CHAPTER 1

INTRODUCTION

Contents

Chapter 1

Introduction

Utilities deliver power to the consumers at rated voltage and frequency. Numerous modern industrial applications require ac power with variable amplitude and adjustable frequency. However for the processes, where utility supply is of no use, and where variable frequency and voltages (i.e. ac/ac power conversion) is required, ac/ac converters are used. Variable frequency drives, constant frequency power supplies for military applications, locomotives are the best-suited examples of such applications [1]-[2]. Using an appropriate power-conditioning interface between the utility source and the load can solve this incompatibility between the available utility supply and the required electrical supply for the load.

1.1 Ideal Characteristics:

Ideally this interface should be capable of accepting fixed/variable voltage at rated/variable frequency and delivering variable voltage at any arbitrary frequency. In fact it must possess and exhibit the transfer properties of generalized voltage/frequency converter.

By definition this ac-ac converter is assumed to possess total flexibility of independently converting voltages and frequencies and delivering reasonably sinusoidal voltages/currents to the load.

The power conversion should be bi-directional in nature.

Also this conversion should be at the cost of least energy consumption i.e. it should be highly efficient or loss free. These characteristics are depicted analytically in Fig 1.1

1.2 Application of AC-AC converters

- Variable frequency AC drives
    - Textile manufacturing industries

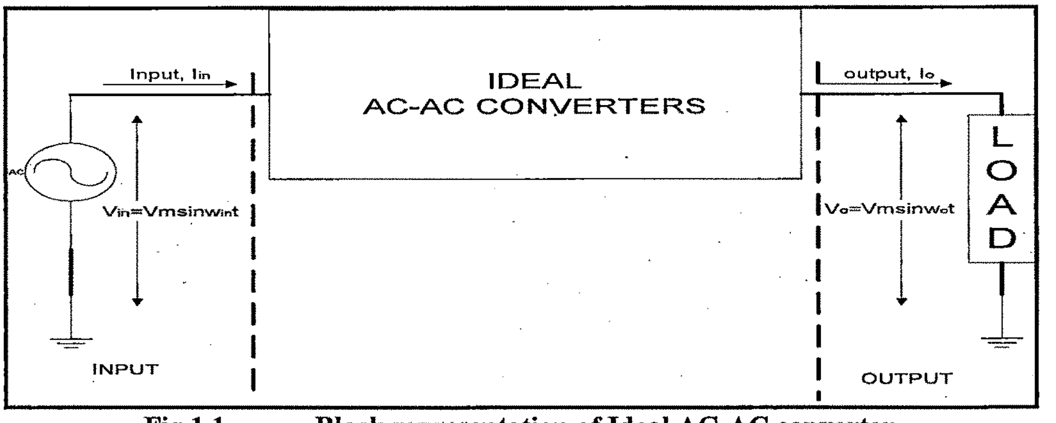


Fig 1.1 Block representation of Ideal AC-AC converter

$V_i = V_{im} \sin \omega_i t$	$V_o = V_{om} \sin \omega_o t$
$Ii = I_{im}(\sin \omega_i t + \phi_i)$	$I_o = I_m(\sin \omega_o t + \phi_o)$
V_i, ω_i *are the inputs*	Z_o, ϕ_o *are the inputs*
ϕ_i *are the controllable parameters*	V_o & ω_o *are the controllable parameters*

- Chemical processes
- Polymer forming

- Food processing
- Cranes and Mine hoist
- Pumps and grinders
- Constant frequency power supplies
    - Aircraft power supplies
    - Mobile ground power generating stations
- Controllable VAr support for energy saving
    - Centrifugal pumps
    - Electrical fans
    - Power factor correction
- Transportation
    - Electric Locomotives
- High frequency applications
    - Switch mode rectifiers & Battery chargers

- Induction heating

1.3 AC/AC conversion

1.3.1 Electromechanical AC-AC converters

First practical implementation of AC/AC converter was made using an electromechanical converter, which consisted a mechanical variable speed motor-alternator set. This set did generate variable frequency voltage but has certain limitations [3]. Fig 1.2 gives a pictorial view of motor generator set installed in the industry.

