Cycloconverters and cycloconverter-fed drives : A review

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Abstract

Significant developments have taken place in control, analysis, modelling and practical implementation aspects of cycloconverters and their applications to the adjustable-speed ac drives. This paper attempts to make a comprehensive and chronological review on the progress of research and industrial development, all over the world, to provide a background information on the present status of cycloconverters and cycloconverter-fed drives. In the process, it highlights the substantial research work done at the Indian Institute of Technology (IIT), Kharagpur towards developing practical control schemes and simulation models for cycloconverter-fed induction and synchronous motor drives.

Keywords: Cycloconverters, Drives, Power Electronics, Induction motor drives, Synchronous motor drives.

Major Discipline: Electrical Engineering (Adjustable-speed drives).

1. Introduction

The cycloconverter is a power-electronic equipment designed to convert constant voltage constant frequency ac power to adjustable voltage adjustable frequency ac power without any intermediate dc link. The basic principle of this converter, conceived and patented by Hazeltine[1] in 1926 is to construct an alternating voltage wave of lower frequency from successive voltage waves of a higher frequency multiphase ac supply by a switching arrangement. Grid-controlled mercury arc rectifiers were used in these converters in 1930's to obtain 1-phase $16^{2}/_{3}$ Hz supplies for ac traction motors in Germany from a 3-phase 50 Hz system[2] while at the same time a cycloconverter using thyratrons[3] for supplying a 400 hp synchronous motor was in operation for some years as a power station auxiliary drive in USA. However, the practical and commercial utilisation of these schemes waited until the thyristors became available in the 1960's. With the availability of large rating SCRs and later the development of microprocessor-based control, the cycloconverter today is a practical proposition in large power applications with synchronous or induction motors like gearless mill drive in cement industry[4-12], centrifugal pump and compressors[13], electric traction[14-15], rolling mills[16-18], variable-speed constant frequency (VSCF) systems[19], static Scherbius drives[20-22], mine winders[23-24], ship propellers[25] etc.

A cycloconverter is a naturally commutated converter with inherent capability of bidirectional power flow and there is no real limitations on its size which is otherwise restricted in the case of a thyristor inverter due to the size of commutating elements. Here the switching losses are considerably low, the regenerative operation at full power over complete speed range is inherent and it delivers a nearly sinusoidal waveform resulting in minimum torque pulsations and harmonic heating effects. It is capable of operation even with blowing out of individual

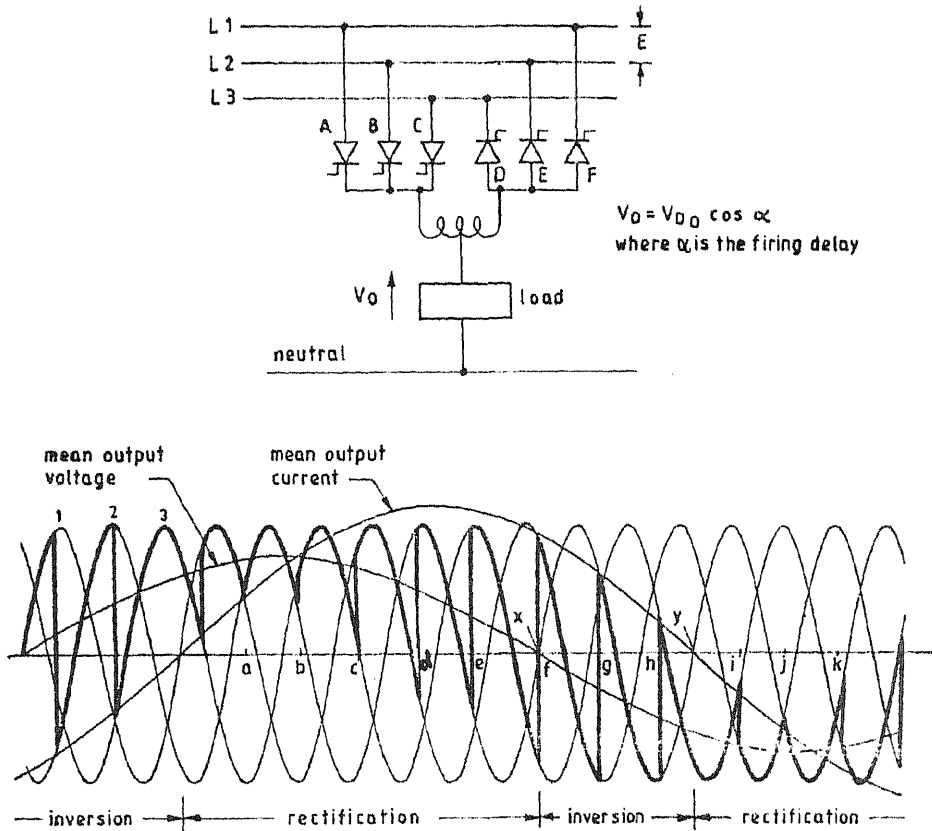*Formerly with the Department of Electrical Engineering, Indian Institute of Technology, Kharagpur 731 302, India.

FIG. 1. Output voltage waveform for one phase of a three phase cycloconverter operating at 15 Hz from 50 Hz supply. 0.6 p. f. lagging load[30].

thyristor fuse (unlike inverter) and the requirements regarding turn-off time, current rise time and dv/dt sensitivity of thyristors are low. The main limitations of the naturally commutated cycloconverters are (1) limited frequency range (less than half of the imput frequency) for sub-harmonic-free and efficient operation and (2) poor input displacement and power factor, particularly at low output voltages. However, with improved control techniques[26-29], these problems are being overcome.

Significant developments, that have taken place in control, modelling and analysis, and application aspects of cycloconverter drives are focussed in the next few sections here.

2. Cycloconverter control

2.1. Basic Principle of Operation

The process of cycloconversion is illustrated in Fig. 1[30] for a 3-pulse cycloconverter at 15 Hz, 0.6 pf lagging load from 50 Hz supply. As the firing delay angle α is cycled from zero at 'a' to 180 at 'j', half a cycle of output frequency is produced. For this load, it can be seen that al-
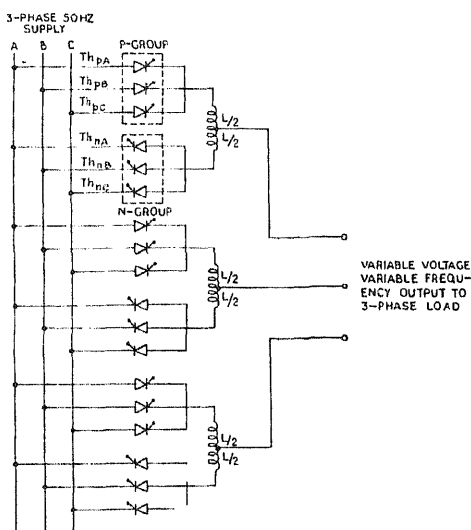
FIG. 2. Three-phase half-wave cycloconverter power circuit.

