Contents

List of Figures

Abstract

This project presents a new single-phase to three-phase cycloconverter suitable for driving an induction motor. Using discrete variable frequency technique, a single-phase to three-phase modulation strategy is proposed, the output frequency of this cycloconvertor can be up to half of the input frequency. Only six naturally communicated thyristors are employed, so the resulting cycloconverter-motor drive system is cheap and compact. Software in C and assembly language has been written for real-time control. The simulation based on Matlab/Simulink is used to predict the performance for the cycloconverter and induction motor.

Chapter 1

Introduction

The three-phase induction motors have some advantages in the machine efficiency, power factor, and torque ripples compared to their single-phase counterparts. Therefore, it is desirable to replace the single-phase induction motor drives by the three-phase induction motor drives in some low-power industrial applications [1]. However, in some rural areas where only a single-phase utility is available, we should convert a single-phase to a three-phase supply.

The conventional method for conversion of a single-phase to three-phase voltage is the utilization of rotary, capacitor or autotransformer converters [2, 3, 4]. Most of these converters remain balanced only at one specified load. There are also many converter topologies that can transform a single-phase AC voltage into variable voltage, variable frequency three-phase voltages supplies [5-10]. Fig.1.1 shows the schematic of the single-phase to three-phase rectifier-inverter system. The voltage transformation generally takes place in two stages: the single-phase AC voltage is converted to a regulated DC voltage which is subsequently mapped into three-phase variable frequency and variable voltage sources. In these topologies, one or two relatively high capacity DC link capacitor is required. The cost of the inverter drive limits its applications.

The thyristor or triac based AC voltage controller using the phase control principle has been popularly used in low power induction motors. The cycloconverter provides one stage AC to AC power conversion. Since this system does not have an energy storage element, it is easy to implement in a small size and achieve a long life. However, for a single-phase supply, it is hard to implement cycloconverters. J. Zhang, G.P. Hunter, et al. have proposed a compact cycloconverter consisting of six triacs as shown in Fig.1.2. Its output is a three-phase supply with variable voltage and variable frequency.

This project is the continuation of the authors work on a cheaper single-phase to three-phase converter for small induction motors. A new simple single-phase to three-phase cycloconverter based on discrete variable frequency technique is proposed. The configuration, shown is Fig.1.3, only consists of six thyristors, and its output frequency can be up to 25Hz. The discrete variable frequency modulation strategy is explained in sections II. Simulation based on Matlab/Simulink is given in sections III.

To verify the proposed discrete variable frequency modulation, the TMS320LF2407A microprocessor is used to implement the core of the control function, which simplifies the hardware setup. Software in C and assembly language has been written for real-time control. The practical circuit for this cycloconverter is under test, and the experimental results will be presented later.

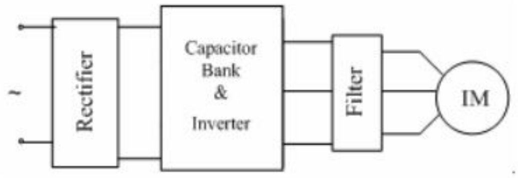


Figure 1.1: Schematic of fully controlled single-phase to three-phase

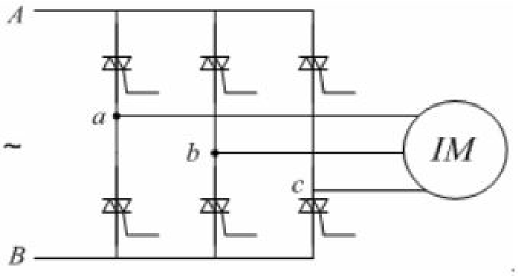


Figure 1.2: Power circuit of single-phase to three-phase cycloconverter

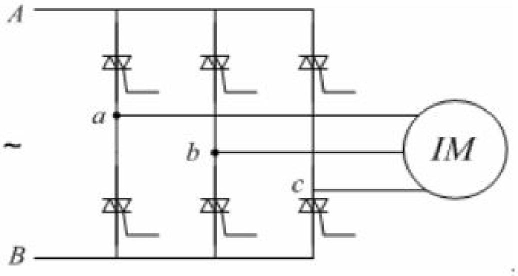


Figure 1.3: Configuration of proposed single-phase to three-phase cycloconverter

Chapter 2

Modulation Strategy

1. **Torque Control**

   The relation between stator currents and electromagnetic torque. Under balanced three-phase conditions, the instantaneous stator currents of induction motor are

$$i_a = I_m \cos\left(\omega_e t\right)$$

$$i_a = I_m \cos\left(\omega_e t - 120^\circ\right) \tag{2.1}$$

$$i_a = I_m \cos\left(\omega_e t + 120^\circ\right)$$

   Where I_m is the maximum value of the current. ω_e is the electrical angular velocity (unit:rad/s).

   Fig.2.1 shows the vector diagram of magnetic motive force (mmf) waves. Torque is produced by the tendency of the rotor and stator magnetic fields to align. Note that the figure is drawn with d sr positive, i.e., with the rotor mmf wave F_r leading that of the stator mmf wave F_s. The result of displacing the three winding by 120° in space phase and displacing the winding current by 120° in time phase is a single positive-traveling mmf wave

$$F = \frac{3}{2}\frac{4}{\pi}\left(\frac{k_w N}{p}\right) I_m \cos(\theta_e - \omega_e t) \tag{2.2}$$

   Where k_w is distributed winding of winding factor; N is total number of series turns per phase; p is the pole number; θ_e is the electrical space angle.

   The torque can then be expressed in terms of the stator and rotor mmf waves F_s and F_r

$$T = \frac{p}{2}\left(\frac{\mu_0 A}{2g}\right) F_s F_r \sin\sigma_s \tag{2.3}$$

Where μ_0 is the permeability of free space; A is the cross-section of magnetic path and g is the air-gap length.

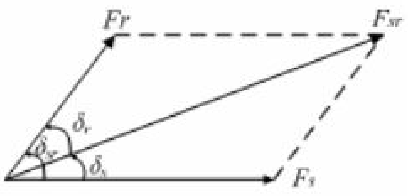
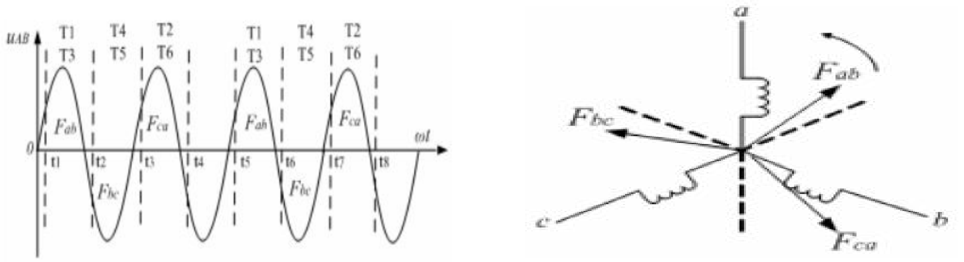


Figure 2.1: Vector diagram of mmf waves of a simplified two-pole machine

Equations 2.1 - 2.3 show that mmf waves are formed by the three-phase stator currents, and the rotating mmf waves produce the electromagnetic torque. i.e., the available electromagnetic torque can be produced by controlling the three-phase stator currents. This is the elementary theory of torque control.



(a) Input voltage and switching sequence (b) Vector diagram of the rotating mmf waves. a,b and c represent the stator windings.

Figure 2.2: Schematic of rotating mmf

Fig.5 shows the corresponding switching sequence with respect to the input voltage μ_{AB}. i.e., T1 and T3 are fired at t1 as shown in Fig.2.2(a). Then the current i_{ab} is obtained. As a result, i_{ab} produces the mmf vector F_{AB} . Similarly, T4 and T5, T2 and T6 will be fired at t2 and t3 respectively. Then the mmf vectors F bc and F ca are formed by i_{bc} and i_{ca} respectively.

Fig.2.2(b) shows the vector diagram of the rotating mmf waves. In order to obtain the positive torque, it is expected that the phase sequences of generated voltages under the new frequency are all positive. The strategy followed to convert the negative sequences into positive ones is unbalancing the system. Thus, the order triggered thyristors must ensure that the mmf vectors F_{ab}, F_{bc} and F_{ca} are produced following a fixed sequence, as shown in Fig.2.2(b).

Because there is no neutral wire, it must be ensured that there must be two thyristors fired at any time.

2. **Principle of discrete variable frequency**

Fig. 2.3 shows the schematic diagram of the proposed cycloconverter. It is composed of six thyristors, the analog interface, and a digital signal processor (DSP). The analog interface circuit receives the single-phase voltage and current. The proposed algorithm will be implemented for the control of the three-phase induction motor drives by a DSP TMS320LF2407A.

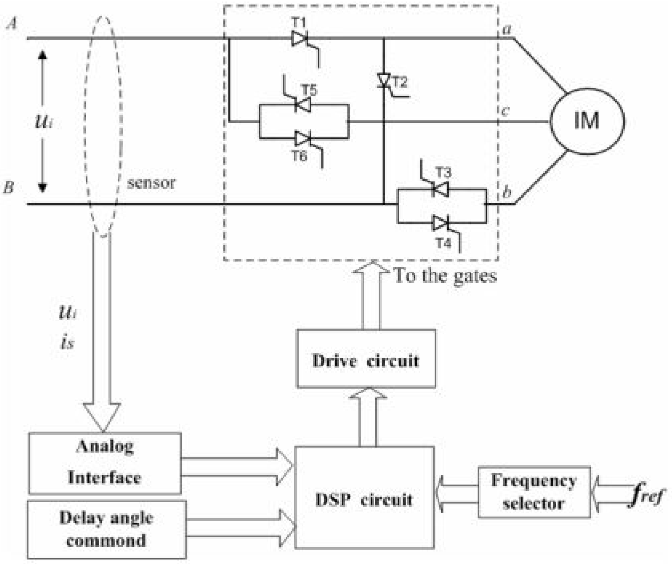
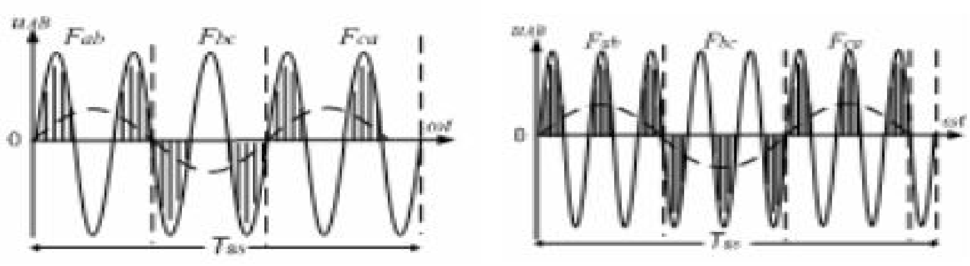


Figure 2.3: Schematic diagram for the proposed cycloconverter

Under the control of power supply frequency, reducing frequency will improve the electromagnetic torque of induction motors at starting. Through controlling the triggering angle of thyristors, discrete variable frequency voltage and current can be produced. Further more, these discrete variable frequencies are sub-harmonics of the ac power supply frequency, which are obtained



(a) 10 Hz

(b) 6.25 Hz

Figure 2.4: Structure for 10 Hz and 6.25 Hz. F_{ab} , F_{bc} and F_{ca} represent the mmf waves produced by the corresponding stator currents.

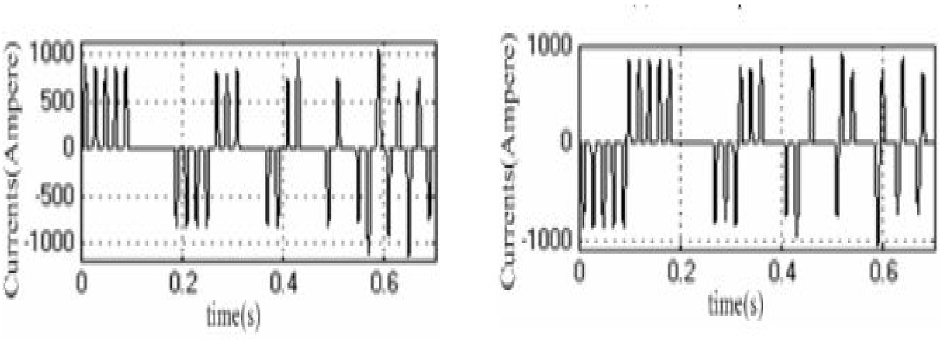
by triggering the thyristors so as to include or omit partial half cycles of the power supply voltage. This can be illustrated in Fig. 2, where the shaded are the included half cycles of the supply. The figure shows the partial half cycles used for generation of 10Hz and 6.25Hz, assuming the power supply frequency is 50Hz. The wave profile under new frequency is not sinusoidal. In effect, the meaning of new frequency implies the one of fundamental component of the generated voltage. Some other discrete frequencies generated from a 50Hz power supply are 25Hz, 16.67Hz, 12.5Hz, 4.55Hz and 3.57Hz.

Chapter 3

Simulation

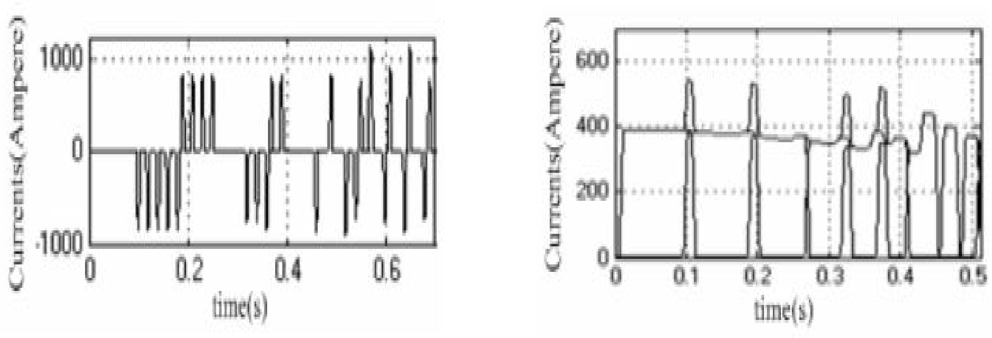
In order to investigate the proposed single-phase to three-phase cycloconverter and the discrete variable frequency modulation strategy, simulations were performed using SIMULINK with postprocessing of data in MATLAB.

The simulation has been carried out with a 380V, 50Hz single-phase supply. The motor selected for the test is an industrial 1475 rev/min, 380V, 130A, 50Hz star connected four-pole motor. The stator resistance r_s =0.03552 Ω. The stator inductance is L_{ls} =335mH. The rotor inductance referred to stator side is r'_r =0.02092 Ω. The rotor inductance referred to stator side is L'_{lr} = 335 mH. The mutual inductance is Lm=15.1mH. From the parameters the rated electromagnetic torque of the motor can be deduced, which is 356.3Nm. Fig. 3 to Fig. 3.4 are the simulation results during motor starting with 200Nm load. Fig. 3 shows a reduction in the RMS current during motor starting. The instantaneous stator currents are used to compute the RMS current value per cycle. The torque and speed of the four-pole motor is shown in Fig. 3. It can be seen that the electromagnetic torque is positive during motor starting. Fig. 3 shows that three-phase approximately symmetrical flux linkages have been obtained from the sing-phase supply. This is a precondition for satisfactory performance of the three-phase motor. Fig. 3.4 shows the supply current waveform.



(a) Current of phase a.

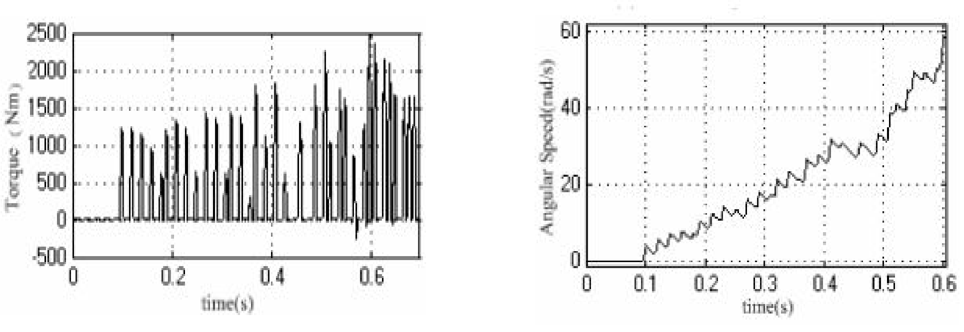
(b) Current of phase b.



(c) Current of phase c.

(d) RMS Amplitude of Stator.

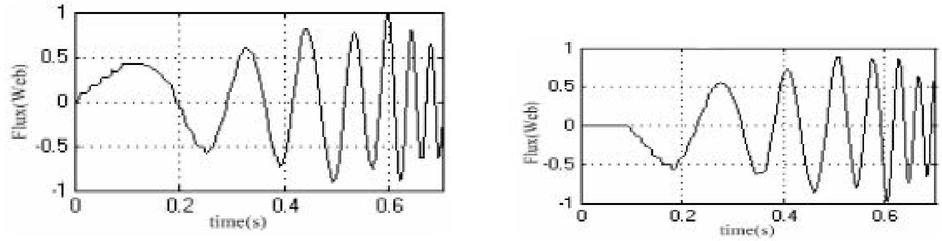
Figure 3.1: Stator currents of the induction motor.