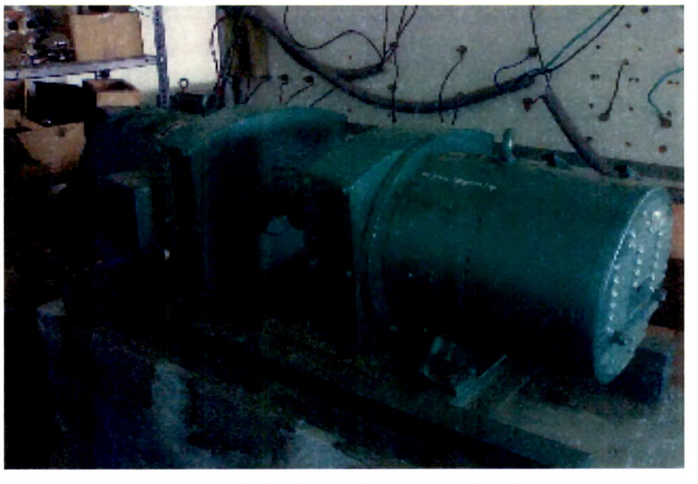


Fig 1.2 A pictorial View of Motor Generator Set

For generating variable frequency, the speed of motor alternator set has to be varied over a wide range resulting in poor dynamic response. The voltage of an alternator is proportional to rate of cutting magnetic flux, i.e. at lower speeds the amplitude of output voltage will be low in spite of high field excitation. Installation is bulky and its life cycle cost is high. Procurement and maintenance cost is high.

1.3.2 Indirect AC-AC converter

Most traditional topology used today, which has been in use for last three decades for ac/ac power converter is a pulse-width modulated voltage source inverter (PWM-VSI) with a diode rectifier at front-end and a dc-link capacitor. The diode rectifier based PWM-VSI, shown in Fig.

1.3. Diode rectifier based PWM-VSI consists of two-stage power conversion and intermediate energy storage element.

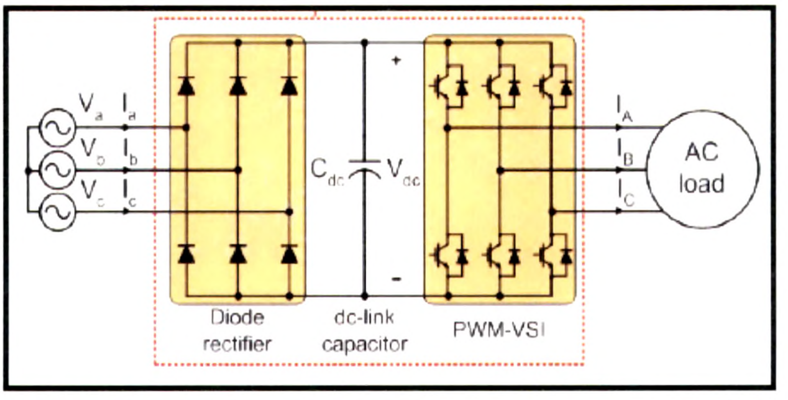


Fig. 1.3 Pulse-width modulated voltage source inverter

The diode rectifier converts the fixed ac signal of the utility supply to uncontrolled dc signal. The DC ripple power is supplied by an intermediate link consisting of energy storage capacitor. The PWM-VSI subsequently generates ac signals with variable amplitude and frequency using high-frequency switching operation. Diode rectifier based PWM-VSI configuration is based on indirect power conversion because the entire ac/ac conversion is performed through intermediate dc power conversion with dc-link between the two ac systems.

The operation of these converter stages is decoupled on an instantaneous basis by means of energy storage element and controlled independently, so long as the average energy flow is equal. Therefore, the instantaneous power flow does not have to equal the instantaneous power output. The difference between the instantaneous input and output power must be absorbed or delivered by an energy storage element within the converter.