(A) Positive group output voltage

(B) Negative group output voltage

(C) Instantaneous difference voltage between positive and negative group.
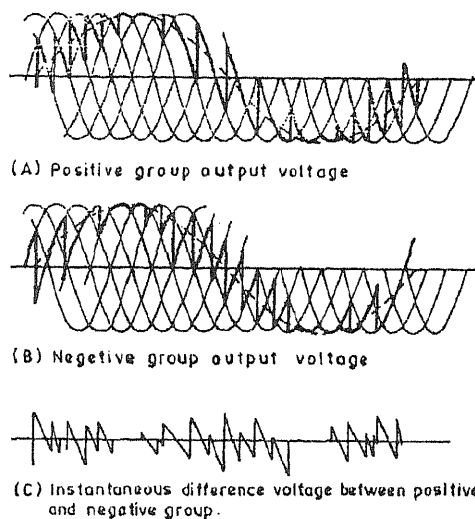
FIG. 3. Voltage waveforms for a six-pulse circulating current cycloconverter.

though the mean output voltage reverses at X, the current (assumed sinusoidal) remains positive until Y. During XY the positive group of rectifier thyristors A,B,C are 'inverting'. A similar period exists at the end of the negative half-cycle of the output voltage when D, E and F thyristors will be 'inverting'. Thus, the operation of the groups follows in the order of 'rectification' and 'inversion' in a cyclic manner, the relative durations being dependent on load p.f. The output frequency is that of the firing delay oscillation about the quiescent point of 90° (condition when the mean output voltage is zero). Actually, the firing angle of each arm of the converter is defined by the time at which a control or reference voltage of output frequency and a modulating voltage of input frequency are identical. Variation of α within the limits of 180° automatically provides for 'natural' line commutation of the thyristors. The P-group or N-group thyristors (Fig. 2 shows the basic 3-pulse or 3-phase half wave cycloconverter with 18 thyristors with 3 thyristors in each group while use of full-wave 3 phase bridge will need 36 thyristors with 6 thyristors in each group) receive firing pulses which are timed such that each group delivers the same mean terminal voltage. This is achieved by maintaining the firing angle constraints of the two groups as $\alpha_P = (180° - \alpha_N)$. However, the instantaneous voltages of the two groups are not identical and large circulating current may result as shown in Fig. 3 for a six pulse cyclocon-verter unless limited by intergroup reactors (circulating current cycloconverter) or completely suppressed by removing the gate pulses from non-conducting group by intergroup blanking logic (circulating current-free cycloconverter). These developments are concurrent with the similar developments in dual converters for supplying reversing dc motor drives.

2.2. Control Schemes: Analog

Various possible analog control schemes for deriving triggering signals for controlling the basic cycloconverter (Fig. 2) as developed in late 60's and early 70's are described in literature[30-40]. It
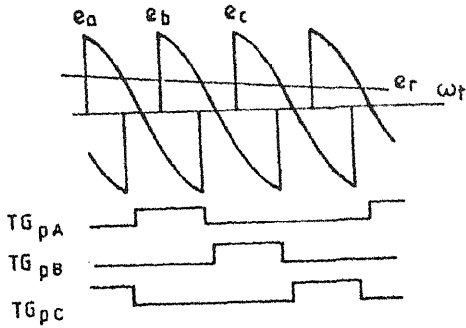
FIG. 4. Deriving firing signals for one group[18].

has been shown that a cosinusoidal reference signal ($e_r = E_r \cos \omega_0 t$) at desired output frequency f_0 and a cosine modulating signal ($e_r = E_r \cos \omega_i t$) at input frequency f_i is the best combination possible to derive the trigger signals (Fig. 4) which produces the output waveform with the lowest total harmonic distortion. The modulating voltages can be obtained as the phase-shifted supply voltages (B-phase voltage for A-phase thyristors, C-phase voltage for B-phase thyristors and so on) as explained in Fig. 5[40], when the cycloconverter output voltage V_0 can be shown as

$$V_0 = V_{d0} \cos \alpha = V_{d0}(E_r / E_m) \sin (\omega_0 t - \phi) \qquad (1)$$

which equation shows that the amplitude, frequency and phase of the output voltage can be controlled by controlling the corresponding parameters of the reference voltages, thus making the transfer-characteristic of the cycloconverter linear. The derivation of two complementary voltage waveforms for the P-group and N-group converter 'banks' in this way is illustrated in Fig. 6. The final cycloconverter output waveshape is composed of alternate half-cycle segments of the complementary P-type and N-type output voltage waveforms which coincide with the positive or negative current half cycles.

2.2.1. Typical Control Implementation

Fig. 7 shows a simplified block diagram of the circulating current-free control circuit of the cycloconverter implementated with IC's using cosine control[38] in the early seventies at the
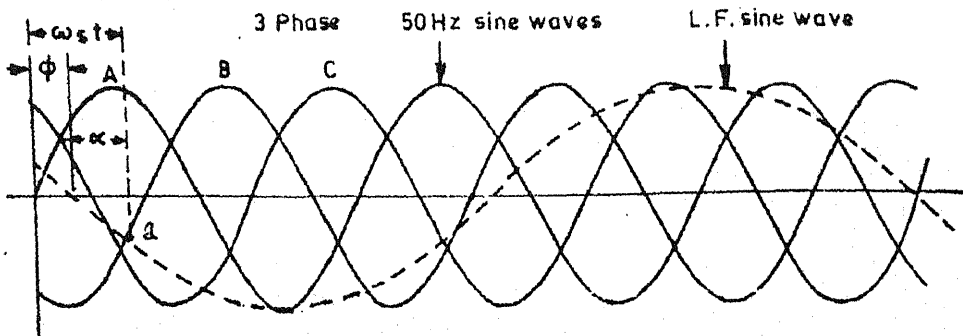

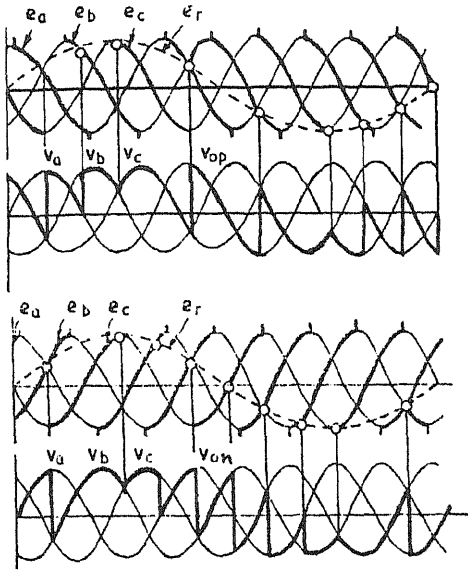FIG. 5. Derivation of cosine modulating voltages[40].