(a) Electromagnetic torque.

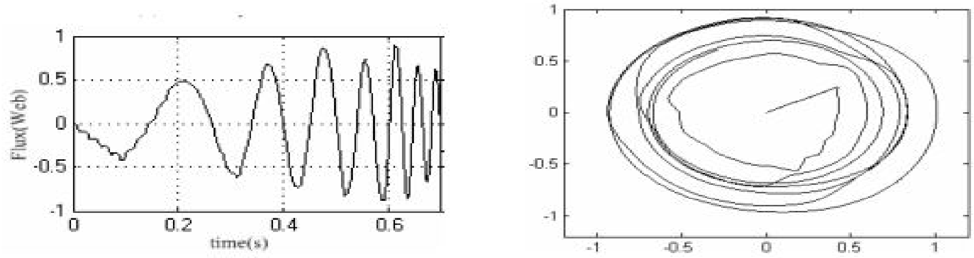
(b) Angular speed.

Figure 3.2: Torque and speed of the four-pole motor.



(a) Flux of phase u.

(b) Flux of phase v.



(c) Flux of phase w.

(d) Rotor flux Polygon.

Figure 3.3: Three Phase motor Flux linkage.

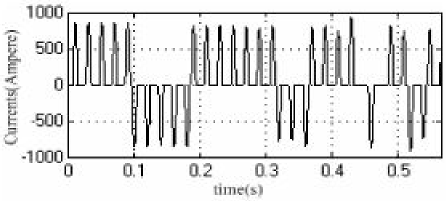


Figure 3.4: Supply Current to Cycloconverter

Chapter 4

Future Scope

New discrete variable frequency control strategy is applied to improve electromagnetic torque at starting and its output frequency can be up to half of the input frequency. Simulation results show the good performance of the cycloconverter and induction motor.

Chapter 5

Conclusion

This paper has proposed a new single-phase to three-phase cycloconverter for a three-phase induction motor drive fed from a single-phase supply. The configuration consisting of six thyristors is simple and compact. The main advantages of the topology include:

1. The thyristors can sustain high inrush currents for a short time, the rating of the drive may not need to be upgraded for higher starting torque requirement.
2. There must be two thyristors fired at any time.
3. This system is easy to implement in a small size for lacking of energy storage element.

New discrete variable frequency control strategy is applied to improve electromagnetic torque at starting and its output frequency can be up to half of the input frequency. Simulation results show the good performance of the cycloconverter and induction motor.

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CHAPTER 1

INTRODUCTION

1.1 What Is Cycloconverter

A cycloconverter is a type of power controlled in which an alternating voltage at supply frequency is converted directly to an alternating voltage at load frequency without any intermediate d.c stage.

A cycloconverter is to controlled through the timing of its firing pulses, so that it produces an alternating output voltage. By controlling the frequency and depth of phase modulation of the firing angles of the converters, it is possible to control the frequency and amplitude of the output voltage.

Thus, a cycloconverter has the facility for continuous and independent control over both its output frequency and voltage. This frequency is normally less than 1/3 of the input frequency. The quality of output voltage wave and its harmonic distortion also impose the restriction on this frequency.The distortion is very low at low output frequency.

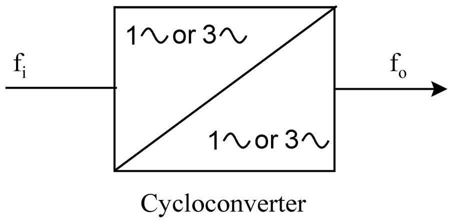


Fig 1.1:Block Diagram Of Cycloconverter

This work addresses with the continuous improvement of technology in power electronics and micro-electronics, variable voltage and variable frequency ac motor drives have come to increased use in various industrial applications. These new approaches need a simple method of control for ac motors. Control of ac motors become very popular because it is possible to obtain the characteristics of dc motors by improving control techniques. It is well-known that the control method of an ac motor is comparatively more difficult to realize because of involvement of various controllable parameters like voltage, current, frequency, torque, flux and so on. Though it is possible to achieve almost the same characteristics of dc motor using induction motor, it is very complicated to realize because of need for on line co-ordinate transformation and continuous need of either speed or position signal.

Cycloconverter eliminates the use of flywheel because the presence of flywheel in machine increases torsional vibration and fatigue in the component of power transmission system. Therefore it is eliminated from the design of any machine. Hence variable voltage variable frequency (vvvf) method is chosen to design three phase cycloconverter to drive three phase induction motor to get required frequency varying with different time interval that generates supply torque characteristics monitoring with demand torque.

1.2 Types Of Cycloconverter:

1.2.1 Single Phase To Single Phase Cycloconverter
1.2.2 Three Phase To Single Phase Cycloconverter
1.2.3 Three Phase To Three Phase Cycloconverter
1.2.4 Single Phase To Three Phase Cycloconverter

1.2.1 Single Phase To Single Phase Cycloconverter

To understand the operation principles of cycloconverters, the single-phase to single-phase cycloconverter (Fig. 2) should be studied first. This converter consists of back-to-backconnection of two full-wave rectifier circuits. Fig 3 shows the operating waveforms for thisconverter with a resistive load.The input voltage, V_s is an ac voltage at a frequency, f_i as shown in Fig. 3a. For easyunderstanding assume that all the thyristors are fired at α=0firing angle, i.e. thyristors act likediodes. Note that the firing angles are named as $_P$ for the positive converter and $_N$ for thenegative converter.

Consider the operation of the cycloconverter to get one-fourth of the input frequency at theoutput. For the first two cycles of V_s, the positive converter operates supplying current to theload. It rectifies the input voltage; therefore, the load sees 4 positive half cycles as seen in Fig.3b. In the next two cycles, the negative converter operates supplying current to the load in thereverse direction. The current waveforms are not shown in the figures because the resistive load current will have the same waveform as the voltage but only scaled by the resistance. Note that when one of the converters operates the other one is disabled, so that there is no current circulating between the two rectifiers.

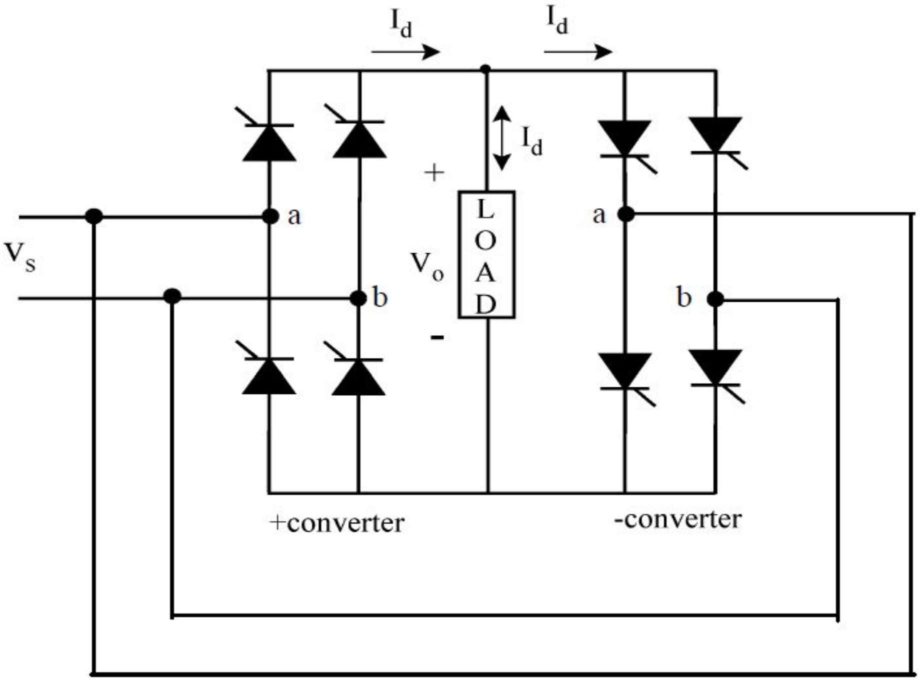


Fig 1.2:Single phase to single phase cycloconverter

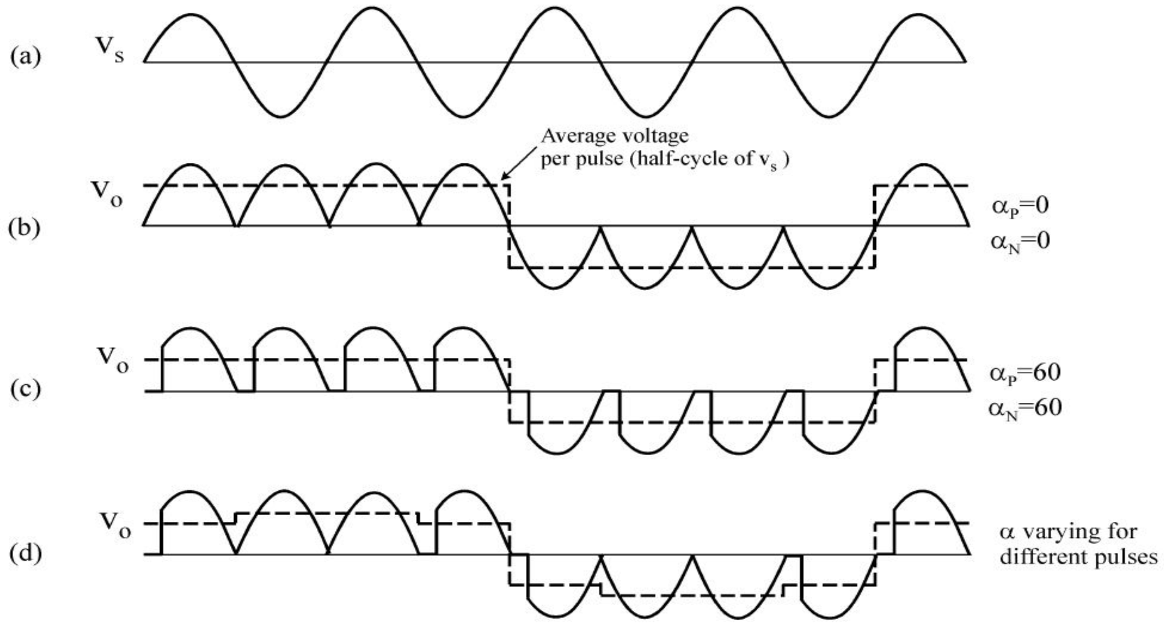


Fig 1.3:Waveform of Single phase to single phase cycloconverter

The frequency of the output voltage, v_o in Fig. 3b is 4 times less than that of v_s, the input voltage, i.e. $f_o/f_i=1/4$. Thus, this is a step-down cycloconverter. On the other hand, cycloconverters that have $f_o/f_i>1$ frequency relation are called step-up cycloconverters. Note that step-down cycloconverters are more widely used than the step-up ones. The frequency of v_o can be changed by varying the number of cycles the positive and the negative converters work. It can only change as integer multiples of f_i in 1-phase-1phase cycloconverters.With the above operation, the 1phase-1phase cycloconverter can only supply a certain voltage at a certain

firing angle α.The dc output of each rectifier is:

$$V_d = \frac{2\sqrt{2}}{\pi} V \cos\alpha$$

where V is the input rms voltage.

The dc value per half cycle is shown as dotted in Fig. 3d.

Then the peak of the fundamental output voltage is

$$v_{o_1}(t) = \frac{4}{\pi} \frac{2\sqrt{2}}{\pi} V \cos\alpha$$

Equation 2 implies that the fundamental output voltage depends on . For α=0,

$V_{o_1} = V_{do} \times 1 = V_{do}$ where $V_{do} = \frac{4}{\pi} \frac{2\sqrt{2}}{\pi} V$. If α is increased to π/3 as in Fig. 3d, then $V_{o_1} = V_{do} \times 0.5$.

Thus varying α, the fundamental output voltage can be controlled.Constantα operation gives a crude output waveform with rich harmonic content. The dotted lines in Fig. 3b and c show a square wave. If the square wave can be modified to look more like a sine wave, the harmonics would be reduced. For this reason is modulated as shown in Fig.3d. Now, the six-stepped dotted line is more like a sinewave with fewer harmonics. The more pulses there are with differentα's, the less are the harmonics.

1.2.2 Three-Phase to Single-Phase (3Φ-1Φ) Cycloconverter:

There are two kinds of three-phase to single-phase (3Φ-1Φ) cycloconverters:

3Φ-1Φhalf-wave cycloconverter (Fig. 4) and 3Φ-1Φbridge cycloconverter (Fig. 5). Like the 1Φ-1Φcase, the 3Φ-1Φcycloconverter applies rectified voltage to the load. Both positive and negative converters can generate voltages at either polarity, but the positive converter can only supply positive current and the negative converter can only supply negative current. Thus, the cycloconverter can operate in four quadrants: (+v, +i) and (-v, -i) rectification modes and (+v, -i) and (-v, +i) inversion modes. The modulation of the output voltage and the fundamental output voltage are shown in Fig. 6. Note thatα is sinusoidally modulated over the cycle to generate a harmonicallyoptimum output voltage.The polarity of the current determines if the positive or negative converter should be supplying power to the load. Conventionally, the firing angle for the positive converter is named P, and that of the negative converter is named N. When the polarity of the current changes, the converter previously supplying the current is disabled and the other one is enabled. The load always requires the fundamental voltage to be continuous.

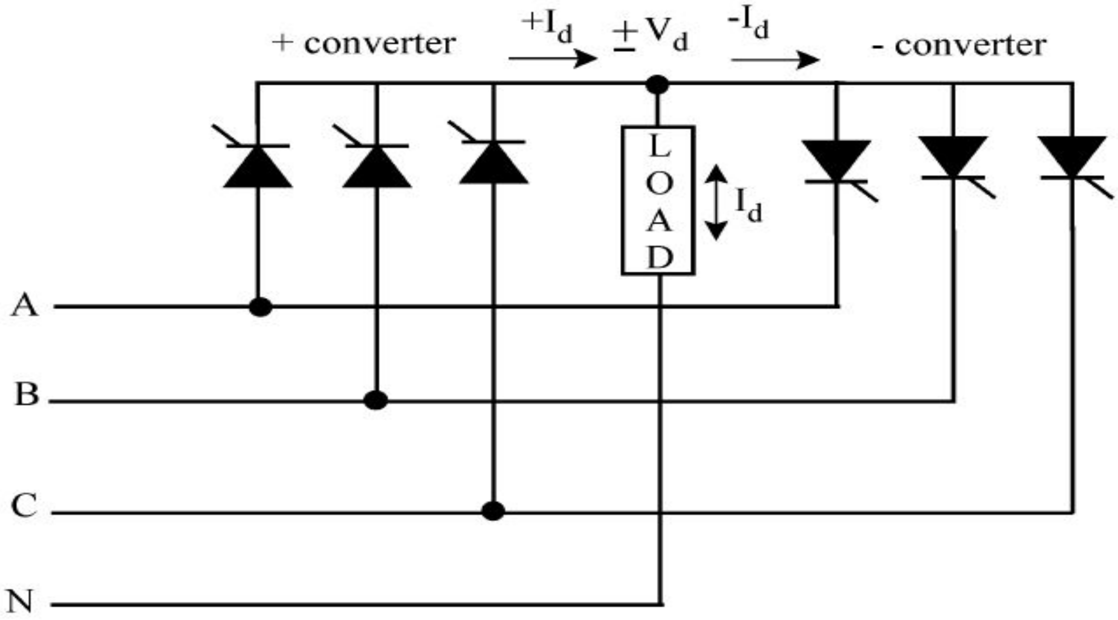


Fig 1.4: Three phase to single phase cycloconverter

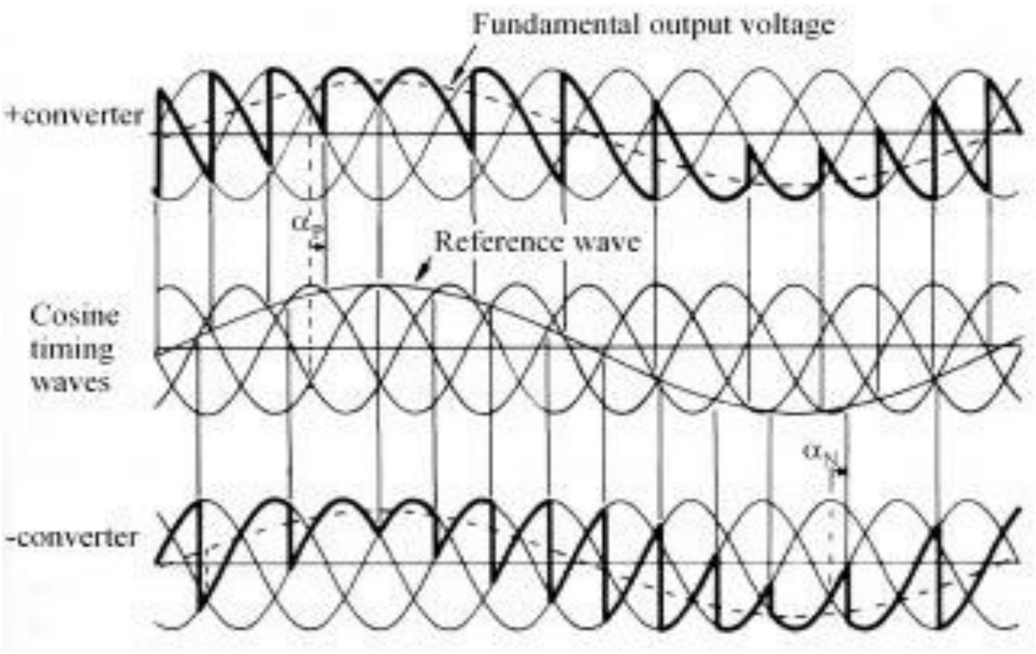


Fig 1.5: Waveform of Three phase to single phase cycloconverter

Therefore, during the current polarity reversal, the average voltage supplied by both of the converters should be equal. Otherwise, switching from one converter to the other one would cause an undesirable voltage jump. To prevent this problem, the converters are forced to produce the same average voltage at all times. Thus, the following condition for the firing angles should be met

$$\alpha_P + \alpha_N = \pi$$

The fundamental output voltage in Fig. 6 can be given as:

$$v_{o_1}(t) = \sqrt{2}V_o \sin \omega_o t$$

where V_o is the rms value of the fundamental voltage

At a time t_o the output fundamental voltage is

$$v_{o_1}(t_o) = \sqrt{2}V_o \sin \omega_o t_o$$

The positive converter can supply this voltage if α_P satisfies the following condition.

$$v_{o_1}(t_o) = \sqrt{2}V_o \sin\omega_o t_o = V_{do}\cos\alpha_P$$

Where,

$$V_{do} = \sqrt{2}V_o \frac{p}{\pi}\sin\frac{\pi}{p}$$

(p=3 for half wave converter and 6 for bridge converter)

From the αcondition (3)

$$v_{o_1} = V_{do}\cos\alpha_P = -V_{do}\sin\alpha_N$$

The firing angles at any instant can be found from above equations.