Disadvantages of the diode rectifier based PWM-VSI are the following:

1. Bulky system size and volume

Massive and bulky dc-link reactive components are the most important part required for the indirect power conversion to decouple two ac stages and store intermediate dc energy. The large electrolytic dc-link capacitor in the diode rectifier based PWM-VSI results in the bulky converter size and volume of the entire converter [4].

2. Limited power rating

The output power level applicable to the diode rectifier based PWM-VSI is limited by the PWM-VSI with gate turn-off switches such as power MOSFETs or insulated gate bipolar transistors (IGBTs). The PWM-VSI based on fast PWM switching operation, has shown intrinsic weakness for high-power areas, because of limited power rating of available gate-turn-off devices and substantial switching losses associated with hard switching operation resulting in heat dissipation issue. In addition, possibility of insulation failures and electromagnetic interference (EMI) due to high *dv/dt* stresses with fast switching operation is aggravated in high power applications [5].

3. Harmonic pollution in utility grid

The harmonic pollution in the electrical utility is caused by the significant harmonic currents of the diode rectifier type utility interface [6]. Due to its uncontrolled operational characteristics, the diode rectifier produces distorted input current waveform with poor power factor. The harmonic utility currents fed by the rectifier yield an inefficient usage of electrical energy, equipment overheating, malfunction of solid-state equipment, interference with communication systems, and power quality degradation in distribution system [7], [8]. By using controlled rectification through power MOSFETs or IGBTs and using SPWM techniques for the device switching it is possible to overcome this problem of non-sinusoidal currents present in the supply networks. But this scheme makes the whole system costly.

1.3.3 Direct AC-AC conversion

Direct AC –AC converters does not need any energy storage element as shown in Fig. 1.4.

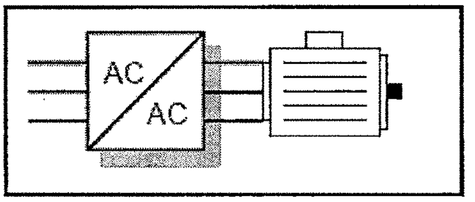


Fig 1.4 Direct AC-AC converters

In General, direct converter can be identified as three distinct topological approaches.

1.3.3.1 AC power controller

The first and simplest topology can be used to change the amplitude of an ac waveform. It is known as an ac controller and functions by simply chopping symmetric notches out of the input waveform. Ac power controllers are broadly classified as

- Single-phase controller
  - Unidirectional or half wave ac controllers
  - Bi-directional or full wave ac controllers
- Three-phase controller
  - Unidirectional or half wave ac controllers
  - Bi-directional or full wave ac controllers

For the power transfer in AC-AC systems, two types of controls are employed

- On –Off control
- Phase angle control

In industries, there are several processes in which mechanical time constant or thermal time constant is of the order of several seconds. In such applications, where no change is observed in control parameters, On-Off control is implemented. In on-off control, thyristors switches connect the load to the ac source for few cycles of the input voltage and disconnect it for another few cycles. In phase control method, thyristor switches connect the load to the ac source for a portion of each cycle of input voltage and hence results in faster response. Single phase AC controller for half wave and full wave configurations are shown in figure 1.5(a) & 1.5(b).