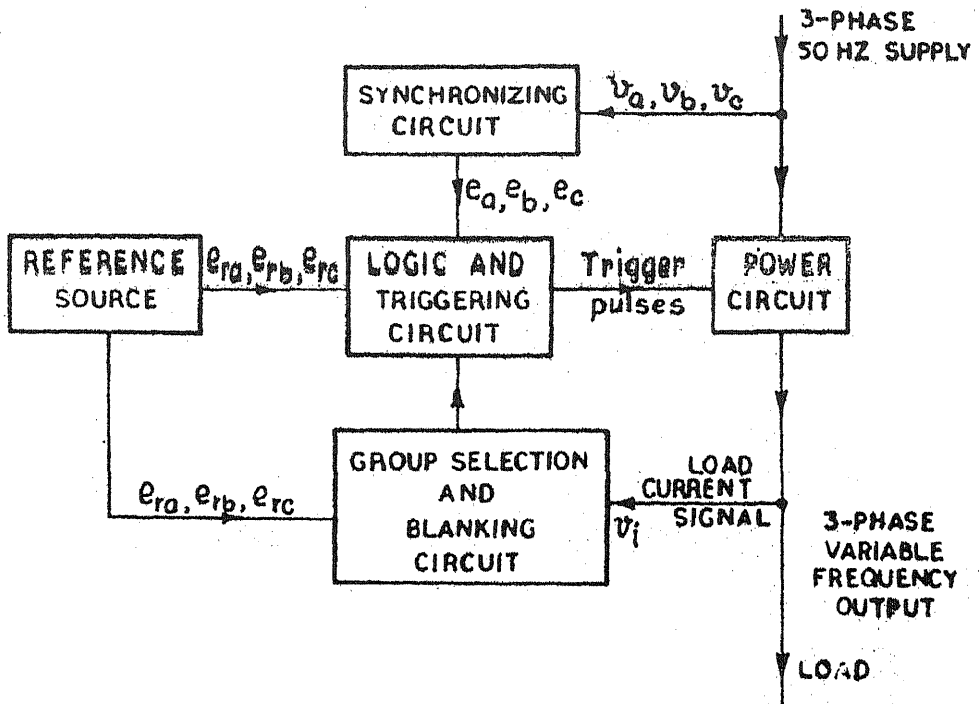FIG. 6. Derivation of P-group and N-group output voltages.

FIG. 7. Block diagram for a circulating current-free cycloconverter control circuit.[38]
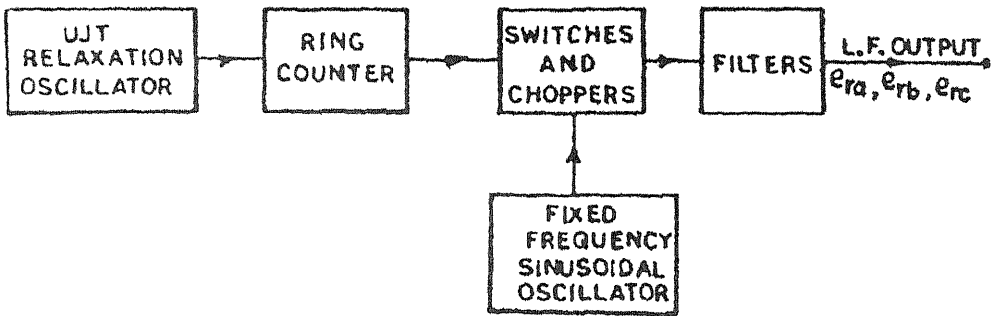
FIG. 8. Block diagram of the variable voltage, variable frequency three phase reference source[38].

Power Electronics Laboratory in IIT Kharagpur. Out of the various blocks shown, the group selection and blanking circuit is not needed for the circulating current mode operation of the cycloconverter.

The synchronising circuit produces the modulating voltages of the input frequency through step-down transformers. One of the ways of obtaining 3-phase variable voltage variable fre-

C – COMPARATOR
I – INVERTER
M – MONO-STABLE ($\bar{Q}$)
L – LATCH

FIG. 9. Block diagram of the main logic and triggering circuit (for phase a of the output only)[38].

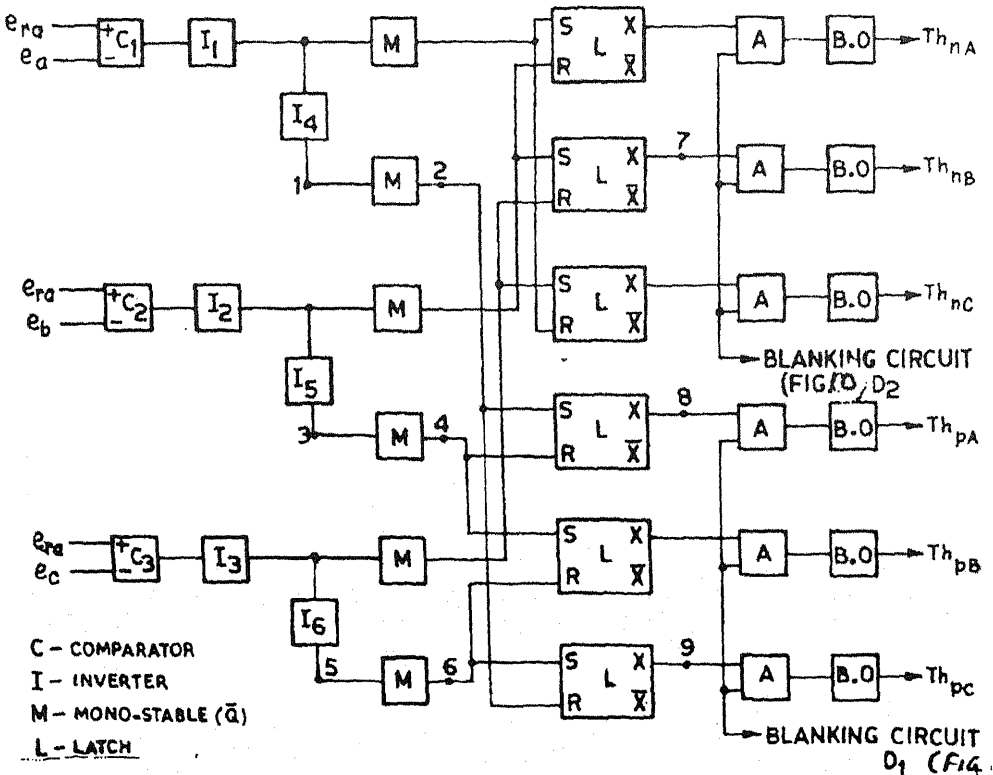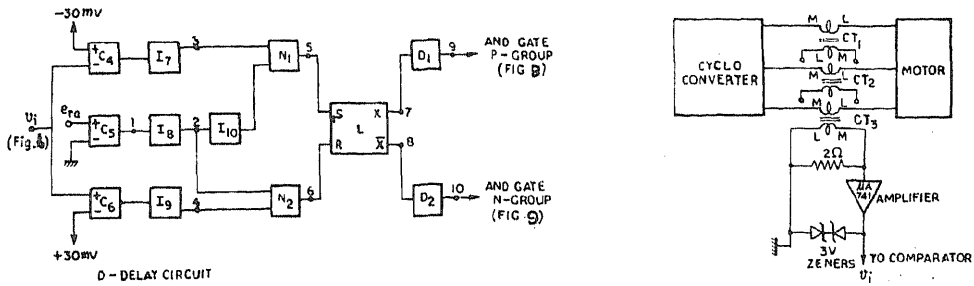FIG. 10a. Group selection and blanking logic circuit for phase a. b. Current sensing circuit[18].

quency reference source using a simple hardware circuit is shown in Fig. 8, when a variable-frequency UJT relaxation oscillator of frequency $6f_d$ triggers a 3-stage ring counter to produce 3-phase square-wave output of frequency f_d which is used to modulate a 1-phase fixed frequency (f_c) variable amplitude sinusoidal voltage in a 3-phase full-wave transistor chopper. The 3-phase output contains $(f_c - f_d)$, $(f_c + f_d)$, $(3f_d + f_c)$ etc. frequency components from where the 'wanted' frequency component $(f_c - f_d)$ is filtered out by using low pass filters. For example, with $f_c = 500$ Hz and frequency of the relaxation oscillator varying between 2820 to 3180 Hz, a 3-phase 0-30 Hz reference output can be obtained with the facility for phase-sequence reversal. The block diagram of Fig. 9 shows the main logic and triggering circuits for one of the phases - where comparators are used to compare the reference voltages with modulating voltages and the inverters shown act as buffer stages. Outputs from the latches feed the thyristor gates through AND gates and blocking oscillators, the second input to the AND gates being from the group-selection and blanking circuit. The 'first zero' crossing of the current which may be discontinuous at the end of each half cycle is detected by a current-sensing circuit and processed through the group-selection and blanking circuit (Fig. 10, for one of the phases) where comparators also monitor the reference voltage source apart from load currents to ensure proper group switching. The delay circuits delay the gate signals to the N-group thyristors until the already conducting P-group thyristors are completely off to avoid circulating currents.