The operation of the 3ϕ-1ϕ bridge cycloconverter is similar to the above 3ϕ-1ϕ half wavecycloconverter. Note that the pulse number for this case is 6.

1.2.3 Three-Phase to Three-Phase (3Φ-3Φ) Cycloconverter:

If the outputs of 3Φ-1Φconverters of the same kind are connected in wye or delta and if the output voltages are 2/3 radians phase shifted from each other, the resulting converter is a three phase to three-phase (3Φ-3Φ) cycloconverter. The resulting cycloconverters are shown in Figs.7 and 8 with wye connections.If the three converters connected are half-wave converters, then the new converter is called a 3Φ-3Φhalf-wave cycloconverter. If instead, bridge converters are used,then the result is a 3Φ-3Φbridge cycloconverter.3Φ-3Φhalf-wave cycloconverter is also called a3-pulse cycloconverter or an 18-thyristor cycloconverter. On the other hand, the 3Φ-3Φbridge cycloconverter is also called a 6-pulse cycloconverter or a 36-thyristor cycloconverter. The operation of each phase is explained in the previous section.

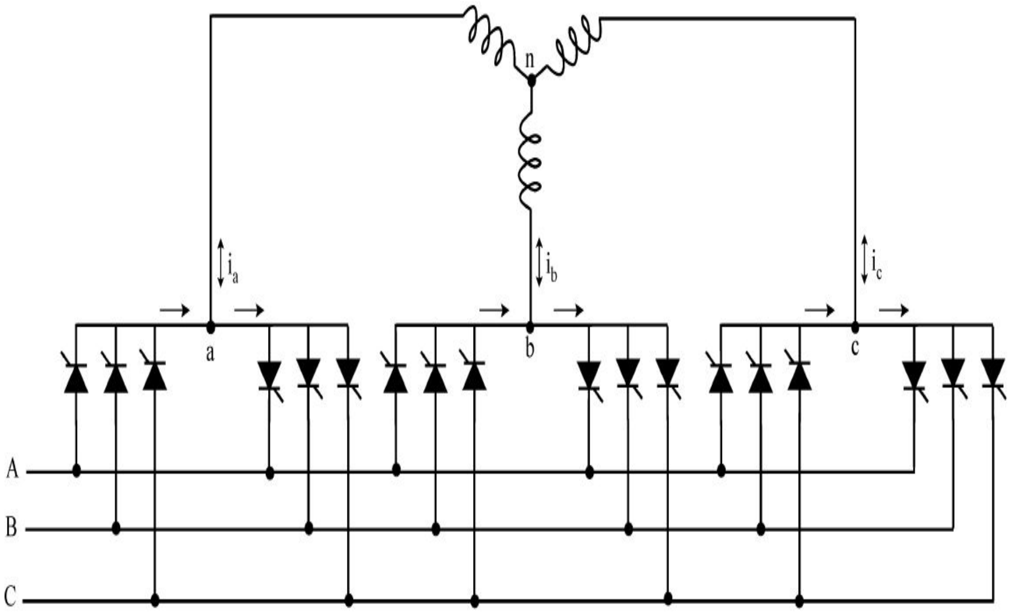


Fig 1.6:Three phase to Three phase cycloconverter

The three-phase cycloconverters are mainly used in ac machine drive systems running three phase synchronous and induction machines. They are more advantageous when used with a synchronous machine due to their output power factor characteristics. A cycloconverter can supply lagging, leading, or unity power factor loads while its input is always lagging. A synchronous machine can draw any power factor current from the converter. This characteristic operation matches the cycloconverter to the synchronous machine. On the other hand, induction machines can only draw lagging current, so the cycloconverter does not have an edge compared to the other converters in this aspect for running an induction machine. However,cycloconverters are used in Scherbius drives for speed control purposes driving wound rotor induction motors.

The operation of the 3ϕ-1ϕ bridge cycloconverter is similar to the above 3ϕ-1ϕ half-

Wave cycloconverter. Note that the pulse number for this case is 6.

Cycloconverters produce harmonic rich output voltages, which will be discussed in the following sections. When cycloconverters are used to run an ac machine, the leakage inductance of the machine filters most of the higher frequency harmonics and reduces the magnitudes of the lower order harmonics.

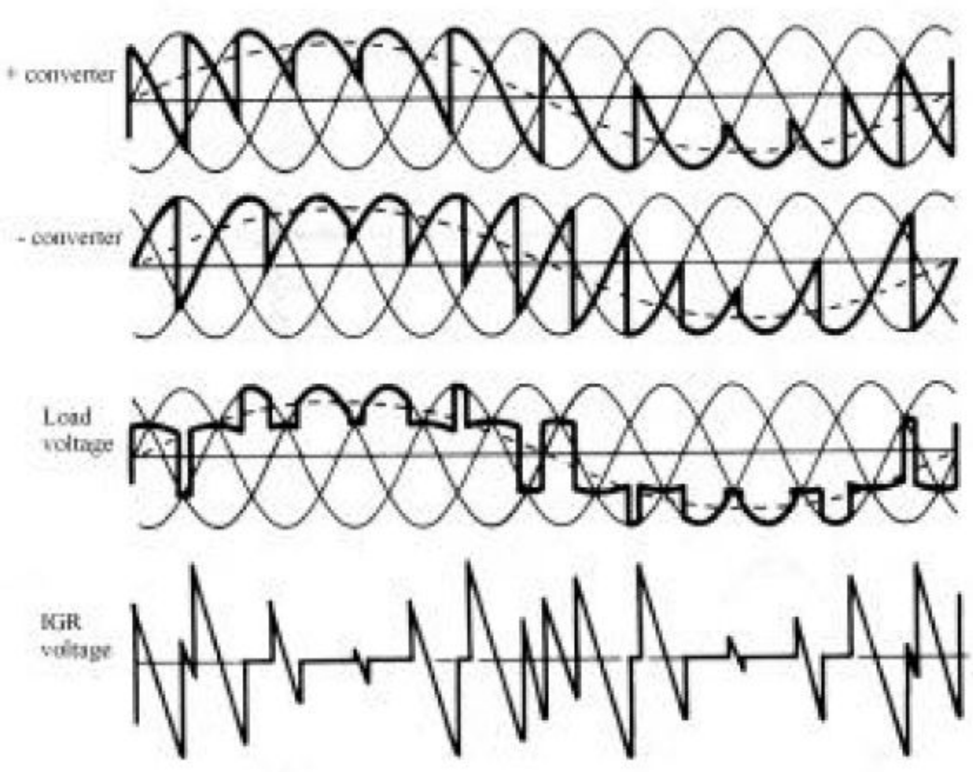


Fig 1.7:Waveform of Three to Three phase cycloconverter

1.2.4: Single Phase To Three Phase Cycloconverter:

The three-phase induction motors have some advantages in the machineefficiency, power factor, and torque ripples compared to their single-phase counterparts. Therefore, drives by the three-phase induction motor drives in some low-power industrial applications. However, in some where only a single-phase utility is available, we should convert a single-phase to a three-phase supply.

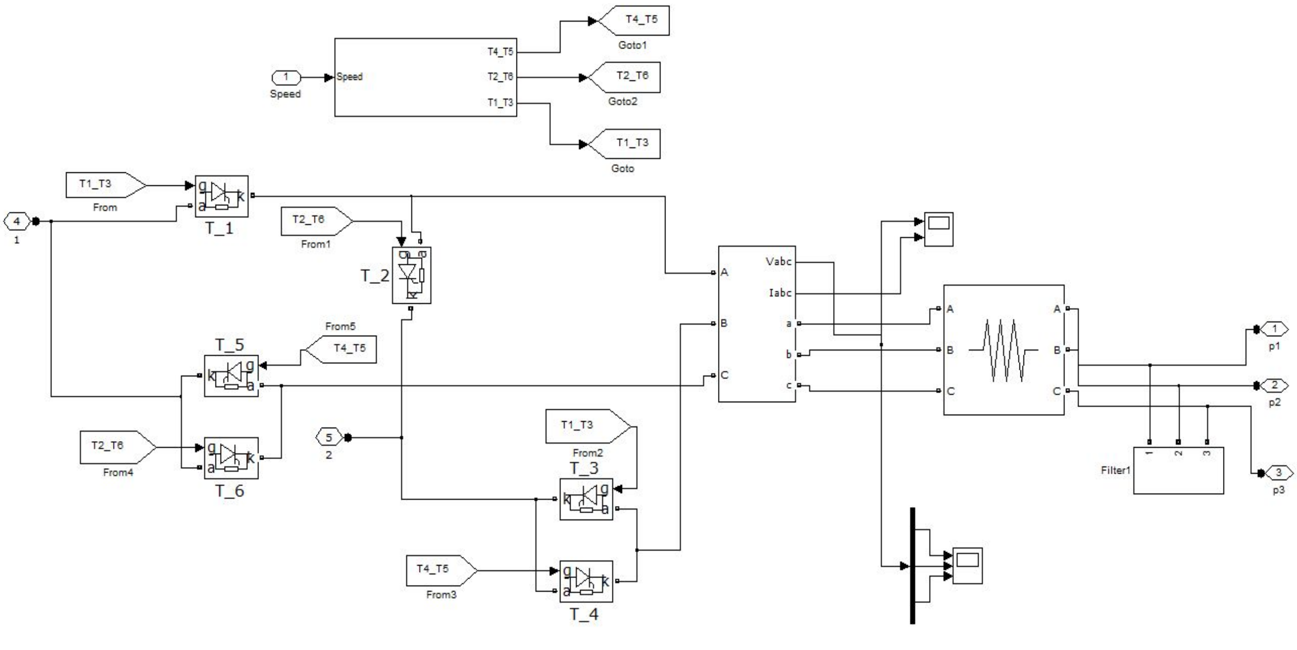


Fig1.8:Single phase To three phase converter

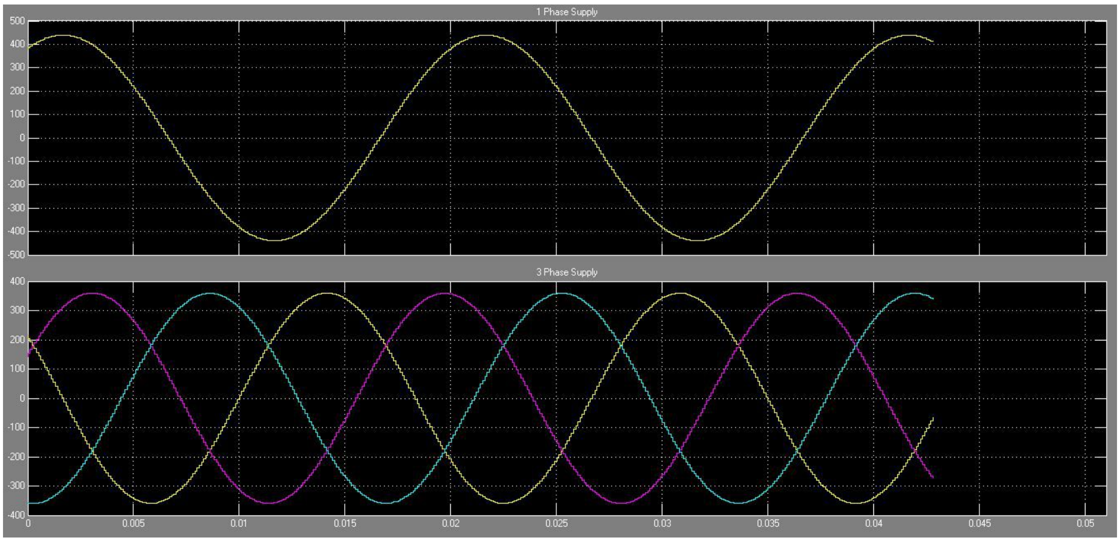


Fig 1.9:Input wave form of single phase and three phase supply

The conventional method for conversion of a single-phase to three-phase voltage is the utilization of rotary, capacitor or autotransformer converters [2, 3, 4]. Most of these converters remain balanced only at one specified load. There are also many converter topologies that can transform a single-phase AC voltage into variable voltage, variable frequency three-phase voltages supplies [5-10]. Fig.1.1 shows the schematic of the single-phase to three-phase rectifier-inverter system. The voltage transformation generally takes place in two stages: the single-phase AC voltage is converted to a regulated DC voltage which is subsequently mapped into three-phase variable frequency and variable voltage

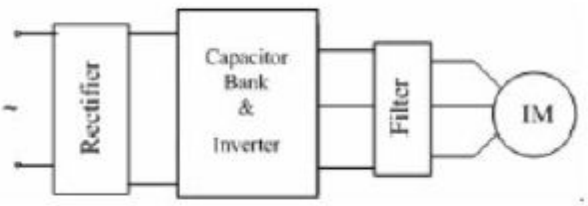


Fig 1.10:Fully controlled of single phase to three phase

sources. In these topologies, one or two relatively high capacity DC link capacitor is required. The cost of the inverter drive limits its applications.The thyristor or triac based AC voltage controller using the phase control prin-ciple has been popularly used in low power induction motors. The cycloconverter provides one stage AC to AC power conversion. Since this system does not have an energy storage element, it is easy to implement in a small size and achieve a long life.

However, for a single-phase supply, it is hard to implement cycloconverters. J. Zhang, G.P. Hunter, et al. have proposed a compact
cycloconverter consisting of six triacs as shown in Fig.1.2. Its output is a three-phase supply with variable voltage and variable frequency.

This project is the continuation of the authors work on a cheaper single-phase to three-phase converter for small induction motors.A new simple single-phase to three-phase cycloconverter based on discrete variable frequency technique is pro-posed. The configuration, shown is Fig.1.3, only consists of six thyristors, and its output frequency can be up to 25Hz. The discrete variable frequency modulation strategy is explained in sections II. Simulation based on Matlab/Simulink is given in sections III.