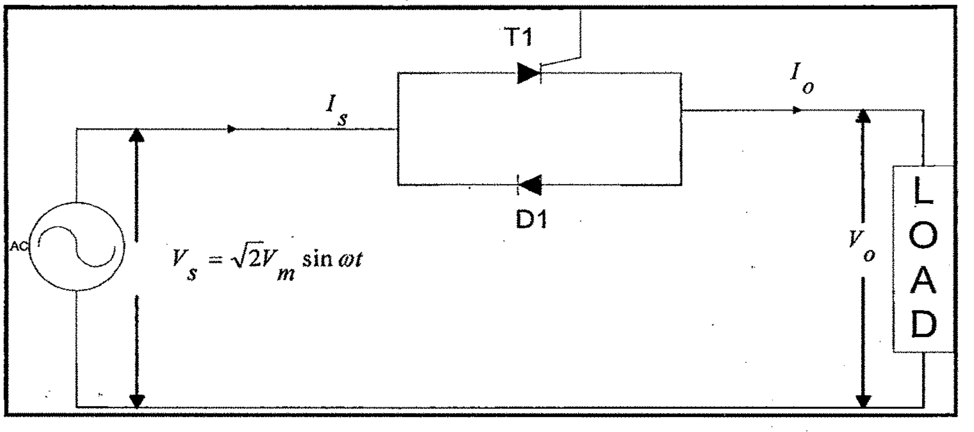


Fig. 1.5 (a) Single half bridge ac power controller

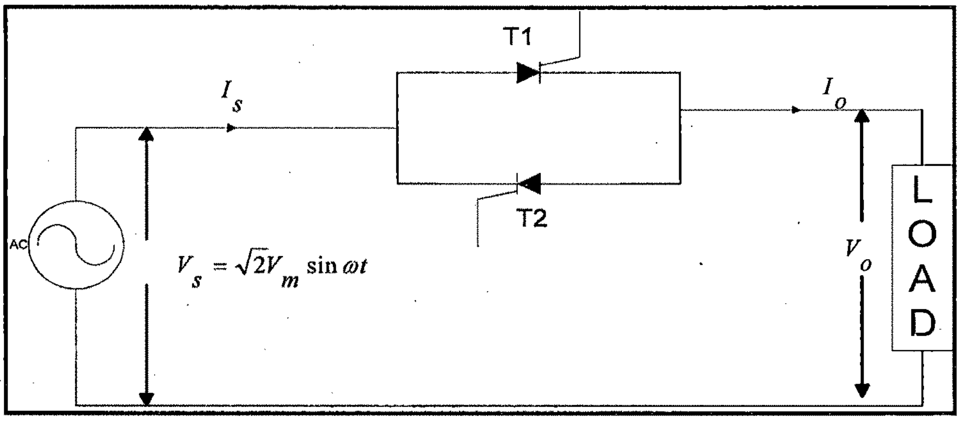


Fig. 1.5(b) Single Phase Full Bridge AC power controller

For a full wave, symmetrical phase control, the SCRs T1 and T2 in Fig. 1.5(b) are gated at a and $\pi + a$, respectively from the zero crossing of the input voltage and by varying a, the power flow to the load is controlled through voltage control in alternate half cycles. As long as one SCR is carrying current, the other SCR remains reverse biased by the voltage drop across the conducting SCR. Input voltage, gate pulses, load current, output voltage and voltage across device are shown in the fig 1.6

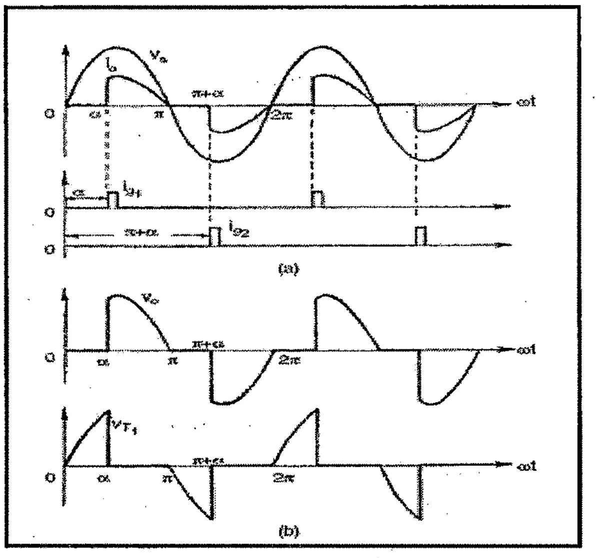
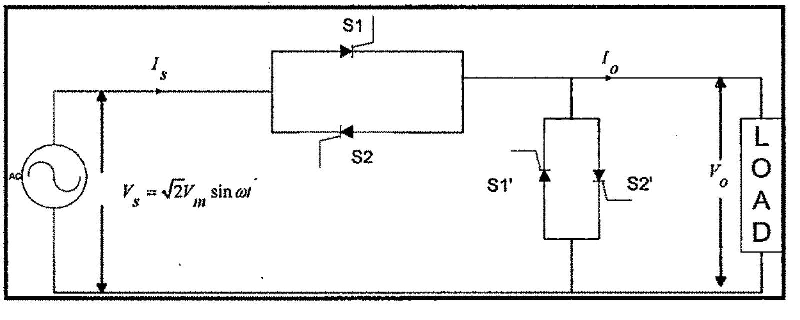


