Where a negative sign is present an inverter is required before the gate. A and B refer to the alternator phases. The outputs of each pair of AND gates for one thyristor are taken to an OR gate and thence to firing circuits.

The connections for the yellow and blue phases will now be apparent since they are similar to those for the red phase.

In table 2 it can be seen that one of the thyristors in the pair connected to the positive windings (R_A , Y_A , B_A , R_B , Y_B and Y_A) conduct when the synchronizing pulse and the square wave have the same polarity; while one of the thyristors in the pair connected to the negative windings (R_A' , Y_A' , B_A' , R_B' , Y_B' and B_B') conduct when the synchronizing pulse and the square wave have opposite polarities.

The OR-gate 96 is coupled to a firing-pulse timing circuit 98 which provides a signal of duration equal to one quarter of an alternator cycle. Since the alternator is assumed to rotate at constant speed, this signal is suitable for operation at all power factors.

The signal from the timing circuit 98 is one of three signals applied to a control network 99, the other signals being two antiphase square waves from a firing-power supply 100, common to all thyristors. The control network 99 rectifies the antiphase signals to provide a thyristor firing pulse, applied between the thyristor cathode and its trigger terminal, of specified amplitude and duration. Generating firing pulses in this way allows a constant gate drive with transformer isolation of the network 99 from the thyristor.

The remaining 23 OR gates are coupled to their respective thyristors in the same way with individual firing-pulse timing circuits and control networks.

As has been mentioned, each thyristor has a group of sensing circuits whose output is connected to one of the AND-gates 83 to 88. One form of these sensing circuits is known and has been described by Shah. Such a circuit will now be described with reference to FIG. 9. Although this description is for the sensing circuits coupled to the thyristor 22, the sensing circuits for the other thyristors are the same.

The anode to cathode voltage of the thyristor 22 is sensed through a high value resistor 102 to limit the current and power drawn from the thyristor circuit. An analogue signal is then produced by a saturating buffer amplifier 103 which reproduces the anode to cathode voltage over the range of ± 10 v.

The thyristor is assumed to be conducting whenever this voltage is 0 to 3 v., and for a brief period whenever the voltage goes negative.

A positive-voltage trigger circuit 104 senses anode voltages above 3 volts and produces a signal signifying that the device is forward biased but not conducting. Such a voltage cannot be maintained more than a few microseconds by a thyristor which is conducting.

A negative voltage trigger circuit 105 senses voltages below 0 v., and a delay circuit 106 provides after a brief delay a signal indicating that the device is reverse biased. After a longer delay, (50-100 μ s), a forward recovery timer circuit 107 signals that conducting has ceased by opening a NAND-gate 109. When nonconduction in both directions has been indicated by a signal from the NAND-gate 109 by way of an inverter 110, or by a signal from the circuit 104 a blocking signal is produced at the output of an OR-gate 111.

A signal generator 112 provides a high-frequency signal when the OR-gate 111 is open. This signal is transformer coupled to the AND-gate 83 which is therefore isolated from the thyristor voltage.

An example of the operation of the arrangement of FIG. 1 when the load power factor is 0.5 lagging will now be given. For this power factor the current in the red phase takes the form shown in FIG. 4(b) where, as before, current in the winding R_A is shown in full lines and in the winding R_A' is shown in dotted lines with its polarity reversed. It will be seen by considering the action of the circuits of FIGS. 8 and 9 that the sequence of firing the thyristors is now as shown below in table 3.