Fig. 11 shows typical oscillograms of the output currents of the implemented cycloconverter feeding induction motors at two different frequencies.
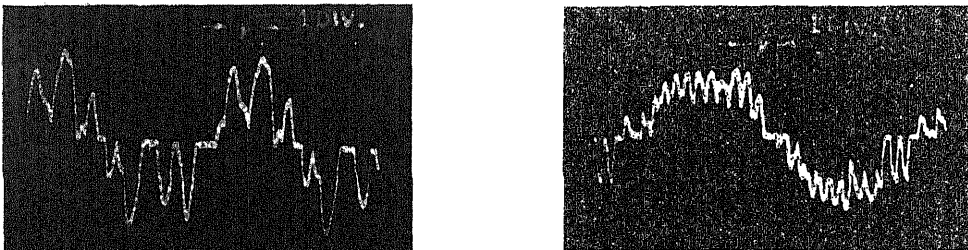

FIG. 11. Typical oscillograms of cycloconverter-fed induction motor current at (a). $16\frac{2}{3}$ Hz (b) 5 Hz.
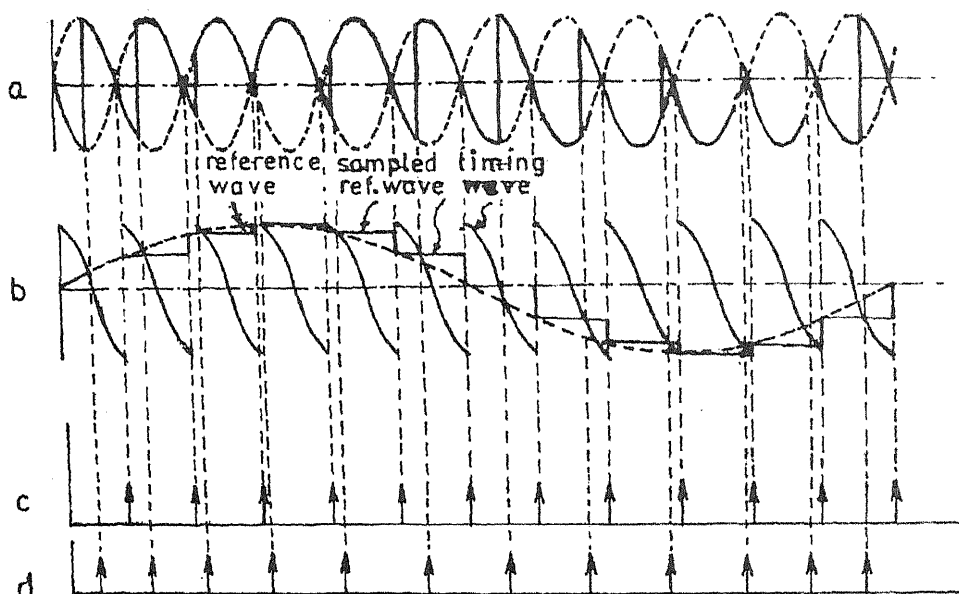
FIG. 12. Cycloconverter operation with regular sampling [26].

2.2.2. Improved control schemes

The output voltage of the cycloconverter contains a complex harmonic pattern given by $k_1 n f_i \pm k_2 f_o$ where n = pulse number and k_1 and k_2 are integers[31]. Although the high frequency harmonics are low with 'cosine wave control', significant subharmonics are produced whose magnitudes are high enough to cause objectionable current in a motor and restrict the output frequency range (e.g., with 50 Hz input frequency and 35 Hz output frequency, a subharmonic of $3 \times 50 - 4 \times 35 = 10Hz$ is produced whose magnitude is 12.5% of 35Hz component). Modification of the firing control using communication principles like 'regular sampling' (Fig. 12) in preference to 'natural sampling' (Fig. 4) of the reference voltage waveform before comparison with the cosine wave has been shown[26-27] to reduce the subharmonics with circulating current cycloconverters leading to expansion of the operating frequency range. A microprocessor-based digital cycloconverter control implementing this scheme is reported in[51]. The application of a fast current control loop in circulating current cycloconverteres and reducing the non-current delay during cross-over also lead to the increase the output frequency range[28]. Another method to improve performance is to use a 12-pulse cycloconverter using 72 thyristors[47,48] which can be only cost-effective for very large (say, 3 MW) drives.

The generation and synchronisation of low frequency three phase sine-waves over a wide range is a difficult problem and several techniques, analog and digital have been presented in the literature[41,45]. An all digital approach which overcomes the poor frequency stability problems is to use EPROM devices to store a digitized representation of the desired output waveform[45,46]. A recent development is to use a hybrid-firing controlled incorporating both digital and analog methods[46]. Current-zero detection schemes with current transformers may not be

sufficient for very low frequencies. Alternative schemes like continuous monitoring of voltage across each thyristor[37] or conduction state of each SCR series thyristor-diode circuits[6] may simplify the requirements of an accurate bank selection signal for eliminating the need of large interphase reactors.

2.3. *Microprocessor-based control schemes*

With the rapid development of microprocessors, software control of cycloconverters has been attempted[49-60] to reduce cost and complexity and increase the accuracy and reliability of the controllers. Early attempt[49] was to directly implement the conventional cosine timing wave approach in connection with sinusoidal reference voltage - in which case it was recognised that the digital comparison of two trigonometric functions as proposed by the numerical technique was too slow to be practical. An efficient algorithm was presented in[51] using regular sampling method with desirable output performance. Experimental arrangement was built around M6800 evaluation kit with MC 6840 timer module and an MC6820 pia unit. There was no need to generate three actual timing waves, nor a continuous reference signal and six channel comparator circuits as in the analog case.

Later developments includes the digital cycloconverter control (DCC) based on the subdivided interval principle[54] where a sinusoidal output voltage is approximated by a stepped waveform to get a suitable amplitude for the mean output voltage at each subdivided interval - the mean value of which was utilised to determine the firing angles. New methods are suggested in[56,59,60] where all the input cosine waves are transferred with a set of parallel lines by means of co-ordinate transformation or a phase plane called a 'time process chart'. The straight line approximations avoid the use of trigonometric or inverse trigonometric functions. Some improvements in implementing cosine wave crossing pulse timing methods in microcomputer-based cycloconverter have been suggested[58] recently.