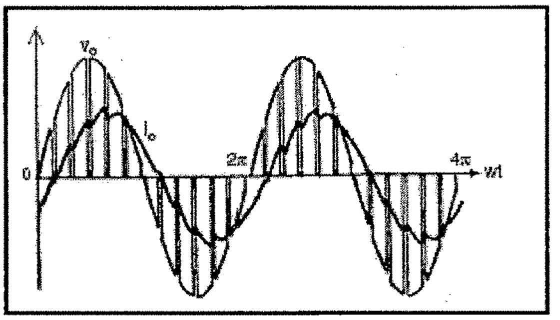
Fig 1.6 Output Waveforms voltage and current waveforms of Single Phase Full Bridge AC power controller

PWM AC Chopper

As in the case of controlled rectifier, the dynamic performance of ac voltage controllers can be improved in terms of harmonics, quality of output current, and input power factor by PWM control in PWM ac choppers, the circuit configuration of one such single-phase unit being shown in Fig. 1.7 (a). Here, fully controlled switches S_1 and S_2 connected in anti-parallel are turned on and off many times during the positive and negative half cycles of the input voltage, respectively.



(a)



(b)

Fig 1.7 (a) configuration of single-phase ac chopper
(b) Output voltage and load current waveforms

S_1' and S_2' provide the freewheeling paths for the load current when S_1 and S_2 are off. An input capacitor filter may be provided to attenuate the high switching frequency currents drawn from the supply and also to improve the input power factor. Figure 1.7 (b) shows the typical output voltage and load current waveform for a single-phase PWM ac chopper. It can be shown that the control characteristics of an ac chopper depend on the *modulation index, M* that theoretically varies from 0 to 1. Three-phase PWM choppers consist of three single-phase choppers either connected in delta or four-wire star.

Three Phase AC-AC Power Controllers

The configurations in fig. 1.8 (a) and fig. 1.8 (b) can be realized by three single-phase ac regulators operating independently of each other and they are easy to analyze. In (a), the SCRs are to be rated to carry line currents and withstand phase voltages whereas in (b) they should be capable to carry phase currents and withstand the line voltage. In (b), the line currents are free from triplen harmonics while these are present in the closed delta. The power factor in (b) is slightly higher.

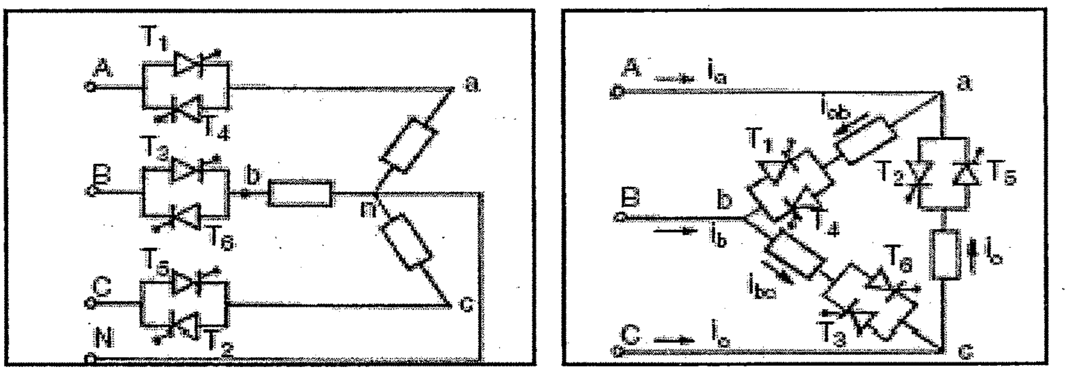


Fig 1.8 **(a) Three phase ac power controller with WYE connection (b) Delta connection configurations.**

1.3.3.2 Cycloconverters

Alternate topology can be utilized if the output frequency is much lower than the input source frequency. This topology is called a cycloconverter, and it approximates the desired output waveform by synthesizing it from pieces of the input waveform. 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 adopting line commutation. Fig 1.9 shows general representation of cycloconverters.