TABLE 3.—THYRISTOR FIRING SEQUENCE—0.5 POWER FACTOR LOAD (LAGGING)

		Polar- ity of alter- nator voltage	Alter- nator half cycle number	Thyristors firing (see Figure 1)	Dirrec- tion of net MMF ¹
Firing order:					
1st.....	+	+	1	27, 24, 25	0
		-	2	21, 30, 31	
		+	3	27, 24, 25	
		-	4	21, 30, 31	
2nd.....	+	+	5	27, 30, 26	$\frac{\pi}{3}$
		-	6	21, 24, 32	
		+	7	27, 30, 26	
		-	8	21, 24, 32	
3rd.....	+	+	9	21, 29, 26	$-\frac{2\pi}{3}$
		-	10	27, 23, 32	
		+	11	21, 29, 26	
		-	12	27, 23, 32	
4th.....	+	+	13	22, 29, 32	π
		-	14	28, 23, 26	
		+	15	22, 29, 32	
		-	16	28, 23, 26	
5th.....	+	+	17	22, 23, 31	$-\frac{4\pi}{3}$
		-	18	28, 29, 25	
		+	19	22, 23, 31	
		-	20	28, 29, 25	
6th.....	+	+	21	28, 24, 31	$-\frac{5\pi}{3}$
		-	22	22, 30, 25	
		+	23	28, 24, 31	
		-	24	22, 30, 25	

¹ With respect to R axis, re: Table 1.

The third firing order in the red phase is now different from that shown in table 1 since in the 13, 14, 15 and 16th half-cycles of the alternator waveform (see FIG. 3(a)) the current in the red phase has the opposite polarity to the red phase voltage. Hence the same thyristors conduct as before the phase voltage changed polarity but in the reverse order with respect to the alternator waveform. Similar differences between table 1 and 3 can be seen in the sequence of firing the yellow phase thyristors (the second column of thyristor designations in the penultimate column of the tables) and in the sequence for the blue phase thyristors but in considering the differences between the tables it should be recognized that while the phases are fired in the order red, blue, yellow in table 1, the order in table 3 is red, yellow, blue.

If the cycloconverter according to the invention and its load have a low leakage inductance, their power factor approaches unity for all loads, since when the magnetizing inductance of the load requires a reactive current it is supplied from windings in other phases which are, in effect, connected across the magnetizing inductance. For example in table 3, during alternator half-cycles 13 and 15, thyristors 29 and 32

are conducting, allowing at least part of the current from one of the windings Y'_A and B'_A to flow in the other of these windings instead of the alternator.

If the ratio of alternator frequency to motor frequency is high the leakage inductance of the alternator and part of the leakage inductance of the motor cause a large reactive drop between the alternator and the motor magnetizing circuit. Since this inductance is determined almost entirely by the alternator frequency and this frequency is high, the inductance may be counteracted by relatively small capacitors in the supply lines. The reactance of these capacitors should be of approximately the same magnitude but opposite to that of the leakage inductance. Such capacitors are shown in dotted lines at 160 and 161 in FIG. 1 and at 162, 163 and 164 in FIG. 7. The use of these capacitors substantially reduces the excitation voltage requirements of the motor.

It has been shown that an induction motor operated in the way described above operates satisfactorily on the voltage waveform shown in FIG. 3(b). Losses are increased modestly, for example 20 percent at 60 Hz., and normal torque-slip characteristics are produced. Higher exciting currents are required because of the localized saturation effects of the harmonics.

The motor in effect operates on a series of high-frequency current pulses and these pulses increase copper losses and local iron losses. The copper losses may be increased by 125 percent depending on the leakage inductance of the winding because the peak current in each coil must be about three times as great to provide the same average current through the winding.

As has been mentioned each winding is in four parts, and these parts could ideally be obtained by a quadrifilar wound set of coils in each phase belt. However, it is more practical to provide a two-layer winding with bifilar windings in each coil.

The leakage flux is only slightly greater, since all conductors of one phase still share the same slot. The insulation requirements are reduced if the upper and lower layers are supplied from separate alternator phases.

FIG. 6 shows torque-speed characteristics of a 2 kw. motor tested using the cycloconverter specifically described above. In this machine the rotor was cage-wound and the stator contained a two-layer winding of single conductor coils. Two poles were fed from each alternator phase. In FIG. 6 curve 55 is for a supply frequency to the induction motor of 12.5 Hz., curve 56 is for a frequency of 25 Hz. and curve 57 is for a frequency of 50 Hz.