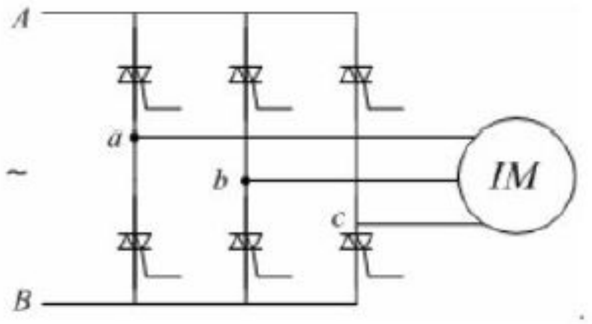


Fig 1.11:Power circuit of single phase to three phase cycloconverter

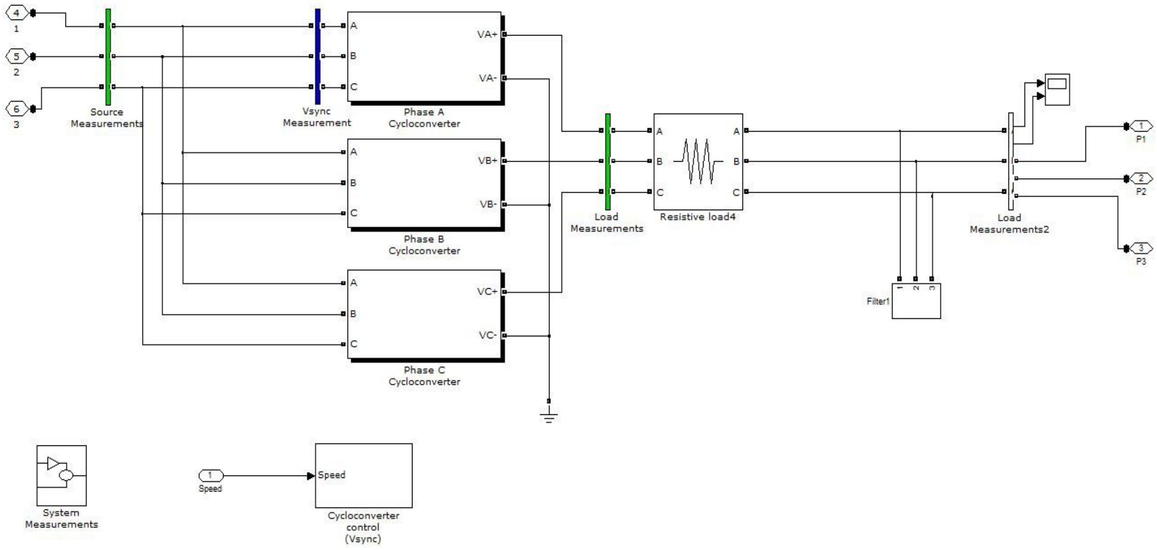


Fig1.12: Three phase To Three phase controller

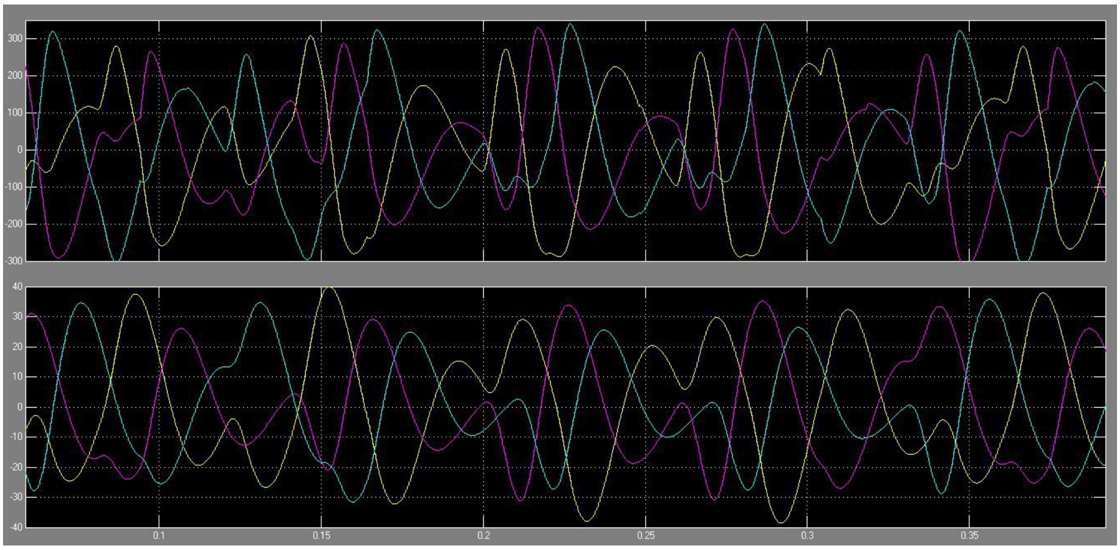


Fig1.13:Three phase controller output

To verify the proposed discrete variable frequency modulation, the TMS320LF2407A microprocessor is used to implement the core of the control function, which simplifies the hardware setup. Software in C and assembly language has been written for real-time control. The practical circuit forthis cycloconverter is under test, and the experimental results will be presented later.The thyristor or triac based AC voltage controller using the phase control prin-ciple has been popularly used in low power induction motors.The cycloconverter provides one stage AC to AC power conversion. Since this system does not have an energy storage element, it is easy to implement in a small size and achieve a long life. However, for a single-phase supply, it is hard to implement cycloconverters. J. Zhang, G.P. Hunter, et al. have proposed a compact cycloconverter consisting of six triacs as shown in Fig.1.2. Its output is a three-phase supply with variable voltage and variable frequency.

CHAPTER 2:

Modulation Strategy

2.1Torque Control

The relation between stator currents and electromagnetic torque. Under balanced three-phase conditions, the instantaneous stator currents of induction motor are

$$i_a = I_m \cos\left(\omega_e t\right)$$

$$i_a = I_m \cos\left(\omega_e t - 120^\circ\right) \qquad (2.1)$$

$$i_a = I_m \cos\left(\omega_e t + 120^\circ\right)$$

Where Im is the maximum value of the current. !e is the electrical angular velocity (unit:rad/s).Fig.2.1 shows the vector diagram of magnetic motive force (mmf) waves.Torque is produced by the tendency of the rotor and stator magnetic fieldsto align.Note that the figure is drawn with d sr positive, i.e., with the rotor mmf wave Fr leading that of the stator mmf wave Fs. The result of displacing the three winding by 120 in space phase and displacing the winding current by 120 in time phase is a single positive-traveling mmf wave

$$F = \frac{3}{2}\frac{4}{\pi}\left(\frac{k_w N}{p}\right) I_m \cos(\theta_e - \omega_e t) \qquad (2.2)$$

Where kw is distributed winding of winding factor; N is total number ofseries turns per phase; p is the pole number; _x0012_e is the electrical space angleThe torque can then be expressed in terms of the stator and rotor mmf wavesFs and Fr.

$$T = \frac{p}{2}\left(\frac{\mu_0 A}{2g}\right) F_s F_r \sin\sigma_s \qquad (2.3)$$

Where µ0 is the permeability of free space; A is the cross-section of magnetic

path and g is the air-gap length.

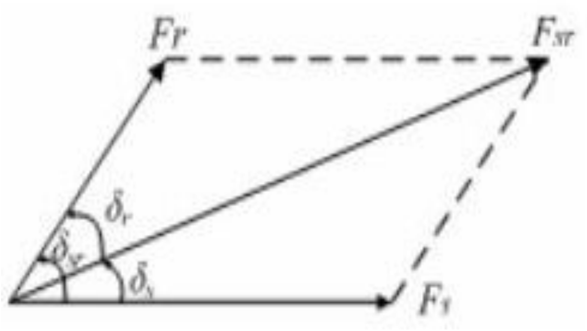


Figure 2.1: Vector diagram of mmf waves of a simplified two-pole machine

Equations 2.1 - 2.3 show that mmf waves are formed by the three-phase statorcurrents, and the rotating mmf waves produce the electromagnetic torque.i.e., the available electromagnetic torque can be produced by controlling thethree-phase stator currents. This is the elementary theory of torque control.

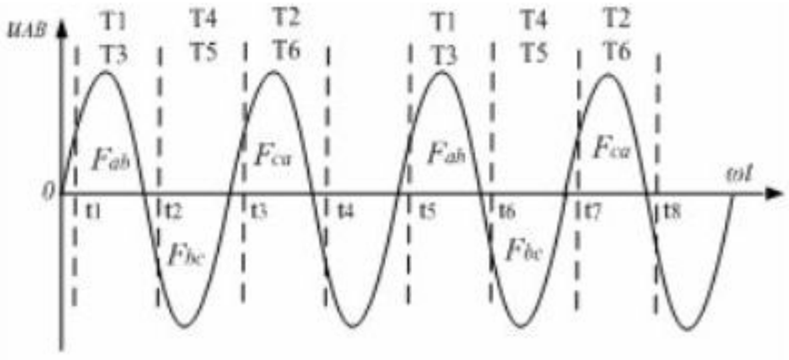


Fig2.2: Input voltage and switching sequence

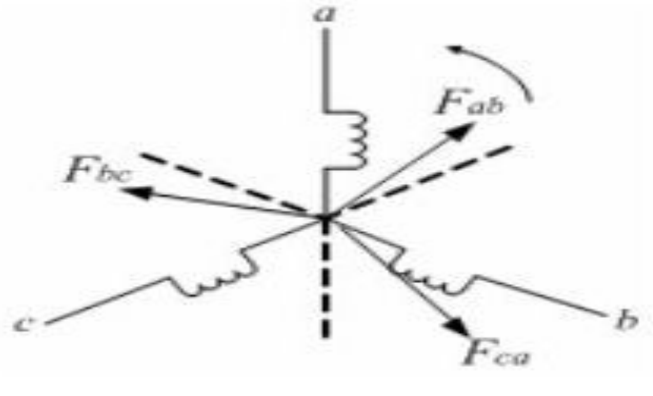


Fig2.3:Vector diagram of the rotating mmf waves.a,b and c represent the stator windings.

Fig.5 shows the corresponding switching sequence with respect to the inputvoltage μAB. i.e., T1 and T3 are fired at t1 as shown in Fig.2.2(a). Thenthe current iab is obtained. As a result, iab produces the mmf vector FAB.Similarly, T4 and T5, T2 and T6 will be fired at t2 and t3 respectively.Then the mmf vectors F bc and F ca are formed by ibc and ica respectively.Fig.2.2(b) shows the vector diagram of the rotating mmf waves. In orderto obtain the positive torque, it is expected that the phase sequences of generatedvoltages under the new frequency are all positive. The strategyfollowed to convert the negative sequences into positive ones is unbalancingthe system. Thus, the order triggered thyristors must ensure that the mmfvectors Fab, Fbc and Fca are produced following a fixed sequence, as shownin Fig.2.2(b).Because there is no neutral wire, it must be ensured that there must be two thyristors fired at any time.

2.2Principle of discrete variable frequency

Fig. 2.3 shows the schematic diagram of the proposed cycloconverter. It iscomposed of six thyristors, the analog interface, and a digital signal processor(DSP). The analog interface circuit receives the single-phase voltage andcurrent. The proposed algorithm will be implemented for the control of thethree-phase induction motor drives by a DSP TMS320LF2407A.

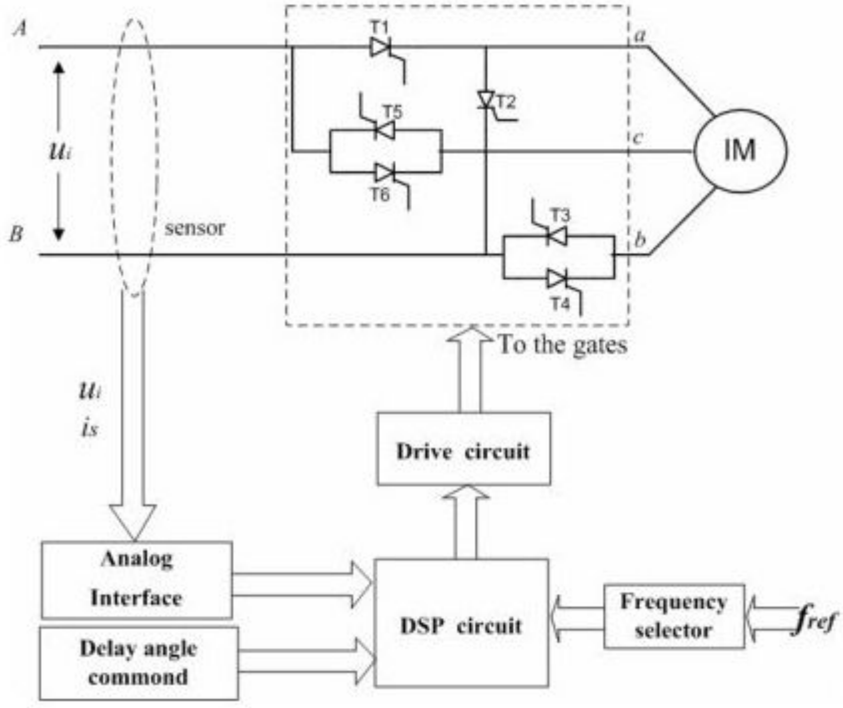
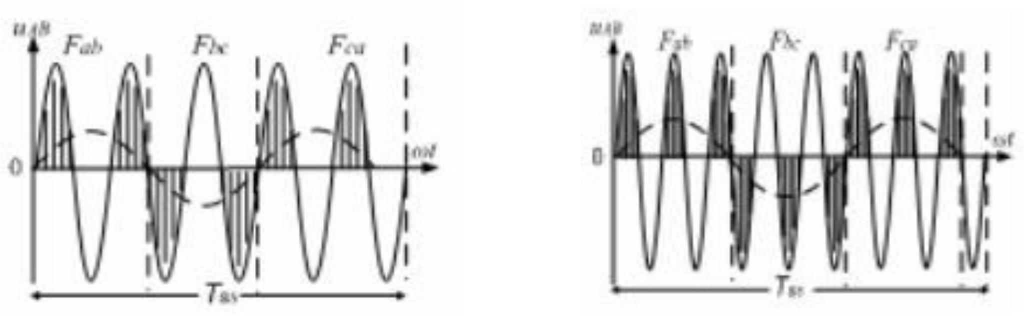


Figure 2.4: Schematic diagram for the proposed cycloconverter

Under the control of power supply frequency, reducing frequency will improvethe electromagnetic torque of induction motors at starting. Through con-trolling the triggering angle of thyristors, discrete variable frequency voltageand current can be produced. Further more, these discrete variable frequen-cies are sub-harmonics of the ac power supply frequency, which are obtainedby the corresponding stator currents.



(a)10 Hz (b)6.25 Hz

Figure 2.5: Structure for 10 Hz and 6.25 Hz. Fab , Fbc and Fca represent the mmf waves produced

by triggering the thyristors so as to include or omit partial half cycles of the power supply voltage. This can be illustrated in Fig. 2, where the shaded are the included half cycles of the supply. The gure shows the partial half cycles used for generation of 10Hz and 6.25Hz, assuming the power supply frequency is 50Hz. The wave profile under new frequency is not sinusoidal. In effect, the meaning of new frequency implies the one of fundamental component of the generated voltage. Some other discrete frequencies generated from a 50Hz power supply are 25Hz, 16.67Hz, 12.5Hz, 4.55Hz and 3.57Hz.

CHAPTER 3

SIMULATION MODEL AND RESULTS

3.1 INTROUCTION TO MATLAB

MATLAB is widely used in all areas of applied mathematics, in education and research at universities, and in the industry. MATLAB stands for MATrix LABoratory and the software is built up around vectors and matrices. This makes the software particularly useful for linear algebra but MATLAB is also a great tool for solving algebraic and differential equations and for numerical integration. MATLAB has powerful graphic tools and can produce nice pictures in both 2D and 3D. It is also a programming language, and is one of the easiest programming languages for writing mathematical programs. MATLAB also has some tool boxes useful for signal processing, image processing, optimization, etc.MATLAB was first adopted by researchers and practitioners in control engineering, Little's specialty, but quickly spread to many other domains. It is now also used in education, in particular the teaching of linea algebra , numerical analysis, and is popular amongst scientists involved in image processing.

Our project is related with the simulation part so we shall discuss about it.\

3.2 SIMULINK IN MATLAB

Simulink, developed by math works, is a graphical programming environment for modeling, simulating and analyzing multidomain dynamic systems. Its primary

interface is a graphical block diagraming tool and a customizable set of block libraries. It offers tight integration with the rest of the MATLAB environment and can either drive MATLAB or be scripted from it. Simulink is widely used in automatic control and digital signal processing for multidomain simulation and model based design.

3.3 Simulation

In order to investigate the proposed single-phase to three-phase cycloconverter andthe discrete variable frequency modulation strategy, simulations were performedusing SIMULINK with postprocessing of data in MATLAB.The simulation has been carried out with a 380V, 50Hz single-phase supply.The motor selected for the test is an industrial 1475 rev/min, 380V, 130A, 50Hzstar connected four-pole motor. The stator resistance rs =0.03552 . The stator inductance is Lls =335mH. The rotor inductance referred to stator side is r0r=0.02092 . The rotor inductance referred to stator side is L0lr = 335 mH. The mutual inductance is Lm=15.1mH. From the parameters the rated Electromagnetic torque of the motor can be deduced, which is 356.3Nm. Fig. 3 to Fig. 3.4 are the simulation results during motor starting with 200Nm load. Fig. 3 shows a reduction in the RMS current during motor starting. The instantaneous stator currentsare used to compute the RMS current value per cycle. The torque and speed of thefour-pole motor is shown in Fig. 3. It can be seen that the electromagnetic torqueis positive during motor starting. Fig. 3 shows that three-phase approximatelysymmetrical ux linkages have been obtained from the sing-phase supply. This

is a precondition for satisfactory performance of the three-phase motor. Fig. 3.4

shows the supply current waveform.