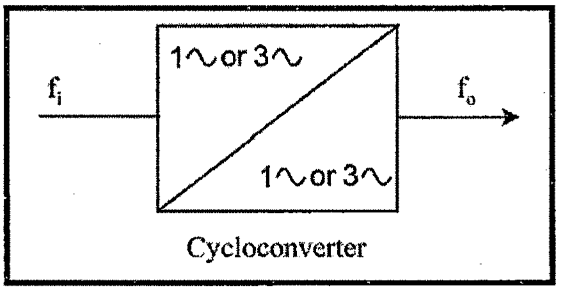


Fig. 1.9 General representation of Cycloconverter

The operation principles of cycloconverter can be studied considering a case of the single-phase to single-phase cycloconverter as shown in fig 1.10. This converter consists of back-to-back connection of two full-wave rectifier circuits. Fig 1.11 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. 1.11(a). 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.1.11. 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.

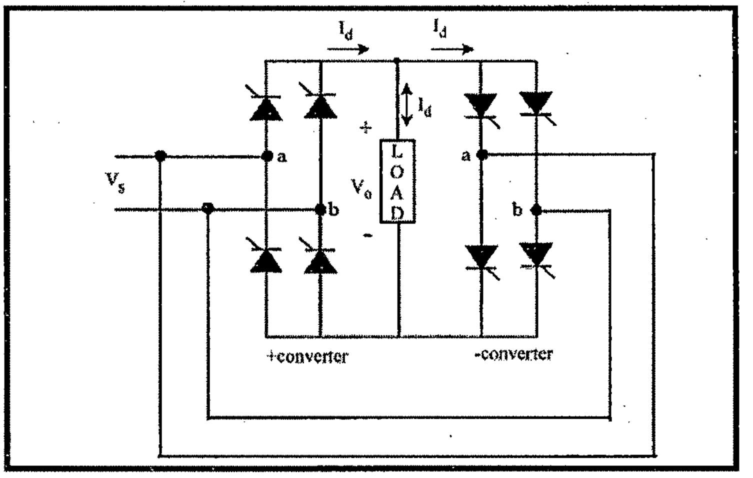


Fig 1.10 Single-phase full bridge cycloconverters

The frequency of the output voltage, v_o in Fig 1.11 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.

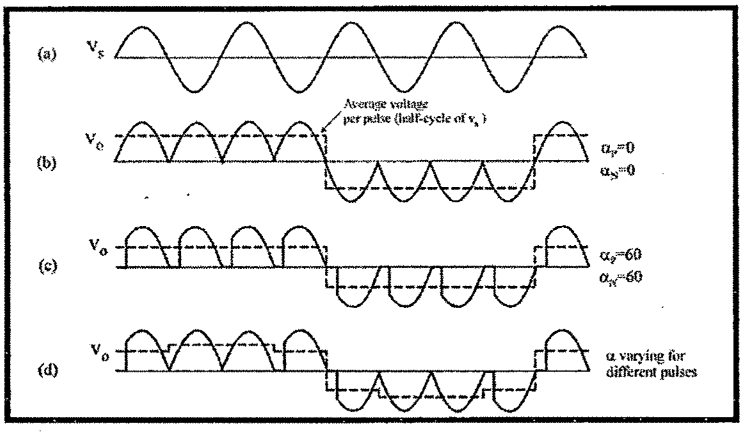


Fig 1.11 Single-phase to single-phase cycloconverter waveforms

a Input voltage

b Output voltage for zero firing angle

c Output voltage with firing angle □/3 rad.

d Output voltage with varying firing angle

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

$$V_d = \frac{2\sqrt{2}}{\pi} V \cos\alpha \qquad (1.1)$$

Where V is the input rms voltage.

The dc value per half cycle is shown as dotted in fig 1.11 d.