A second embodiment of a cycloconverter according to the invention, with input terminals 165, 166 and 167 and three input and three output phases, is shown in part circuit-part block diagram form in FIG. 7. A generator, only the three-phase stator 70 of which is shown, is connected to an induction motor with three trifilar sets of stator windings, 71, 72 and 73. Each set consists of one winding in each of three phase belts, designated R, Y and B, the three sets being suffixed A, B and C.

The windings are connected in star with two oppositely poled, parallel connected, thyristors between each winding and the neutral point.

A control circuit is provided to fire the thyristors and each thyristor is connected individually to the control circuit as shown for thyristors 75, 76 and 77. The design of the control circuit 74 will be apparent to those familiar with the construction of banks of thyristors feeding multiphase machines, particularly in view of the detailed explanation of two control circuits given above.

A cycloconverter according to the invention need not have a two-phase input and a three-phase output or three input and output phases as specifically described so long as the output is multiphase. Furthermore, the cycloconverter can be used for other purposes than supplying induction motors provided the load can combine the outputs at a number of output terminals in a satisfactory manner.

Thyristors need not necessarily be used and other types of controlled rectifiers or groups of controlled-rectifiers such as Triacs can be used. The term controlled rectifier in this

specification means any device which will not pass significant current in one direction but will after receiving a control signal, pass current in the other direction.

Thus this term includes for example, thyristors, semiconductor diodes, transistors, and metal-oxide semiconductor transistors (MOSTs).

The control signal is sometimes known as a firing or triggering signal.

In this specification the term controlled-rectifier means has the meaning of means which include controlled rectifiers.

The logic circuits can, of course, be of any desired type so long as the thyristors are fired in a sequence which synthesizes an output voltage of the required number of phases and a conducting path in the required direction through those phases.

I claim:

1. Cycloconverter apparatus for converting a high-frequency electrical multiphase supply having a first predetermined number of phases to a low-frequency supply for a load having a second predetermined number of star-connected phases, including:

at least as many controlled-rectifier means as the larger of the said predetermined numbers,

each controlled rectifier means being capable of passing current selectively in either direction and

control means for providing control signals for the controlled-rectifier means to synthesize a low-frequency output having the same number of phases as the load,

the controlled-rectifier means being connected to provide a number of bidirectional current paths, one said path for each combination of load phase and supply phase and particular to that combination, and the only paths for substantial currents from the supply, when the load and supply are connected to the cycloconverter apparatus, being by way of the load, even if all the rectifier means were to receive control signals enabling them to conduct.

2. Cycloconverter apparatus for converting a high-frequency electrical multiphase supply having a first predetermined number of phases to a low-frequency supply, comprising:

a plurality of input terminals adapted to be connected to said supply,

an AC load having a second predetermined number of star-connected phases including a number of groups of windings equal to said second predetermined number, a number of controlled-rectifier means, one for each combination of one input terminal and one load phase and particular to that combination,

each controlled-rectifier means being capable of passing current selectively in either direction, and

control means for providing control signals for the controlled-rectifier means to synthesize a low-frequency output having the same number of phases as the load, the only paths for substantial currents from the supply, when the supply is connected to the cycloconverter apparatus, being by way of the load, even if all the rectifier means were to receive control signals enabling them to conduct.

3. Apparatus according to claim 2 including a plurality of capacitor means one for each supply phase and connected in series with an input terminal of that phase, the total reactance of all the capacitor means being substantially equal but opposite to the reactance of the leakage inductance of the apparatus.

4. Electrical apparatus adapted to be supplied from a high-frequency supply, including a plurality of input terminals adapted to be connected to a multiphase AC supply having a first predetermined number of phases, a load requiring a low-frequency supply, having a second predetermined number of star-connected phases, a number of controlled-rectifier means at least equal to the larger of the said predetermined numbers, each controlled-rectifier means being connected between an input terminal particular thereto and the common connection between the load phases, and each controlled-rectifier means being capable of passing current selectively in either direction, and control means for providing control signals for the con-

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trolled-rectifier means to synthesize a low-frequency output having the same number of phases as the load, the only paths for substantial currents from the supply when connected to the apparatus, being by way of the load, even if all the rectifier means were to receive control signals enabling them to conduct.