● Simulink model

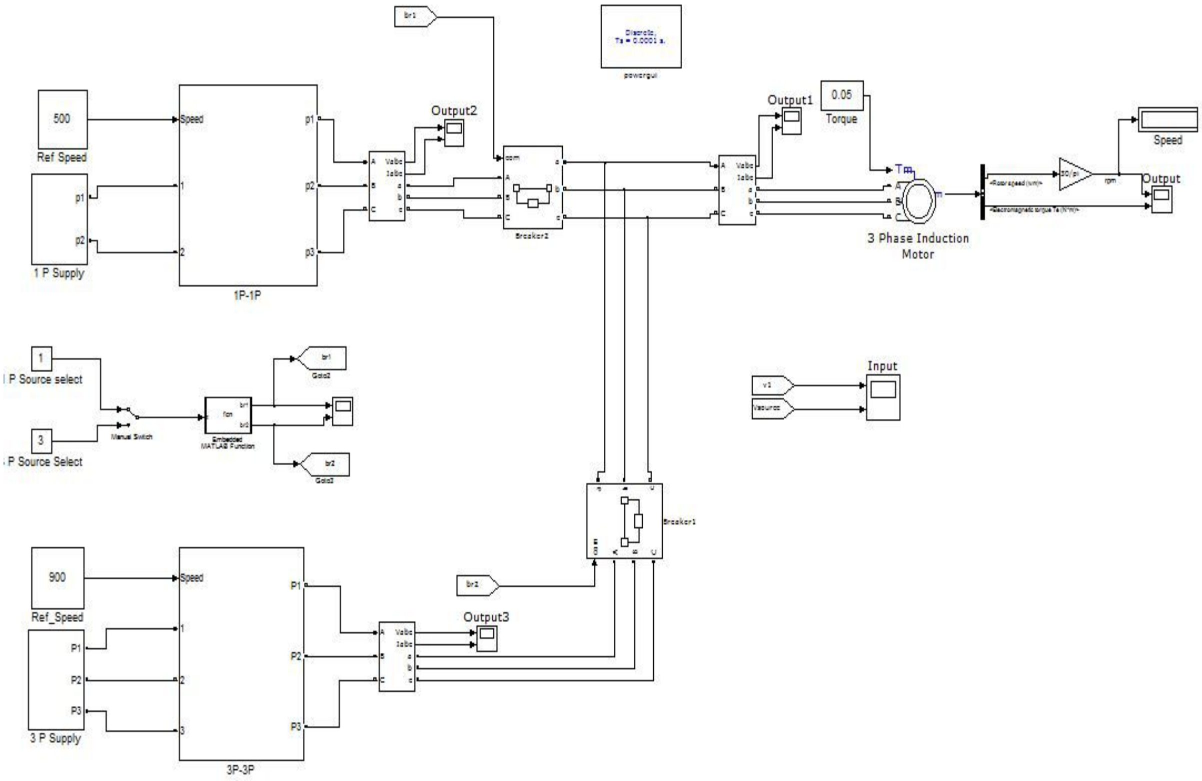


Fig3.1 : Simulation model of single phase to three phase cycloconverter

CHAPTER 4

OUTPUT WAVEFORMS:

- **Three phase cycloconverter output phase A**

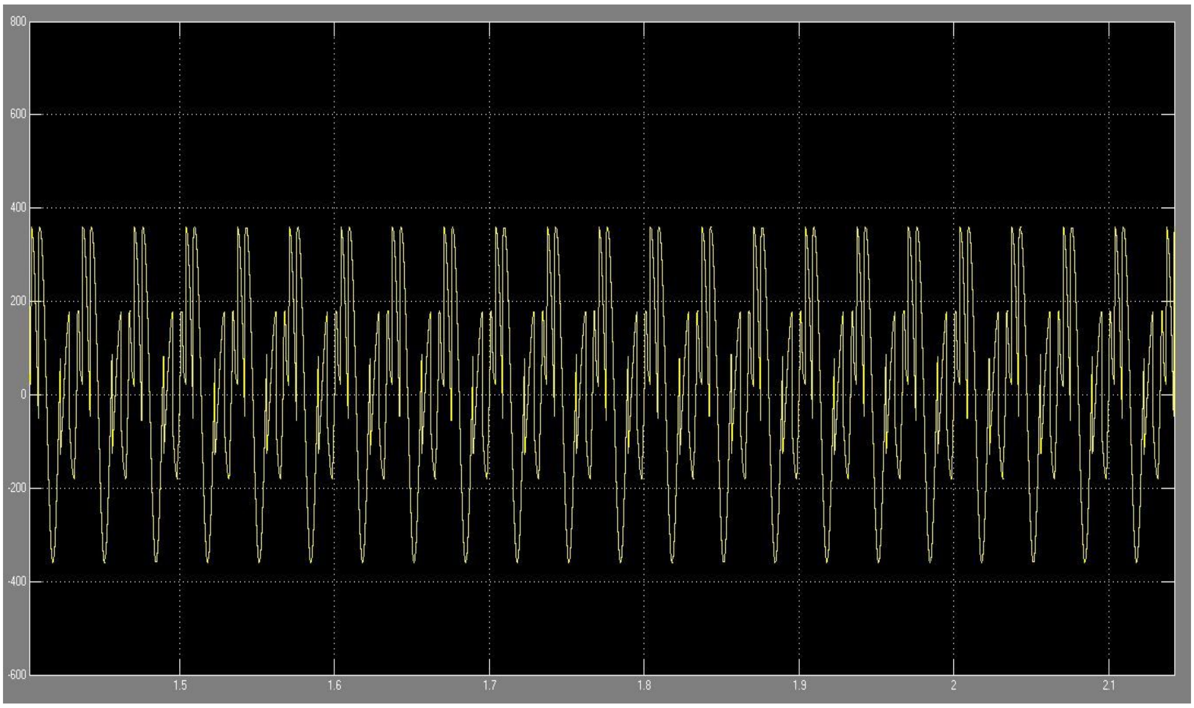


Fig4.1 :Three phase cycloconverter output phase A

➢ Three phase cycloconverter phase B

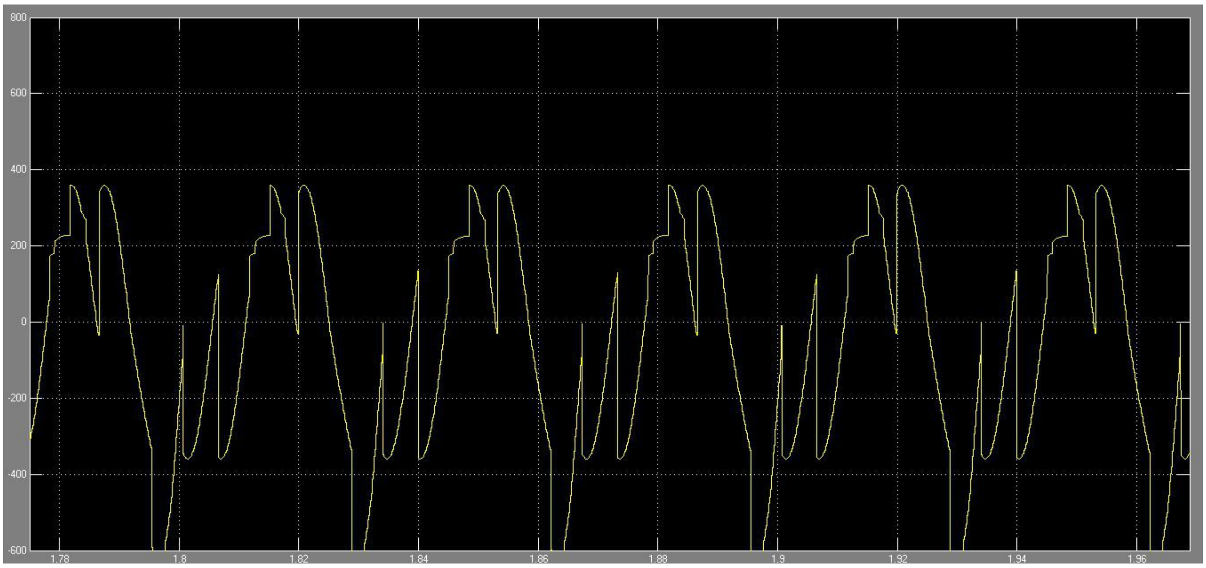


Fig4.2: Three phase cycloconverter output phase B

➢ Three phase cycloconvereter phase C

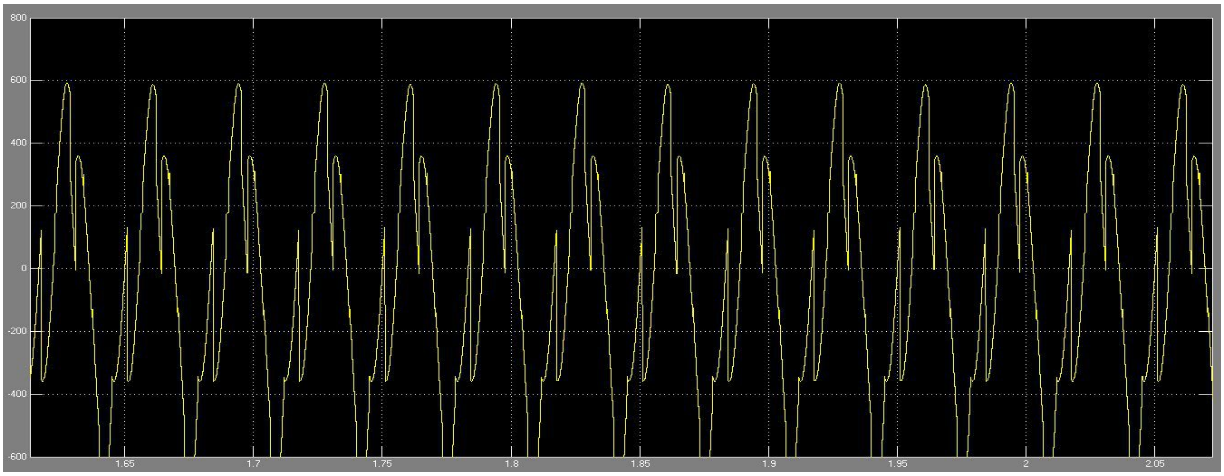


Fig4.3 : Three phase cycloconverter output phase C

➢ Control output to control switching of thyristor

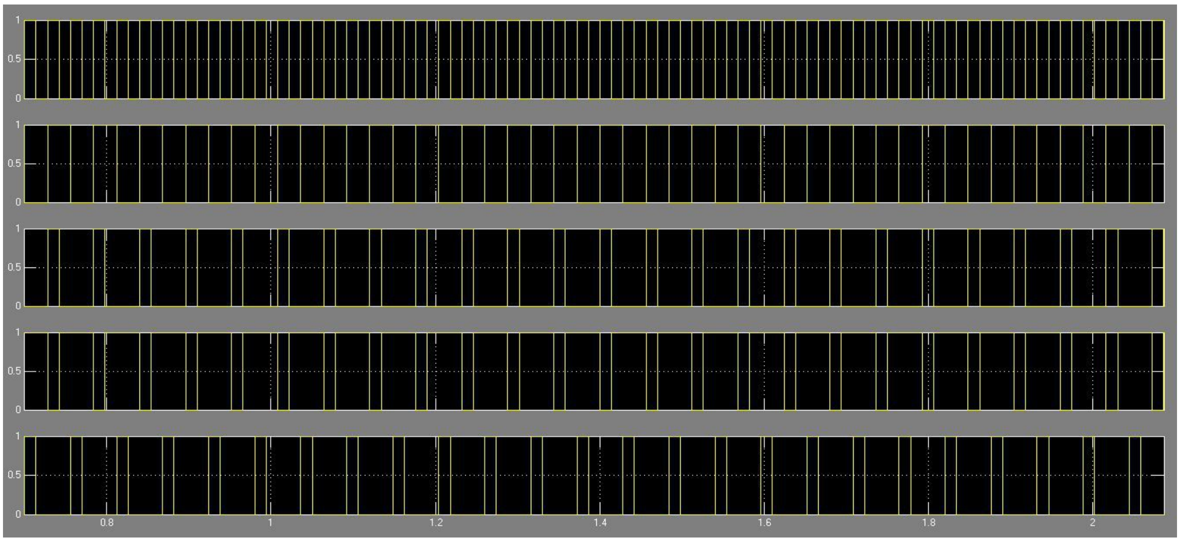


Fig4.4 : Control output to control swithching of thyristor

➢ Cycloconverter output

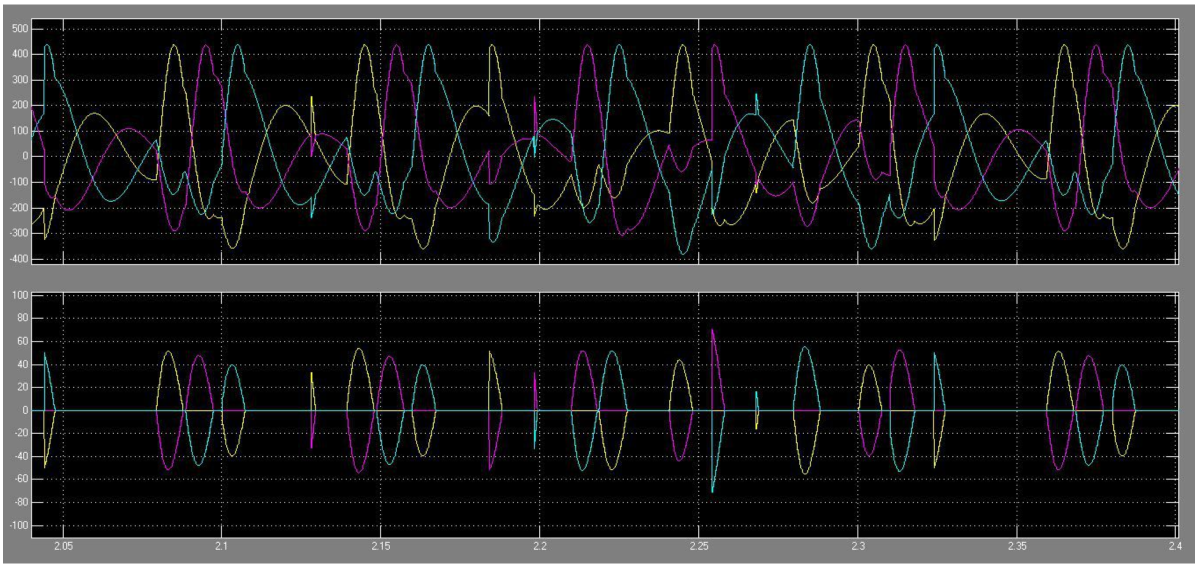


Fig4.5 : Cycloconverter output

➢ Input to switching circuit

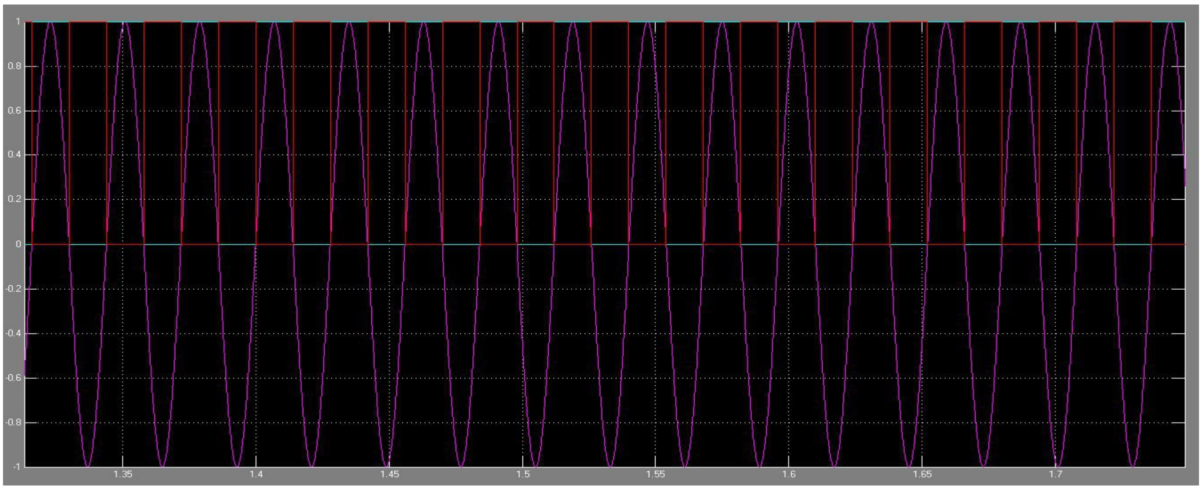


Fig4.6 : Input to switching circuit

➢ Speed vs time

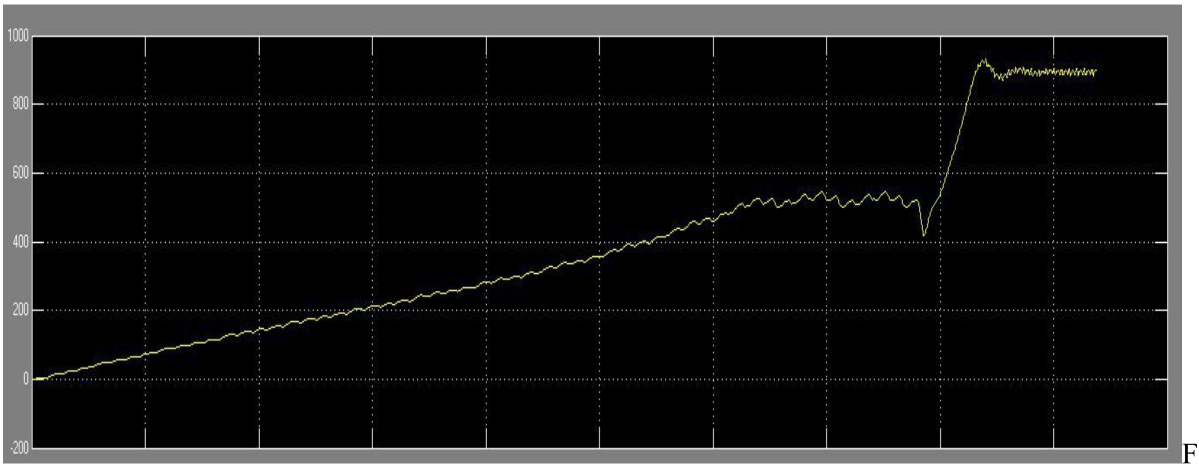


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Fig4.7 :Speed vs time

➢ Switching action from single pahse to three phase

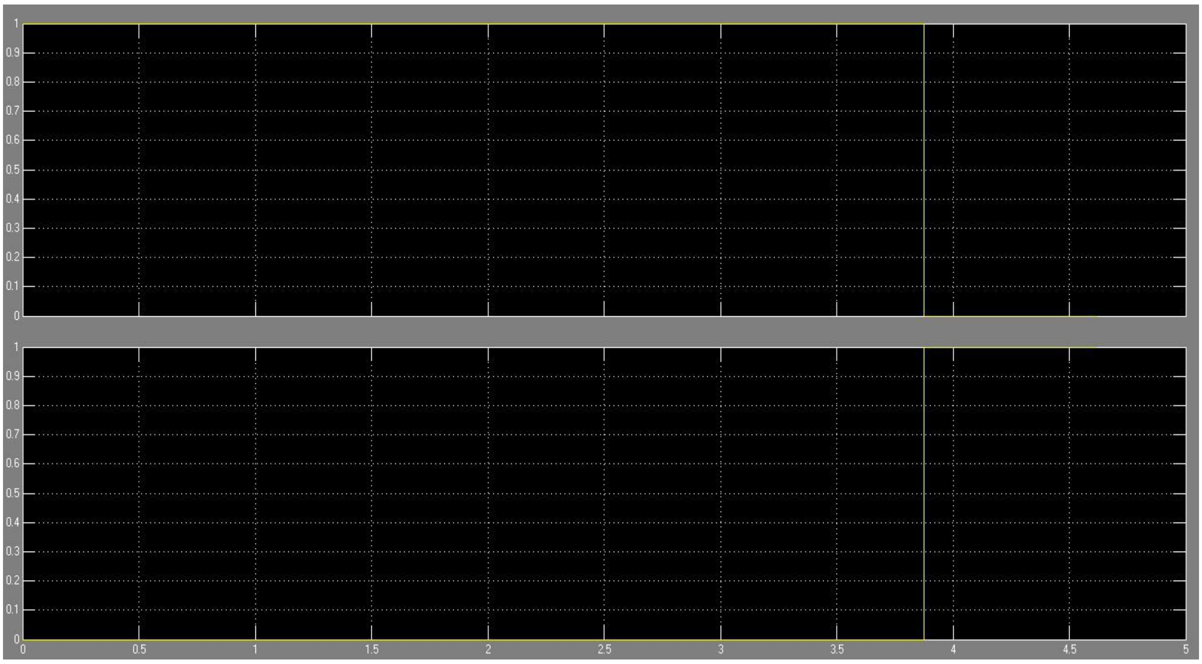


Fig4.8 : switching action from single phase to three phase

➢ Torque vs Time

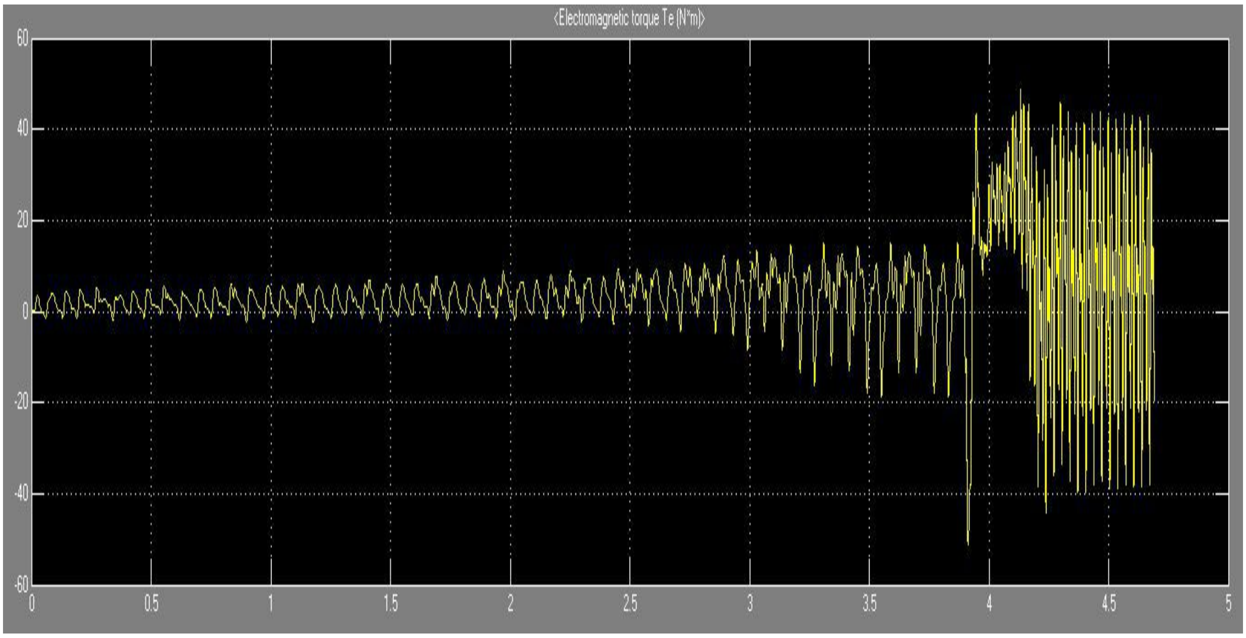
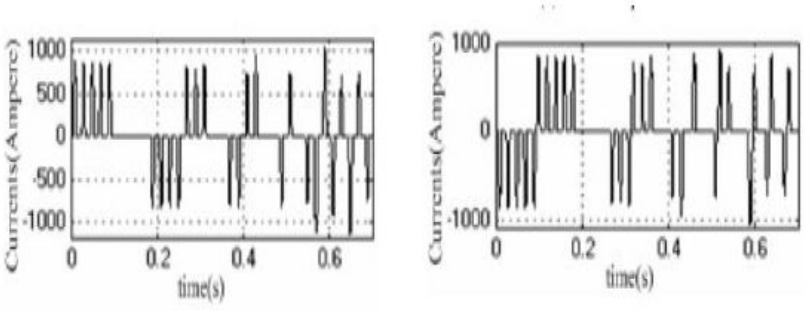
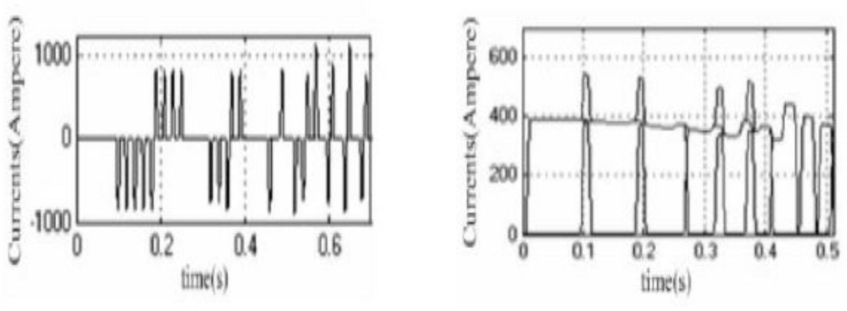


Fig4.9 : torque vs time



(a) Current of phase a.

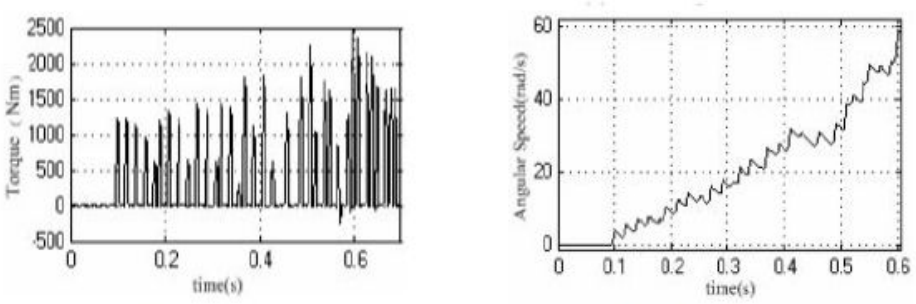
(b) Current of phase b.



(c) Current of phase c.

(d) RMS Amplitude of Stator.

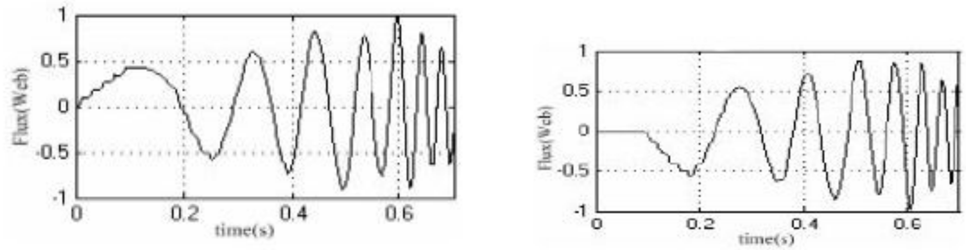
Fig 4.10:Stator currents of the induction motor



(a) Electromagnetic torque.

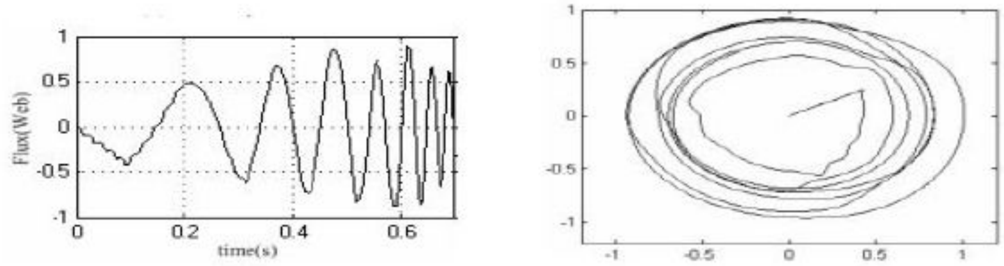
(b) Angular speed.

Fig4.11:Torque and speed of the four-pole motor



(a) Flux of phase u.

(b) Flux of phase v.



(c) Flux of phase w.

(d) Rotor flux Polygon.

Fig4.12:Three phase motor flux linkage

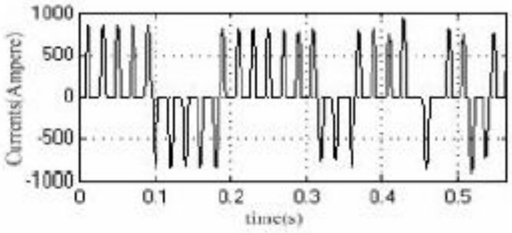


Fig4.13:Supply current cycloconverter

CHAPTER 5

Future Scope

New discrete variable frequency control strategy is applied to improve electromagnetic torque at starting and its output frequency can be up to half of the input frequency. Simulation results show the good performance of the cycloconverter and induction motor.. Our project is used in the rural areas where the three phase supply is not present.

CHAPTER 6

CONCLUSION

This paper has proposed a new single-phase to three-phase cycloconverter for a three-phase induction motor drive fed from a single-phase supply. The configura-tion consisting of six thyristors is simple and compact. The main advantages of the topology include:

1. The thyristors can sustain high inrush currents for a short time, the rating of the drive may not need to be upgraded for higher starting torque requirement.

2. There must be two thyristors fired at any time.

3. This system is easy to implement in a small size for lacking of energy storage element.

New discrete variable frequency control strategy is applied to improve electromag-netic torque at starting and its output frequency can be up to half of the input frequency. Simulation results show the good performance of the cycloconverter and induction motor.

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CYCLOCONVERTERS

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In industrial applications, two forms of electrical energy are used: direct current (dc) and alternating current (ac). Usually constant voltage constant frequency single-phase or three-phase ac is readily available. However, for different applications, different forms, magnitudes and/or frequencies are required. There are four different conversions between dc and ac power sources. These conversions are done by circuits called power converters. The converters are classified as:

1-rectifiers: from single-phase or three-phase ac to variable voltage dc

2-choppers: from dc to variable voltage dc

3-inverters: from dc to variable magnitude and variable frequency, single-phase or three-phase ac

4-cycloconverters: from single-phase or three-phase ac to variable magnitude and variable frequency, single-phase or three-phase ac

The first three classes are explained in other articles. This article explains what cycloconverters are, their types, how they operate and their applications.

Traditionally, ac-ac conversion using semiconductor switches is done in two different ways: 1- in two stages (ac-dc and then dc-ac) as in dc link converters or 2- in one stage (ac-ac) cycloconverters (Fig. 1). Cycloconverters are used in high power applications driving induction and synchronous motors. They are usually phase-controlled and they traditionally use thyristors due to their ease of phase commutation.

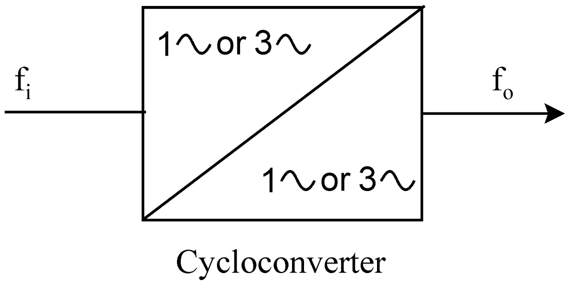

Fig.1 Block diagram of a cycloconverter

There are other newer forms of cycloconversion such as ac-ac matrix converters and high frequency ac-ac (hfac-ac) converters and these use self-controlled switches. These converters, however, are not popular yet.

Some applications of cycloconverters are:

- Cement mill drives
- Ship propulsion drives
- Rolling mill drives
- Scherbius drives
- Ore grinding mills
- Mine winders

1.Operation Principles:

The following sections will describe the operation principles of the cycloconverter starting from the simplest one, single-phase to single-phase (1ϕ-1ϕ) cycloconverter.

1.1. Single-phase to Single-phase (1ϕ-1ϕ) Cycloconverter:

To understand the operation principles of cycloconverters, the single-phase to single-phase cycloconverter (Fig. 2) should be studied first. This converter consists of back-to-back connection of two full-wave rectifier circuits. Fig 3 shows the operating waveforms for this converter with a resistive load.

The input voltage, v_s is an ac voltage at a frequency, f_i as shown in Fig. 3a. For easy understanding assume that all the thyristors are fired at $\alpha=0°$ firing angle, i.e. thyristors act like diodes. Note that the firing angles are named as α_P for the positive converter and α_N for the negative converter.

Consider the operation of the cycloconverter to get one-fourth of the input frequency at the output. For the first two cycles of $v_{s,}$ the positive converter operates supplying current to the load. It rectifies the input voltage; therefore, the load sees 4 positive half cycles as seen in Fig. 3b. In the next two cycles, the negative converter operates supplying current to the load in the reverse direction. The current waveforms are not shown in the figures because the resistive load current will have the same waveform as the voltage but only scaled by the resistance. Note that when one of the converters operates the other one is disabled, so that there is no current circulating between the two rectifiers.