Then the peak of the fundamental output voltage is approximated as

$$V_{01}(t) = \frac{4}{\pi}\frac{2\sqrt{2}}{\pi} V \cos\alpha \qquad (1.2)$$

Equation 1.2 implies that the fundamental output voltage depends on α.

For $\alpha = 0°$, $\boxed{V_{01}(t) = V_{do} \times 1 = V_{do}}$, where $\boxed{V_{do} = \frac{4}{\pi}\frac{2\sqrt{2}}{\pi}V}$.

(1. 3)

If α is increased to π/3 as in fig. 1.11 d, $\boxed{V_{01}(t) = V_{do} \times 0.5}$.

Thus by 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. 1.11 (b) and (c) represent 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. 1.11 (d). Now, the six-stepped dotted line (six levels generated in one complete cycle as a result of modulating firing angle α) is more like a sine wave with fewer harmonics. The more pulses there are with different α's, the less are the harmonics. It is also possible to modulate the firing angle α sinusoidally over each half cycle of output to produced improved output voltage waveform.

1.3.3.2.a 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. 1.12) and 3Φ-1Φ bridge cycloconverter (Fig. 1.13). 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. 1.14. Note that α is sinusoidally modulated over the cycle to generate a harmonically optimum output voltage. The polarity of the current (depending on load power factor) 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.

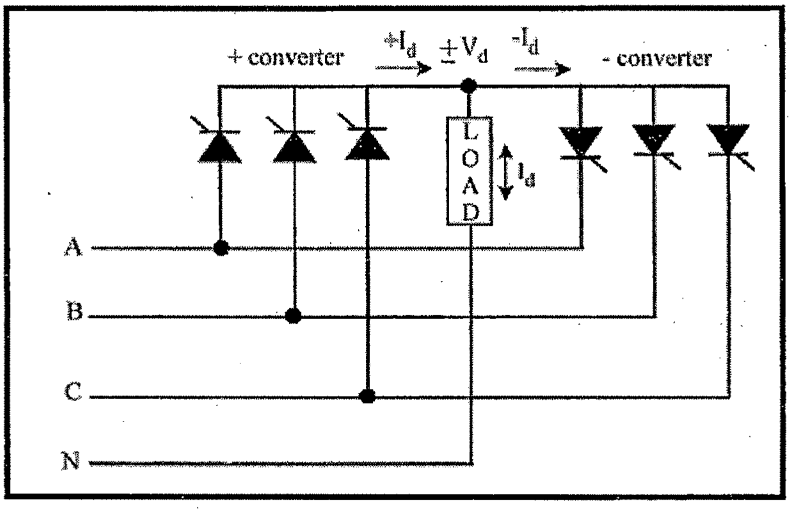


Fig 1.12 3ϕ-1ϕ Half bridge cycloconverter

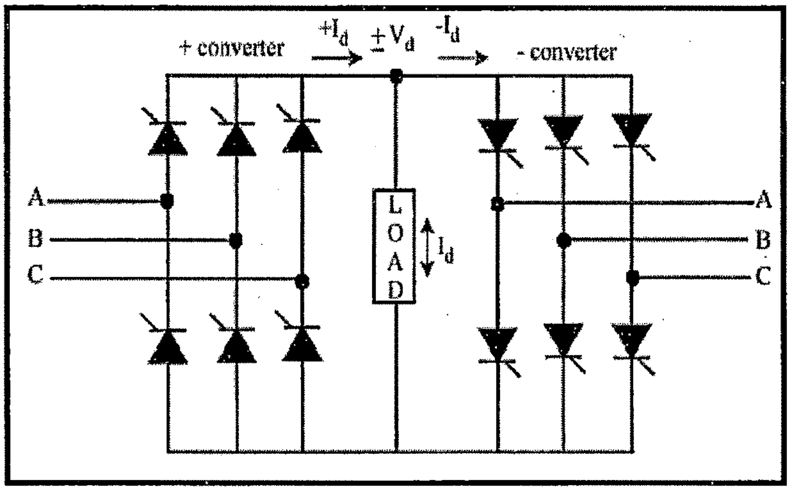


Fig 1.13 3ϕ-1ϕ Full bridge cycloconverter

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.