2.4. *PC-based hybrid control scheme*

For a six pulse non-circulating current cycloconverter-fed synchronous motor drive with a vector control scheme and flux observer, a combination of analog and digital control (called hybrid control scheme) has been recently developed at IIT Kharagpur[94]. Here the function such as comparison, group selection, blanking between the groups and the triggering signal generation, filtering and phase conversion are left to the analog controller and the digital controller takes care of more serious tasks like voltage decoupling for current regulation, flux estimation using observer, speed, flux and field current regulators using PI-controllers, position and speed calculation leading to an improvement of sampling time and design accuracy. The scheme as shown in block diagram form in Fig.13 has been implemented with a 386-DX PC based system with 387 support[94].

3. Cycloconverter-controlled induction motor drives

In earlier applications[63], cycloconverter fed multiple induction motor drives were used to drive hot-strip mill run out table motors. In one installation, 300 motors of 2.6 hp, 212 rpm each were used and the speed range (13-0-13 Hz) with 6 pole was suitable for the application with a 60 Hz system. Individual induction motor drive for high performance servo applications with in-
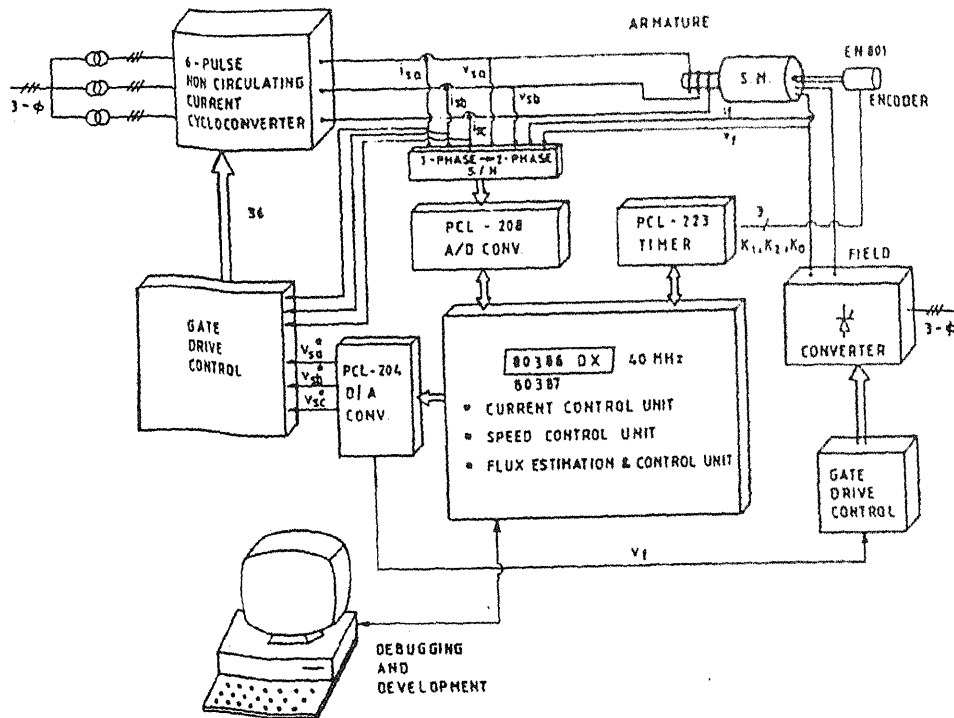
Fig. 13. Hybrid implementation of a cycloconverter-fed synchronous motor with a 386 PCAT[74].

corporated 'slip-limit' device[30], 'flux controller'[65] and controlled slip-frequency drive for diesel electric locomotive[66] were developed in 1960's. Slip power controller drives with slipring induction motors either in the form of a cycloconverter type thyristor commutator[20] in the rotor to inject a slip-frequency emf as in the case of a stator-fed commutator motor (Fig. 14) or with a normal cycloconverter[21-22] were also developed. Another interesting application of cycloconverter was in realising the dc series motor characteristics with stator and rotor windings connected in series[69] where the torque angle was controlled by a shaft coupled transducer which manipulates the firing of the thyristors (Fig. 15) to provide a stabilised operation.

The development of vector-control or field orientation control in Germany[77] and its implementation[67] with microprocessors for both induction and synchronous motor control boosted up their applications for large capacity (> 1 MW) cycloconverter drives. This method of control permits optimum transient response of the drive. Though synchronous motors have been preferred in these schemes as described in the next section, with the improvements of their ratings and development of large capacity reactive power compensated cycloconverter[93] and absence of excitation control loop, the induction motor having a simple and robust structure, easy manitainability and quick response is now being favoured for cycloconverter applications in rolling mill drives, particularly in Japan[17,71]. A microcomputer-based cycloconverter-fed induction motor drive for seemless tube piercing mill is described in[17] where a squirrel cage 6 pole, 3 MW, 188/300 rpm, 9.6/15.38 Hz, 2700 V motor with overload capacity of 200% for 60 secs is controlled by a cycloconverter bank of capacity 3750 KVA and output voltage 3190 volts. The
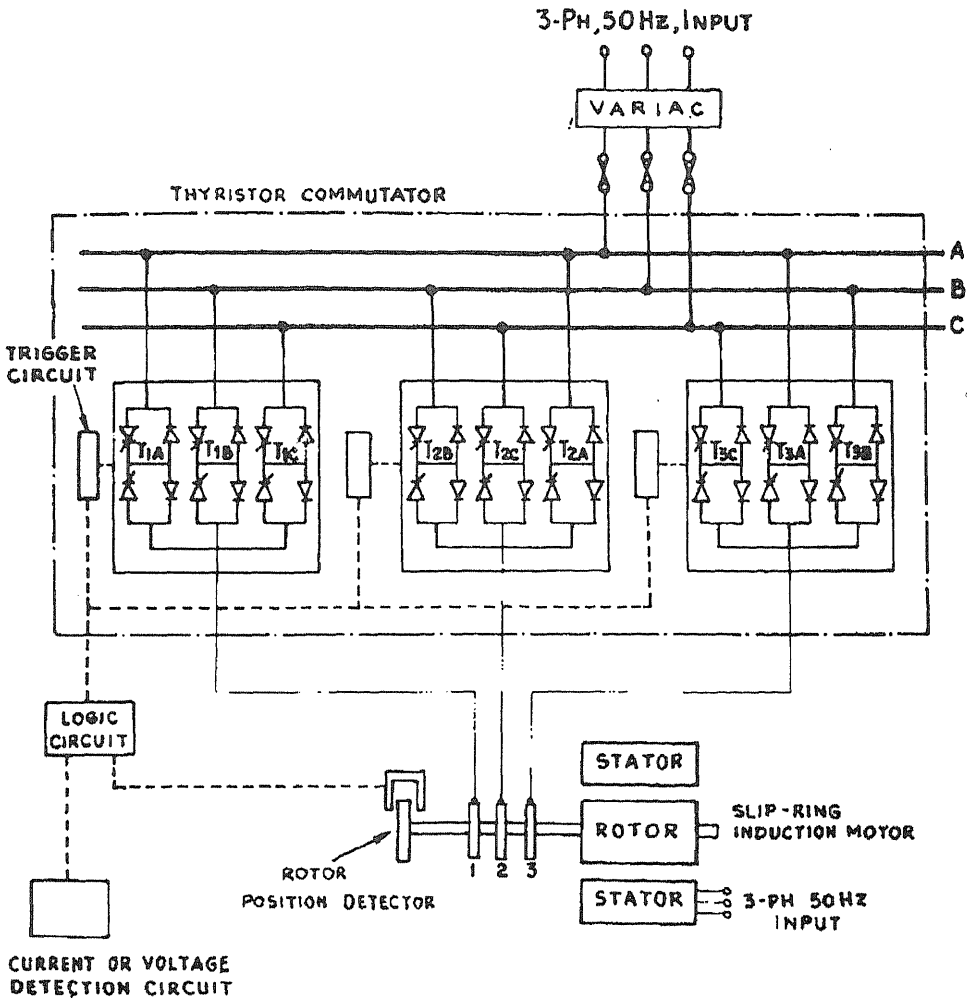
FIG. 14. Cycloconverter-type thyristor commutator motor[20].