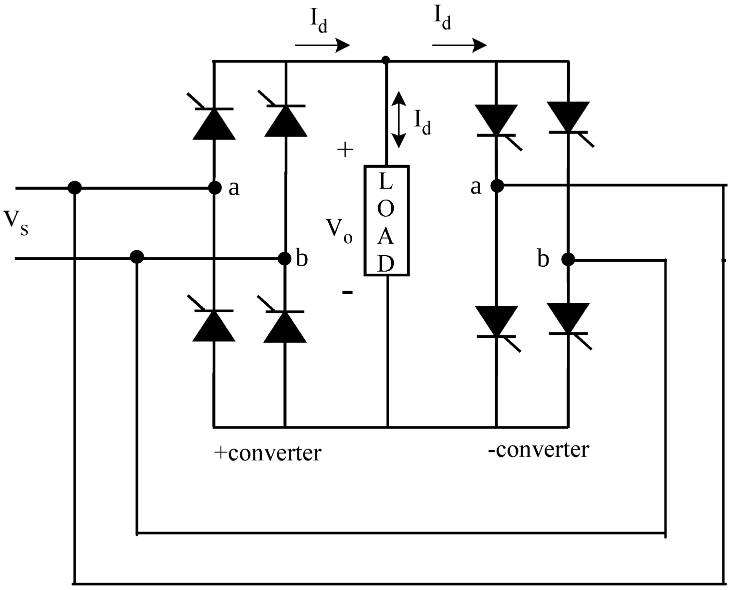

Fig. 2 Single-phase to single-phase cycloconverter

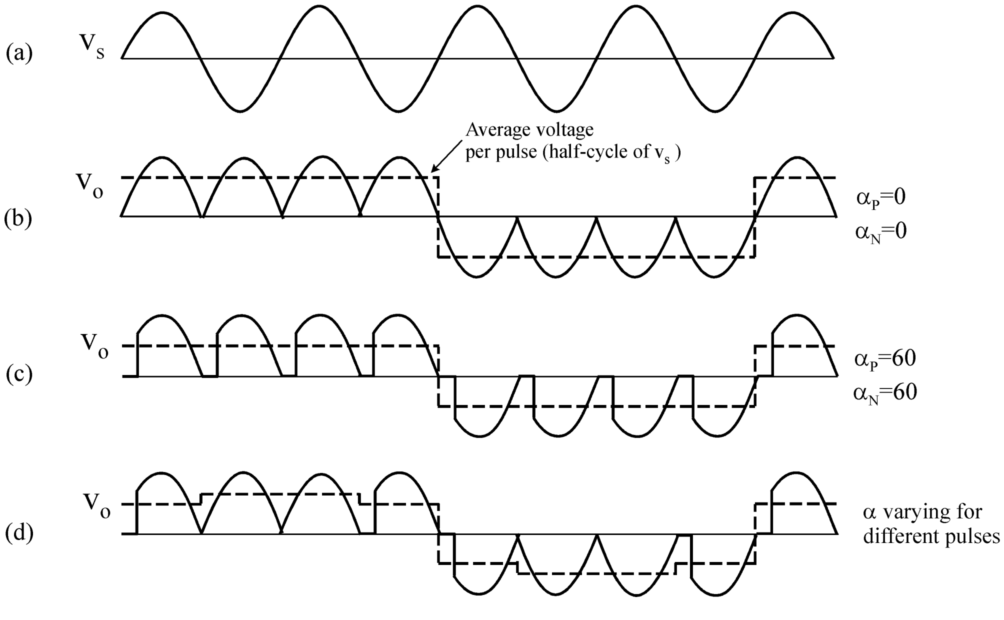

Fig. 3 Single-phase to single-phase cycloconverter waveforms
a) input voltage
b) output voltage for zero firing angle
c) output voltage with firing angle π/3 rad.
d) output voltage with varying firing angle

The frequency of the output voltage, v_o in Fig. 3b is 4 times less than that of v_s, the input voltage, i.e. $f_o/f_i=1/4$. Thus, this is a step-down cycloconverter. On the other hand, cycloconverters that have $f_o/f_i>1$ frequency relation are called step-up cycloconverters. Note that step-down cycloconverters are more widely used than the step-up ones.

The frequency of v_o can be changed by varying the number of cycles the positive and the negative converters work. It can only change as integer multiples of f_i in 1ϕ-1ϕ cycloconverters.

With the above operation, the 1ϕ-1ϕ cycloconverter can only supply a certain voltage at a certain firing angle α. The dc output of each rectifier is:

$$V_d = \frac{2\sqrt{2}}{\pi} V \cos\alpha \qquad (1)$$

where V is the input rms voltage.

The dc value per half cycle is shown as dotted in Fig. 3d.

Then the peak of the fundamental output voltage is

$$v_{o_1}(t) = \frac{4}{\pi}\frac{2\sqrt{2}}{\pi} V \cos\alpha \qquad (2)$$

Equation 2 implies that the fundamental output voltage depends on α. For α=0°, $V_{0_1} = V_{do} \times 1 = V_{do}$ where $V_{do} = \frac{4}{\pi}\frac{2\sqrt{2}}{\pi} V$. If α is increased to π/3 as in Fig. 3d, then $V_{o_1} = V_{do} \times 0.5$. Thus varying α, the fundamental output voltage can be controlled.

Constant α operation gives a crude output waveform with rich harmonic content. The dotted lines in Fig. 3b and c show a square wave. If the square wave can be modified to look more like a sine wave, the harmonics would be reduced. For this reason α is modulated as shown in Fig. 3d. Now, the six-stepped dotted line is more like a sinewave with fewer harmonics. The more pulses there are with different α's, the less are the harmonics.

1.2. Three-Phase to Single-Phase (3ϕ-1ϕ) Cycloconverter:

There are two kinds of three-phase to single-phase (3ϕ-1ϕ) cycloconverters: 3ϕ-1ϕ half-wave cycloconverter (Fig. 4) and 3ϕ-1ϕ bridge cycloconverter (Fig. 5). Like the 1ϕ-1ϕ case, the 3ϕ-1ϕ cycloconverter applies rectified voltage to the load. Both positive and negative converters can generate voltages at either polarity, but the positive converter can only supply positive current and the negative converter can only supply negative current. Thus, the cycloconverter can operate in four quadrants: (+v, +i) and (-v, -i) rectification modes and (+v, -i) and (-v, +i) inversion modes. The modulation of the output voltage and the fundamental output voltage are shown in Fig. 6. Note that α is sinusoidally modulated over the cycle to generate a harmonically optimum output voltage.

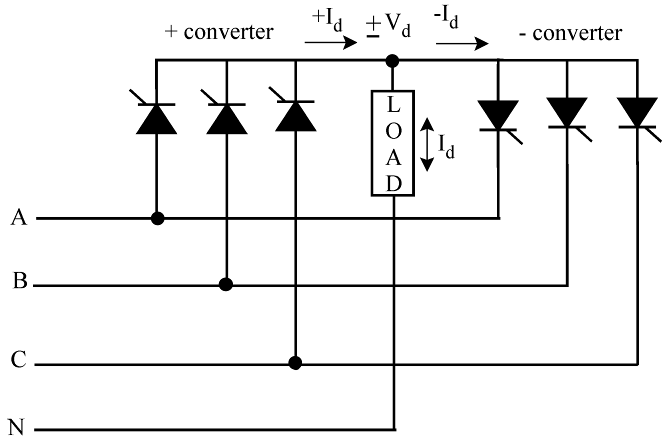

Fig. 4 3ϕ-1ϕ half-wave cycloconverter

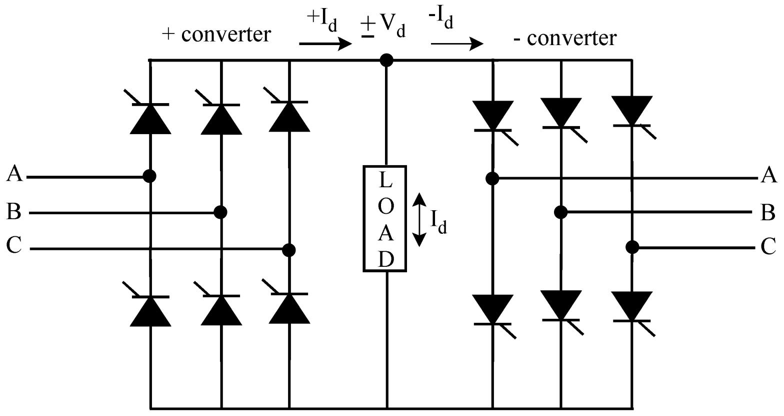

Fig. 5 3ϕ-1ϕ bridge cycloconverter

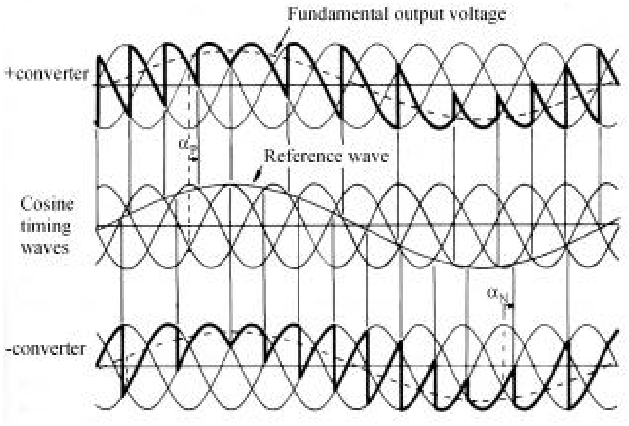

Fig. 6 3ϕ-1ϕ half-wave cycloconverter waveforms
a) + converter output voltage
b) cosine timing waves
c) – converter output voltage

The polarity of the current determines if the positive or negative converter should be supplying power to the load. Conventionally, the firing angle for the positive converter is named α_P, and that of the negative converter is named α_N. When the polarity of the current changes, the converter previously supplying the current is disabled and the other one is enabled. The load always requires the fundamental voltage to be continuous. Therefore, during the current polarity reversal, the average voltage supplied by both of the converters should be equal. Otherwise, switching from one converter to the other one would cause an undesirable voltage jump. To prevent this problem, the converters are forced to produce the same average voltage at all times. Thus, the following condition for the firing angles should be met.

$$\alpha_P + \alpha_N = \pi \tag{3}$$

The fundamental output voltage in Fig. 6 can be given as:

$$v_{o_1}(t) = \sqrt{2}V_o \sin \omega_o t \tag{4}$$

where V_o is the rms value of the fundamental voltage

At a time t_o the output fundamental voltage is

$$v_{o_1}(t_o) = \sqrt{2}V_o \sin \omega_o t_o \tag{5}$$

The positive converter can supply this voltage if α_P satisfies the following condition.

$$v_{o_1}(t_o) = \sqrt{2}V_o \sin \omega_o t_o = V_{do} \cos \alpha_P \tag{6}$$

where $V_{do} = \sqrt{2}V_o \frac{p}{p}\sin\frac{p}{p}$ (p=3 for half wave converter and 6 for bridge converter)

From the α condition (3)

$$v_{o_1} = V_{do}\cos a_P = -V_{do}\sin a_N \tag{7}$$

The firing angles at any instant can be found from (6) and (7).

The operation of the 3ϕ-1ϕ bridge cycloconverter is similar to the above 3ϕ-1ϕ half-wave cycloconverter. Note that the pulse number for this case is 6.

1.3 Three-Phase to Three-Phase (3ϕ-3ϕ) Cycloconverter:

If the outputs of 3 3ϕ-1ϕ converters of the same kind are connected in wye or delta and if the output voltages are 2π/3 radians phase shifted from each other, the resulting converter is a three-phase to three-phase (3ϕ-3ϕ) cycloconverter. The resulting cycloconverters are shown in Figs. 7 and 8 with wye connections. If the three converters connected are half-wave converters, then the new converter is called a 3ϕ-3ϕ half-wave cycloconverter. If instead, bridge converters are used, then the result is a 3ϕ-3ϕ bridge cycloconverter. 3ϕ-3ϕ half-wave cycloconverter is also called a 3-pulse cycloconverter or an 18-thyristor cycloconverter. On the other hand, the 3ϕ-3ϕ bridge cycloconverter is also called a 6-pulse cycloconverter or a 36-thyristor cycloconverter. The operation of each phase is explained in the previous section.

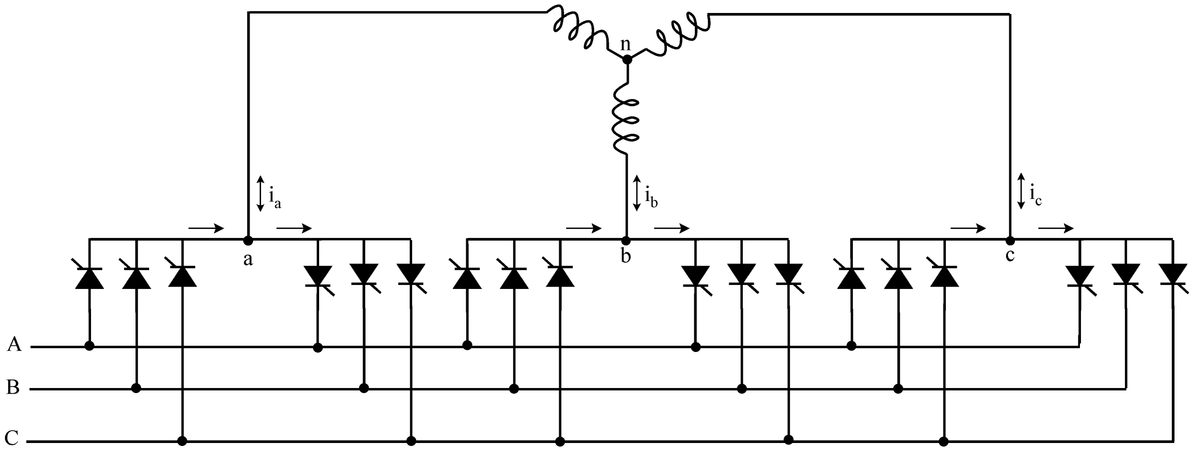

Fig. 7 3ϕ-3ϕ half-wave cycloconverter

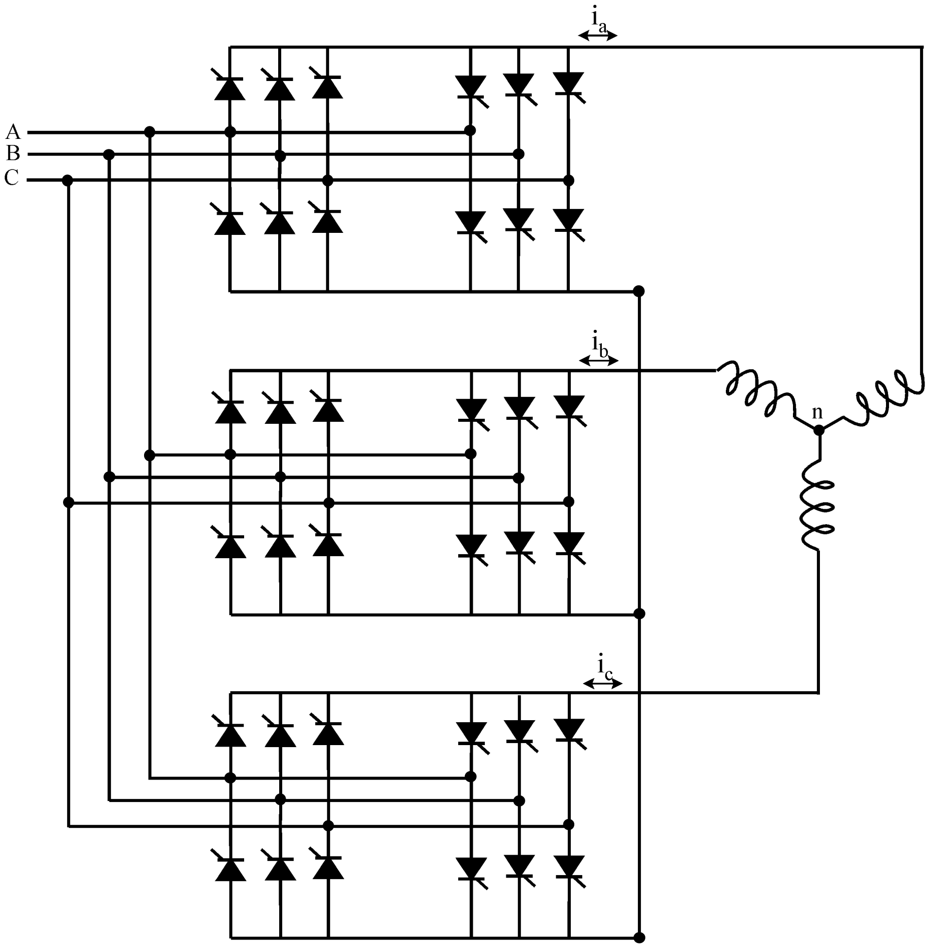

Fig. 8 3ϕ-3ϕ bridge cycloconverter

The three-phase cycloconverters are mainly used in ac machine drive systems running three-phase synchronous and induction machines. They are more advantageous when used with a synchronous machine due to their output power factor characteristics. A cycloconverter can supply lagging, leading, or unity power factor loads while its input is always lagging. A synchronous machine can draw any power factor current from the converter. This characteristic operation matches the cycloconverter to the synchronous machine. On the other hand, induction machines can only draw lagging current, so the cycloconverter does not have an edge compared to the other converters in this aspect for running an induction machine. However, cycloconverters are used in Scherbius drives for speed control purposes driving wound rotor induction motors.

Cycloconverters produce harmonic rich output voltages, which will be discussed in the following sections. When cycloconverters are used to run an ac machine, the leakage inductance of the machine filters most of the higher frequency harmonics and reduces the magnitudes of the lower order harmonics.

2. Blocked Mode and Circulating Current Mode:

The operation of the cycloconverters is explained above in ideal terms. When the load current is positive, the positive converter supplies the required voltage and the negative converter is disabled. On the other hand, when the load current is negative, then the negative converter supplies the required voltage and the positive converter is blocked. This operation is called the blocked mode operation, and the cycloconverters using this approach are called blocking mode cycloconverters.