5. Apparatus according to claim 4 wherein the load has a number of groups of pairs of windings equal to the first predetermined number, the numbers of pairs of windings in each group equals the second predetermined number, and the number of controlled rectifier means equals the number of windings, each pair of windings being connected in star with the other pairs of windings in the group, and each rectifier means being connected in series with a winding particular thereto, and associated therewith between an input terminal and the common connection between phases.

6. Apparatus according to claim 5 wherein, in each star connection two common input terminals are provided, and the controlled-rectifier means coupled to the windings of each pair, are coupled to the common input terminals, respectively, between the windings and the input terminals.

7. Apparatus according to claim 6 including a two-phase alternator forming the AC supply, wherein the load is a three-phase induction motor with two pairs of windings for each phase, each pair connected in star with one pair from each other phase.

8. Apparatus according to claim 5 wherein each controlled-rectifier means includes a pair of oppositely poled thyristors connected in parallel.

9. Apparatus according to claim 5 wherein the load is three-phase star connected and each rectifier means is connected in series with a load phase particular thereto.

10. Apparatus according to claim 6 wherein the control circuit includes means for providing first and second control signals to cause the controlled-rectifier means connected to the input terminals for each supply phase to pass currents for equal alternate intervals in the one and the other directions, respectively, in each load phase, the changeover in current direction in the phases being separated by the said interval divided by the second predetermined number.

11. Apparatus according to claim 10, wherein the means providing the first and second signals applies the first signal alternately to the controlled-rectifier means associated with the windings in each pair during each alternate interval, and applies the second signal alternately to the controlled-rectifier means associated with the windings in each pair for the other intervals.

12. Apparatus according to claim 11 wherein the control circuit includes a clock pulse generator coupled to a shift register having a number of stages equal to twice the second predetermined number, and a logic circuit so coupling the

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shift register to the controlled-rectifier means the first and second control signals are applied to a different combination of the controlled-rectifier means while each different stage is in a predetermined conduction state.

13. Apparatus according to claim 11 wherein the control circuit includes a logic circuit connected to receive input signals from sensing means for sensing the direction of current flow in the thyristors, from synchronizing means for sensing the polarity and start of each half-cycle of the supply voltage, and from polarity-indicating means for indicating the polarities of the load phase voltages.

14. Apparatus according to claim 13 wherein, in operation, logic circuit provides the second and first control signals for one controlled-rectifier means in each phase if the sensing means indicates that the other rectifying means of that same phase are not conducting in the said one or the said other direction respectively and if the polarity of the supply voltage and the load phase voltage are the same, and for the other controlled-rectifier means in each phase if the sensing means indicates that the other rectifying means of that phase are not conducting in the said one or the said other direction, respectively, and if the polarity of the supply voltage and the load phase voltage are opposite.

15. Apparatus according to claim 12 wherein the logic circuit includes first and second AND gates for each phase adapted to be opened if the rectifying means associated with the pair of windings of that phase are not conducting in the one and the other directions, respectively.

16. Apparatus according to claim 15 wherein each controlled-rectifier means includes a pair of oppositely poled controlled rectifiers connected in parallel, each controlled rectifier is associated with the phase of the winding whose current it controls, and the logic circuit includes a number of OR gates each with inputs coupled to a pair of AND gates, there being one OR gate and one pair of AND gates for each controlled rectifier, and the AND gates in each pair being coupled to receive output signals from that first or second AND gate of the phase associated with that controlled rectifier which indicates that current in that phase is not in forward direction of that controlled rectifier, one AND gate in each pair receiving enabling signals from the synchronizing means and the polarity-indicating means when the load phase voltage and the supply voltage have first and second polarities, respectively, and the other gate of that pair receiving enabling signals when the said voltages have the opposite polarities, the first and second polarities being the same for the controlled rectifiers in the controlled-rectifier means associated with one winding in each pair, but opposite for the controlled rectifiers in the controlled-rectifier means associated with the other winding in each pair.

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