control scheme as developed by Toshiba with Sumitomo Industries of Japan consists of three 16-bit microprocessors and six single chip microcomputers for executing various control functions and firing of 72 thyristors. A high performance cross-current type cycloconverter configuration, controlled by two 16-bit microprocessors was suggested in[62] where the output voltage waveform is built up by simultaneously using positive and negative converters and allowing the mean voltage of the two converters to appear across the load. The advantages claimed are increase of output frequency limit and high input pf.

4. Cycloconverter-controlled synchronous motor drives

The first ever experimental semiconductor cycloconverter variable drive began with a synchronous motor drive[91]. The cycloconverter-fed synchronous motor proved itself successful in
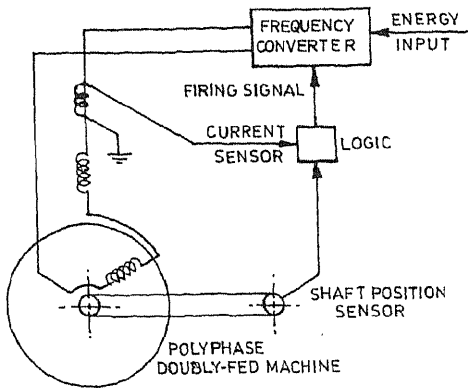
FIG. 15. Cycloconverter control of a doubly-fed induction motor[60].

practice in the cement industry for large gearless Tube or Ball mills (8 MW) since early 1970's as developed by Siemens and Brown Boveri. One of the early installations (1969) employs a motor rating of 8700 hp, having a rotor drum 5 m in diameter and 16.5 m long while the stator

FIG. 16. Block diagram of the stator flux oriented vector control scheme with flux observer for a cycloconverter-fed synchronous motor[94].

construction was similar to that of a hydroelectric generator with 44 poles requiring 5.5 Hz for maximum speed of 15 rpm. The motor is flanged into the mill cylinder without any additional bearings or 'wrapped' directly round it - known as 'ring motor'[10]. With 'self control mode' or as 'commutatorless ac motor'[95], hunting and stability problems are eliminated and the torque is not limited to pull out value.

With field control, the operation can be at unity power factor. With 'field orientation' or vector control[18,25,92,94] (Fig. 16), the transient magnetizing current demand to maintain the rated flux can temporarily be supplied from the stator side to improve the response time instead of the field current control which is sluggish because of large time constant. A stator flux oriented vector control scheme for a 6-pulse non-circulating current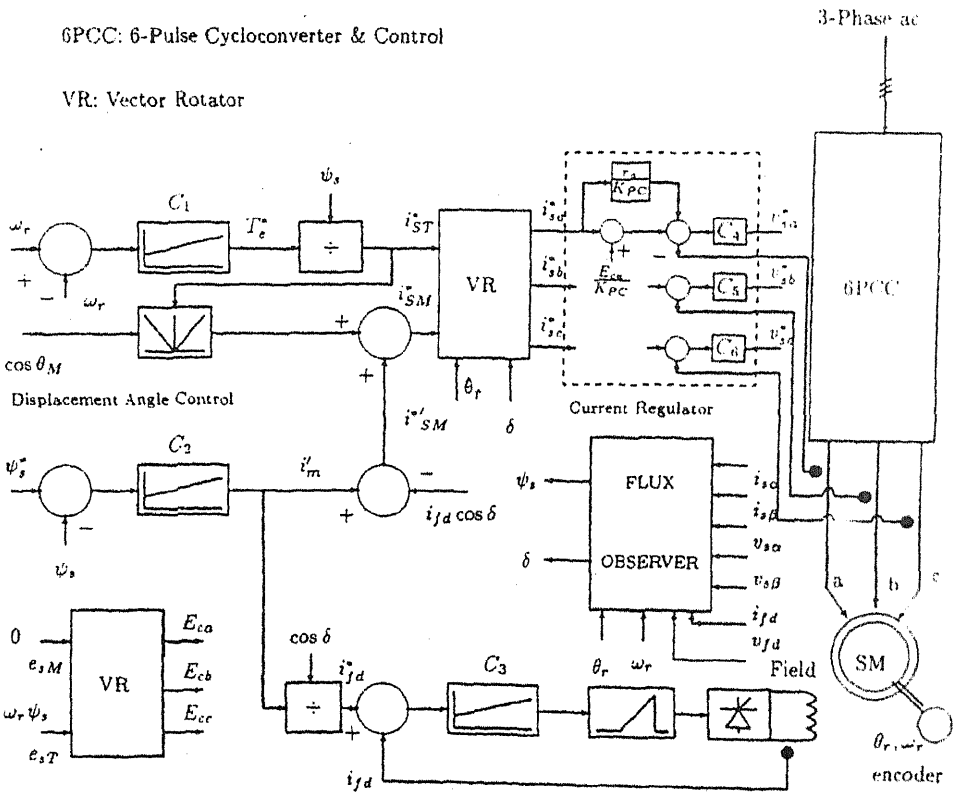 cycloconverter-fed synchronous motor with a flux observer as developed recently at I.I.T. Kharagpur for a rolling mill drive is reported in Reference [94]. Fig. 16 shows the implementation scheme which aims at a stator flux oriented vector control that maintains a spatial orthogonality between the flux vector ψ_x and the armature current vector i_a as shown in the space phasor diagram of Fig. 17. The reference speed and the reference flux commands are given to the vector controller that generates the reference analog voltages for the cycloconverter and the field converter. The stator flux is estimated by a closed loop robust reduced order flux observer. Referring to Fig. 16, C_1 is the speed controller that generates the torque command which is divided by the stator flux to generate the torque component of current i_{ST}. The magnetising current along the flux axis $\left(i'_m\right)$ is obtained from a flux controller C_2. The transient stator flux component of current i_{SM}^* is obtained from the relationship, $i_{SM}^* = i'_M - I_{fd} \cos\delta$ which decays down to zero in the steady state. The steady state displacement angle is decided by the displacement angle controller. The set value of the field current is obtained from the relation $i_{fd}^* = i'_M / \cos\delta$. C_3 is the field current controller that generates the control voltage for triggering the field converter. The vector rotator (VR) transforms the vectors from the two-axes flux-torque reference frame to abc stationary reference frame. The observer and the controller design aspects together with a PC-based implementation are detailed in Reference[94].