However, if by any chance both of the converters are enabled, then the supply is short-circuited. To avoid this short circuit, an intergroup reactor (IGR) can be connected between the converters as shown in Fig. 9. Instead of blocking the converters during current reversal, if they are both enabled, then a circulating current is produced. This current is called the circulating current. It is unidirectional because the thyristors allow the current to flow in only one direction. Some cycloconverters allow this circulating current at all times. These are called circulating current cycloconverters.

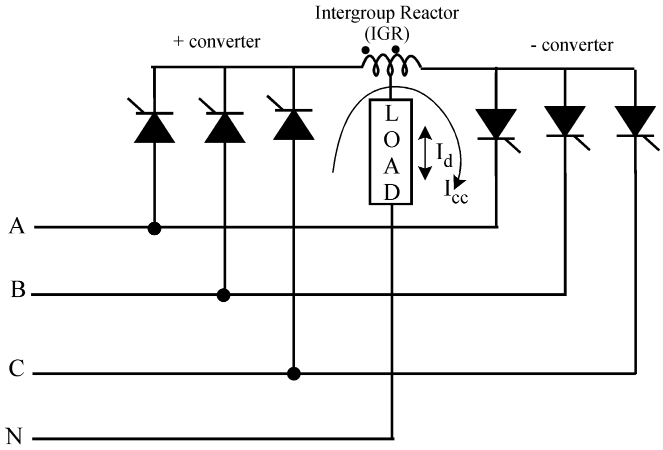

Fig. 9 Circulating current and IGR

2.1 Blocking Mode Cycloconverters:

The operation of these cycloconverters was explained briefly before. They do not let circulating current flow, and therefore they do not need a bulky IGR. When the current goes to zero, both positive and negative converters are blocked. The converters stay off for a short delay time to assure that the load current ceases. Then, depending on the polarity, one of the converters is enabled. With each zero crossing of the current, the converter, which was disabled before the zero crossing, is enabled. A toggle flip-flop, which toggles when the current goes to zero, can be used for this purpose. The operation waveforms for a three-pulse blocking mode cycloconverter are given in Fig. 10.

The blocking mode operation has some advantages and disadvantages over the circulating mode operation. During the delay time, the current stays at zero distorting the voltage and current waveforms. This distortion means complex harmonics patterns compared to the circulating mode cycloconverters. In addition to this, the current reversal problem brings more control complexity. However, no bulky IGRs are used, so the size and cost is less than that of the circulating current case. Another advantage is that only one converter is in conduction at all times rather than two. This means less losses and higher efficiency.

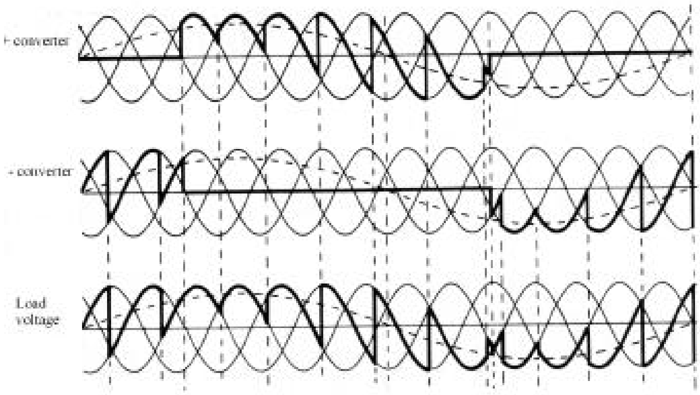

Fig. 10 Blocking mode operation waveforms
a) + converter output voltage
b) – converter output voltage
c) load voltage

2.2 Circulating Current Cycloconverters:

In this case, both of the converters operate at all times producing the same fundamental output voltage. The firing angles of the converters satisfy the firing angle condition (Eq. 3), thus when one converter is in rectification mode the other one is in inversion mode and vice versa. If both of the converters are producing pure sine waves, then there would not be any circulating current because the instantaneous potential difference between the outputs of the converters would be zero. In reality, an IGR is connected between the outputs of two phase controlled converters (in either rectification or inversion mode). The voltage waveform across the IGR can be seen in Fig. 11d. This is the difference of the instantaneous output voltages produced by the two converters. Note that it is zero when both of the converters produce the same instantaneous voltage. The center tap voltage of IGR is the voltage applied to the load and it is the mean of the voltages applied to the ends of IGR, thus the load voltage ripple is reduced.

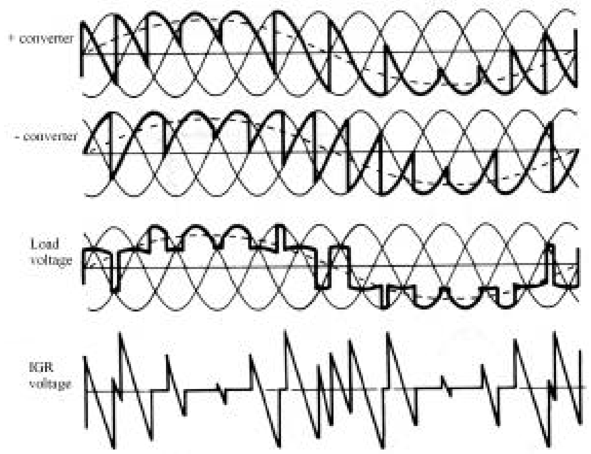

Fig. 11 Circulating mode operation waveforms
a) + converter output voltage
b) – converter output voltage
c) load voltage
d) IGR voltage

The circulating current cycloconverter applies a smoother load voltage with less harmonics compared to the blocking mode case. Moreover, the control is simple because there is no current reversal problem. However, the bulky IGR is a big disadvantage for this converter. In addition to this, the number of devices conducting at any time is twice that of the blocking mode converter. Due to these disadvantages, this cycloconverter is not attractive.

The blocked mode cycloconverter converter and the circulating current cycloconverter can be combined to give a hybrid system, which has the advantages of both. The resulting cycloconverter looks like a circulating mode cycloconverter circuit, but depending on the polarity of the output current only one converter is enabled and the other one is disabled as with the blocking mode cycloconverters. When the load current decreases below a threshold, both of the converters are enabled. Thus, the current has a smooth reversal. When the current increases above a threshold in the other direction, the outgoing converter is disabled. This hybrid cycloconverter operates in the blocking mode most of the time so a smaller IGR can be used. The efficiency is slightly higher than that of the circulating current cycloconverter but much less than the blocking mode cycloconverter. Moreover, the distortion caused by the blocking mode operation disappears due to the circulating current operation around zero current. Moreover, the control of the converter is still less complex than that of the blocking mode cycloconverter.

3. Output and Input Harmonics:

The cycloconverter output voltage waveforms have complex harmonics. Higher order harmonics are usually filtered by the machine inductance, therefore the machine current has less harmonics. The remaining harmonics cause harmonic losses and torque pulsations. Note that in a cycloconverter, unlike other converters, there are no inductors or capacitors, i.e. no storage devices. For this reason, the instantaneous input power and the output power are equal.

There are several factors effecting the harmonic content of the waveforms. Blocking mode operation produces more complex harmonics than circulating mode of operation due to the zero current distortion. In addition to this, the pulse number effects the harmonic content. A greater number of pulses has less harmonic content. Therefore, a 6-pulse (bridge) cycloconverter produces less harmonics than a 3-pulse (half-wave) cycloconverter. Moreover, if the output frequency gets closer to the input frequency, the harmonics increase. Finally, low power factor and discontinuous conduction, both contribute to harmonics.

For a typical p-pulse converter, the order of the input harmonics is "$pn \pm 1$" and that of the output harmonics is "pn", where p is the pulse number and n is an integer. Thus for a 3-pulse converter the input harmonics are at frequencies $2f_i$, $4f_i$ for n=1, $5f_i$, $7f_i$ for n=2, and so on. The output harmonics, on the other hand, are at frequencies $3f_i$, $6f_i$, …

The firing angle, α, in cycloconverter operation is sinusoidally modulated. The modulation frequency is the same as the output frequency and sideband harmonics are induced at the output. Therefore, the output waveform is expected to have harmonics at frequencies related to both the input and output frequencies.

For blocking mode operation, the output harmonics are found at "$pnf_i \pm Nf_o$", where N is an integer and $pn \pm N$=odd condition is satisfied. Then the output harmonics for a 3-pulse cycloconverter in blocking mode will be found at frequencies
n=1 $3f_i, 3f_i \pm 2f_o, 3f_i \pm 4f_o, 3f_i \pm 6f_o, 3f_i \pm 8f_o, 3f_i \pm 10f_o$ …
n=2 $6f_i, 6f_i \pm 1f_o, 6f_i \pm 3f_o, 6f_i \pm 5f_o, 6f_i \pm 7f_o, 6f_i \pm 9f_o$ …
n=3 $9f_i, 9f_i \pm 2f_o, 9f_i \pm 4f_o, 9f_i \pm 6f_o, 9f_i \pm 8f_o, 9f_i \pm 10f_o$, …
n=4, 5,…
Some of the above harmonics might coincide to frequencies below f_i. These are called subharmonics. They are highly unwanted harmonics because the machine inductance cannot filter these.

For the circulating mode operation, the harmonics are at the same frequencies as the blocking mode, but N is limited to (n+1). Thus, the output harmonics for a 3-pulse cycloconverter in circulating mode will be found at frequencies
n=1 $3f_i, 3f_i \pm 2f_o, 3f_i \pm 4f_o$
n=2 $6f_i \pm 1f_o, 6f_i \pm 3f_o, 6f_i \pm 5f_o, 6f_i \pm 7f_o$
n=3 $9f_i, 9f_i \pm 2f_o, 9f_i \pm 4f_o, 9f_i \pm 6f_o, 9f_i \pm 8f_o, 9f_i \pm 10f_o$
n=4, 5,…

With N limited in the circulating mode, there are fewer subharmonics expected. According to calculations done in [1], subharmonics in this mode exist for $f_o/f_i>0.6$. For the blocking mode, [1] states that the subharmonics exist for $f_o/f_i>0.2$.

The output voltage of a cycloconverter has many complex harmonics, but the output current is smoother due to heavy machine filtering. The input voltages of a cycloconverter are sinusoidal voltages. As stated before the instantaneous output and input powers of a cycloconverter are balanced because it does not have any storage devices. To maintain this balance on the input side with sinusoidal voltages, the input current is expected to have complex harmonic patterns. Thus as expected, the input current harmonics are at frequencies "$(pn\pm1)f_i\pm Mf_o$" where M is an integer and $(pn+1)\pm M$=odd condition is satisfied. Thus, a 3-pulse cycloconverter has input current harmonics at the following frequencies:

n=0 f_i, $f_i\pm6f_o$, $f_i\pm12f_o$, …

n=1 $2f_i\pm3f_o$, $2f_i\pm9f_o$, $2f_i\pm15f_o$ …

$4f_i\pm3f_o$, $4f_i\pm9f_o$, $4f_i\pm15f_o$,…

n=2, 3,…

4. Newer Types of Cycloconverters:

4.1 Matrix Converter:

The matrix converter is a fairly new converter topology, which was first proposed in the beginning of the 1980s. A matrix converter consists of a matrix of 9 switches connecting the three input phases to the three output phases directly as shown in Fig. 12. Any input phase can be connected to any output phase at any time depending on the control. However, no two switches from the same phase should be on at the same time, otherwise this will cause a short circuit of the input phases. These converters are usually controlled by PWM to produce three-phase variable voltages at variable frequency.

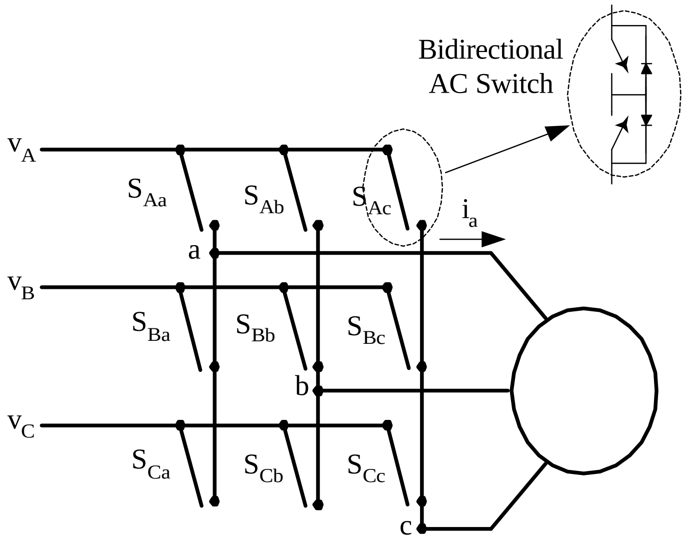

Fig. 12 Matrix converter

This direct frequency changer is not commonly used because of the high device count, i.e. 18 switches compared to 12 of a dc link rectifier-inverter system. However, the devices used are smaller because of their shorter ON time compared to the latter.

4.2 Single-Phase to Three-Phase (1ϕ-3ϕ) Cycloconverters:

Recently, with the decrease in the size and the price of power electronics switches, single-phase to three-phase cycloconverters (1ϕ-3ϕ) started drawing more research interest. Usually, an H-bridge inverter produces a high frequency single-phase voltage waveform, which is fed to the cycloconverter either through a high frequency transformer or not. If a transformer is used, it isolates the inverter from the cycloconverter. In addition to this, additional taps from the transformer can be used to power other converters producing a high frequency ac link. The single-phase high frequency ac (hfac) voltage can be either sinusoidal or trapezoidal. There might be zero voltage intervals for control purposes or zero voltage commutation. Fig. 13 shows the circuit diagram of a typical hfac link converter. These converters are not commercially available yet. They are in the research state.

Among several kinds, only two of them will be addressed here:

4.2.1 Integral Pulse Modulated (1ϕ-3ϕ) Cycloconverters [4]:

The input to these cycloconverters is single-phase high frequency sinusoidal or square waveforms with or without zero voltage gaps. Every half-cycle of the input signal, the control for each phase decides if it needs a positive pulse or a negative pulse using integral pulse modulation. For integral pulse modulation, the command signal and the output phase voltage are integrated and the latter result is subtracted from the former. For a positive difference, a negative pulse is required, and vice versa for the negative difference. For the positive (negative) input half-cycle, if a positive pulse is required, the upper (lower) switch is turned on; otherwise, the lower (upper) switch is turned on.

Therefore, the three-phase output voltage consists of positive and negative half-cycle pulses of the input voltage. Note that this converter can only work at output frequencies which are multiples of the input frequency.

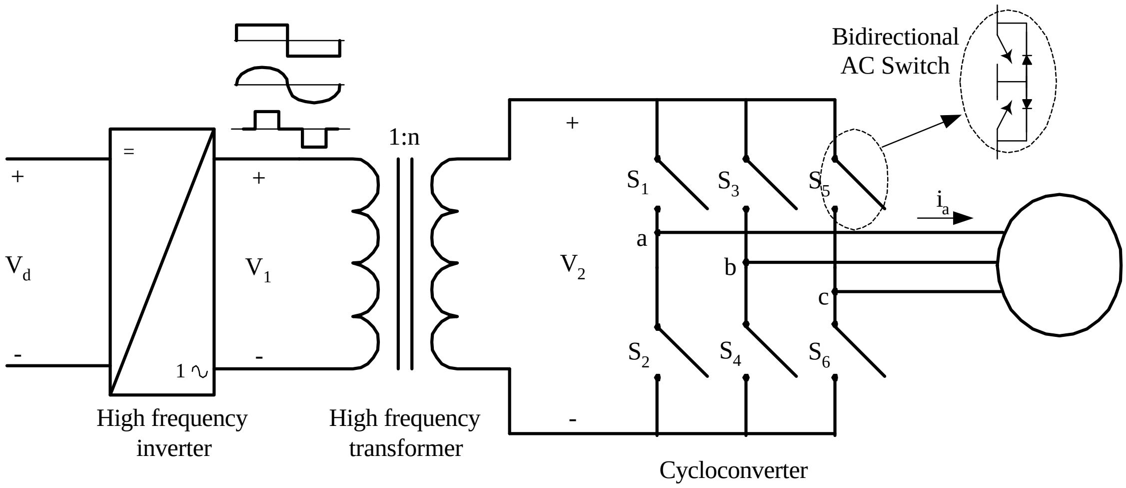

Fig. 13 High frequency ac link converter (1ϕ hf inverter + (1ϕ-3ϕ) Cycloconverter)

4.2.2 Phase-Controlled (1ϕ-3ϕ) Cycloconverter [5]:

This cycloconverter converts the single-phase high frequency sinusoidal or square wave voltage into three-phase voltages using the previously explained phase control principles. The voltage command is compared to a sawtooth waveform to find the firing instant of the switches. Depending on the polarity of the current and the input voltage, the next switch to be turned on is determined. Compared to the previous one, this converter has more complex control but it can work at any frequency.

5. Summary:

Cycloconverters are widely used in industry for ac-to-ac conversion. With recent device advances, newer forms of cycloconversion are being developed. These newer forms are drawing more research interest.

In this article, the most commonly known cycloconverter schemes are introduced, and their operation principles are discussed. For more detailed information, the following references can be used.

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