The application of cycloconverter-fed synchronous motor drive with vector control have been extended to rolling Mills[16] (2/4 MW), mine-winders and haulage[24] and traction[15] which were dominated by dc drives due to requirements of speed accuracy and dynamic speed control. Methods of compensating armature reaction and control delay of current control circuit were suggested in Reference[75].

.Two different modes of operation were used to control the cycloconverter over the entire speed or frequency range for a cycloconverter-fed synchronous motor drive[18]: sinusoidal and trapezoidal. The trapezoidal mode is employed to improve the mains power factor in the upper speed range where the cycloconverter also has to supply higher voltages. Closed loop control methods with static and dynamic flux models were also described in Reference[76].

Synchronous machines have been preferred as they can be built for higher capacity at low speed and their speed can be maintained constant for a particular frequency regardless of load or line voltage variation and the line power factor can be improved through excitation control with possible dual method of commutation[14].
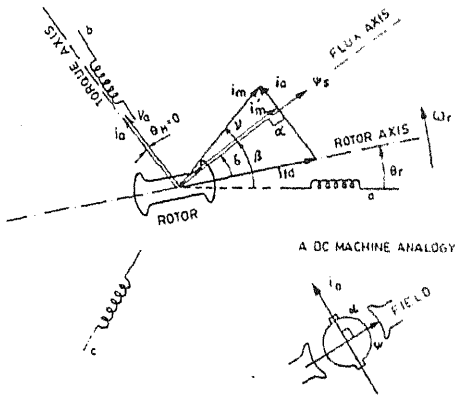
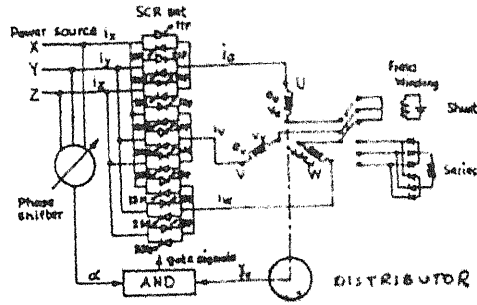FIG. 17. Space phasor diagram of a vector controlled   FIG. 18. Cycloconverter-fed commutatorless motor.
synchronous motor[94].

An extremely flexible drive arrangement of a cycloconverter-type commutatorless motor
with no theoretical speed limit was reported in[72], Fig. 18, where both line and load commutation
are employed and thyristors are triggered by a shaft position sensor. Depending on how the
machine-field is connected, the machine characteristics can be 'series' or 'shunt' type.

5. Modelling and simulation analysis of cycloconverters drives

The non-linearity and discrete time nature of the cycloconveter-machine system makes an exact
analysis quite complex. An ac equivalent circuit (Fig. 19) was developed earlier[79] with simplify-
ing assumptions for a cycloconverter and was proposed for use with motor equivalent circuit to
determine the performance of the cycloconverter-fed drives. However, a valuable design tool is
the simulation of the drive system in an analog/digital/hybrid computer by which the effects of
parameter variation can be readily examined and different open loop and closed loop designs
may be tested by studying the dynamic performance without costly and time-consuming ex-
periments with hardware.

Digital and hybrid computer simulation of induction motor drive fed from group - triggered
mode cycloconverter which provides a trapezoidal waveform have been studied earlier[80,81]. A
comprehensive two-axes digital model of a 3-pulse phase controlled cycloconverter-induction
motor system suitable for dynamic and steady state analysis of the systems was presented[82,83].
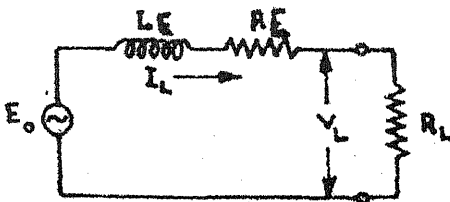
FIG. 19. Cycloconverter equivalent circuit [79], $R_E =$ FIG. 20. Representation of induction motor with
$(p/2\pi)w_sL$; $L_E = L$; $E_0 = KE_{d0} \sin w_0 t$.   switchings in the stator[83].
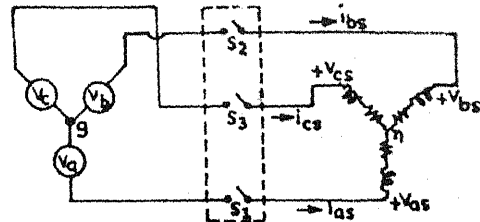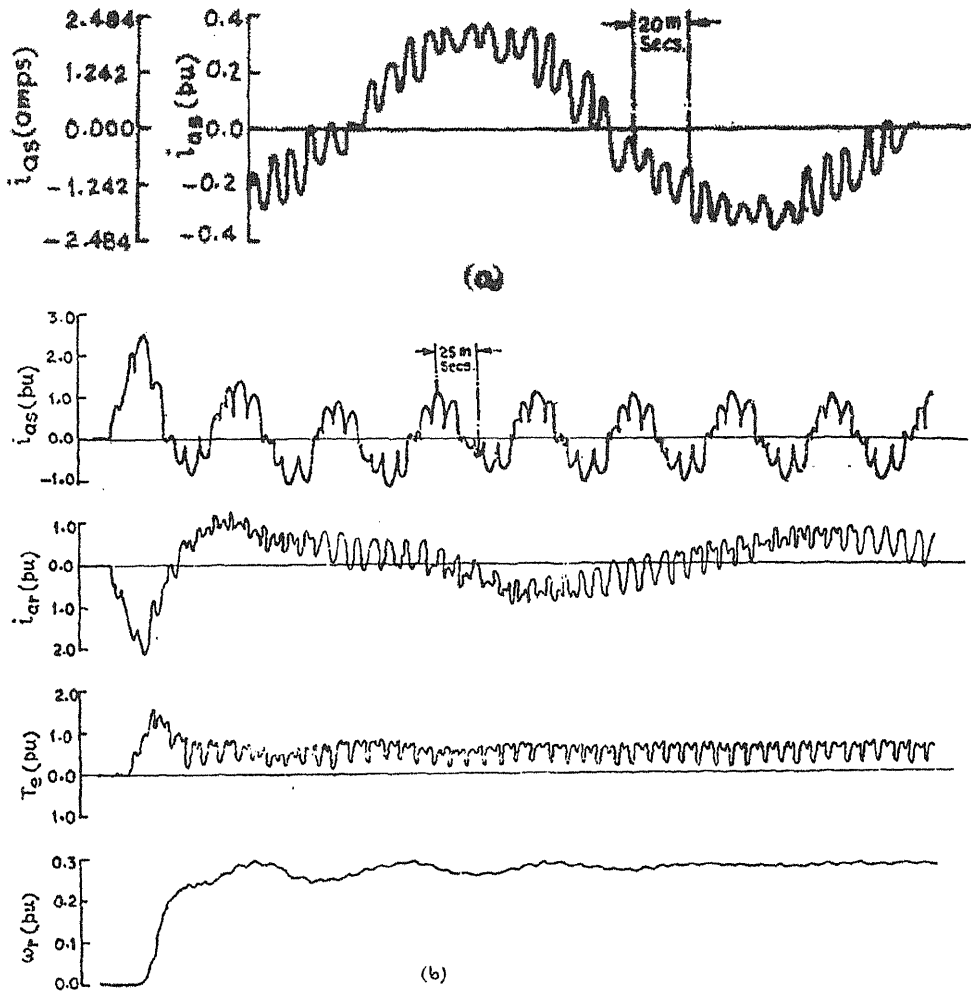
Fig. 21a. Digitally computed steady-state current waveform for 5 Hz. b. Dynamic performance of induction motor with 3-pulse cycloconverter. Digital simulation results. $f_o = 16$ Hz, $k_r = 0.806$, $V_s = 0.5$ pu, $T_L = 0.5$ pu (Non-circulating current mode)[82].

for both continuous and discontinuous current operation under circulating as well as non-circulating current operation. The induction motor model used follows the approach suitable for any reference frame[84]. A generalized mathematical model has been derived in Reference[83] for this purpose using switching variables to represent thyristors' conducting states (Fig. 20) and combining five sets of equations in five relevant modes of operation involving only a 4×4 matrix without need of any matrix inversion. The cycloconverter model for digital computation of output waveforms is discussed in Reference[85]. One of the methods which is very fast and convenient is the 'cross-over points' method - which gives the cross-over points (intersections of modulating and reference waves) and the conducting phase numbers for both P- and N groups

from which the output waveforms for a particular load current may be digitally computed at any interval of time as in a practical cycloconverter. Typical computer results presented in Fig. 21. show the dynamic and steady state performance of the system as computed. An experimental oscillogram recorded for the same condition has been shown in Fig. 11 earlier. An attempt to obtain directly (without iteration) the steady state performance of the same drive by using 'state variable technique has also been reported[86]. Both analog and digital computer simulations of an induction motor drive with cycloconverter-type thyristor-commutator in the rotor have been presented earlier[87,88]. Analysis of dynamics of a cycloconverter- fed squirrel cage motor for mine winders by computer simulation was reported quite early[89]. A simulation study of an optimal numerical control of a cycloconverter is reported in Reference[90].

A simulation method for cycloconverter-fed 3-phase and 6-phase synchronous motors based on equivalent voltage sources during discontinuous stator current was presented in Reference[96]. Digital simulations as developed for a vector-controlled six-pulse cycloconverter-fed synchronous motor drive with flux observer are detailed in[94,100], and for a a.c. commutator motor with
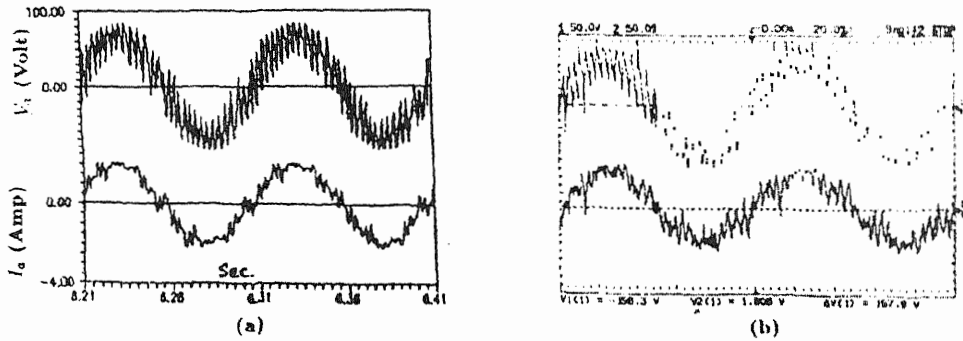
FIG. 22a. Sinusoidal mode of operation (a) Simulated (b) Experimental[95] 6-pulse cycloconverter-fed synchronous motor drive, 300 rpm, U.P.F.
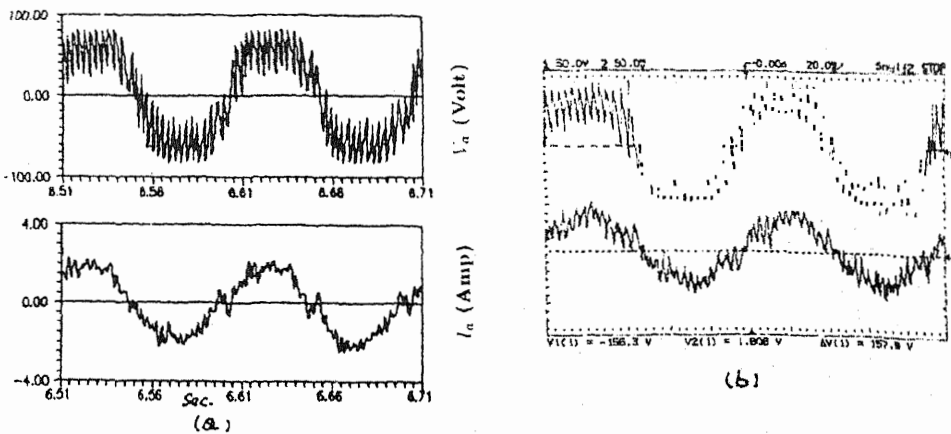
FIG. 22b. Trapezoidal mode of operation (a) Simulated (b) Experimental[95].
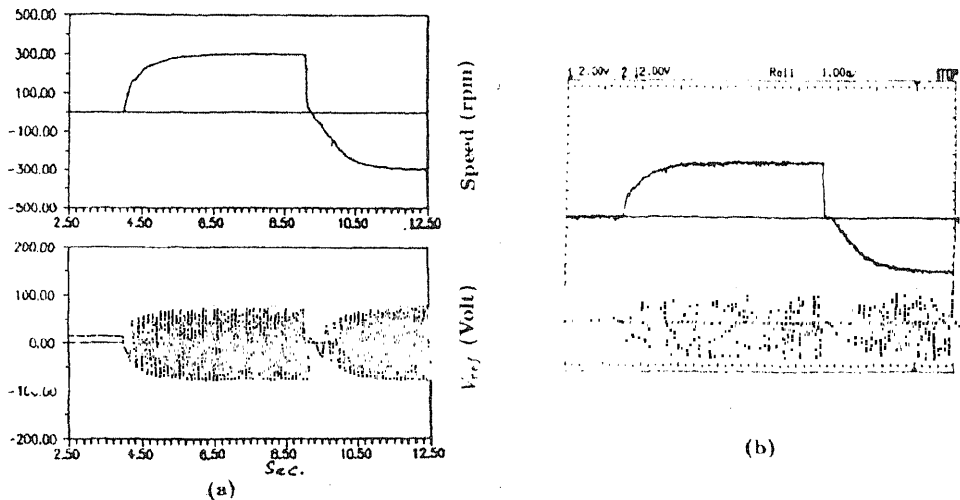
FIG. 22c. Response of the drive to step speed changes (a) Simulated (b) Experimental[95] +300 to –300 rpm.

out vector control in[95]. Fig.22 shows typical simulated and experimental results (for sinusoidal and trapezoidal mode of operation). The factors to be considered for selecting either a synchronous motor or an induction motor for cycloconverter use have been discussed in a recent paper[99].

6. Conclusions

A comprehensive but brief survey of cycloconverters and their applications to the control of ac drives has been presented here to provide background information regarding the present research and development trends in the area. Systems employing cycloconverter are gaining ground steadily with inclusion of microcomputers and literature on them have proliferated. Only some salient features and significant developments have been highlighted here and for proper design and evaluation for a particular application, one has to study in depth many trade-off considerations and relevant texts given in the references.

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