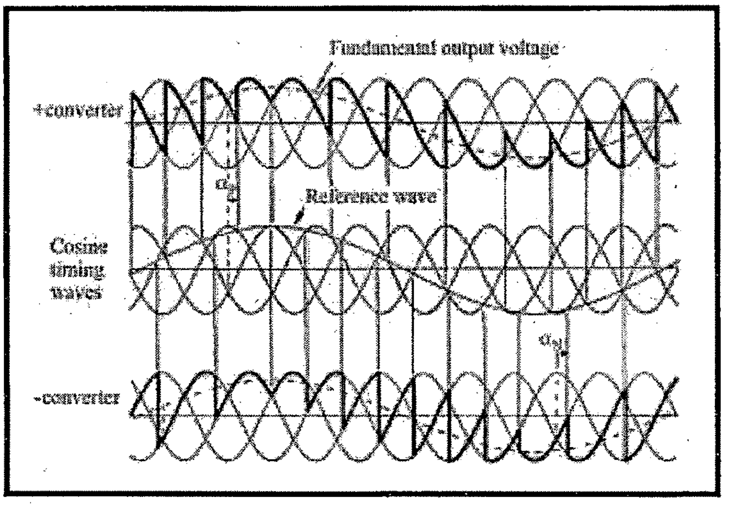


Fig. 1.14 3Φ-1Φhalf-wave cycloconverter waveforms

a) + converter output voltage

b) cosine timing waves

c) – converter output voltage

$$\alpha_P + \alpha_N = \pi \qquad (4)$$

The fundamental output voltage in fig. 1.14 can be given as:

$$v_{o1}(t) = \sqrt{2}V_o \sin \omega_o t \qquad (5)$$

where V_o is the rms value of the fundamental voltage

At a time t_o the output fundamental voltage is

$$v_{o1}(t_0) = \sqrt{2}V_o \sin \omega_o t_o \qquad (6)$$

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

$$v_{o1}(t_o) = \sqrt{2}V_o \sin \omega_o t_o = V_{do} \cos \alpha_P$$

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

From the α condition (3)

$$\boxed{v_{o1} = V_{do} \cos\alpha_P = -V_{do} \sin\alpha_N}$$

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.

1.3.3.2.b) Three-Phase to Three-Phase (3Φ-3Φ) Cycloconverter

If the outputs of three 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. 1.15 and 1.16 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.

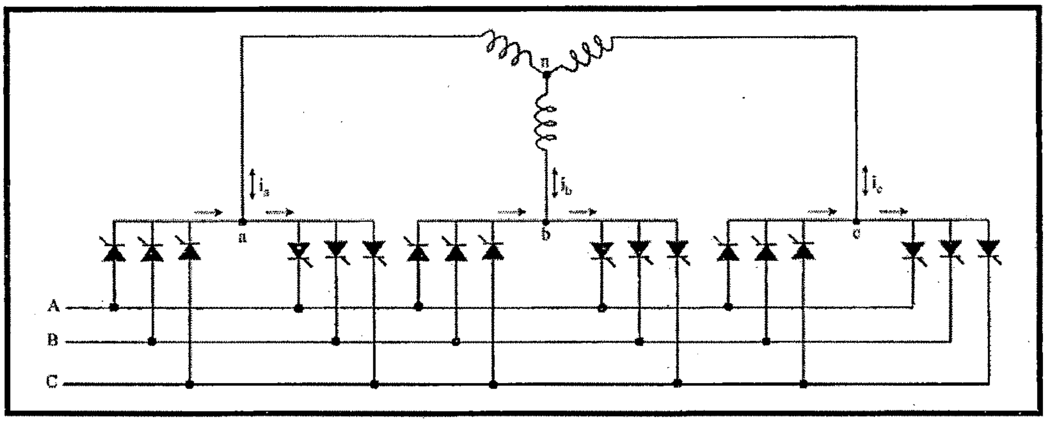


Fig. 1.15 3ϕ-3ϕ half-wave cycloconverter

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.

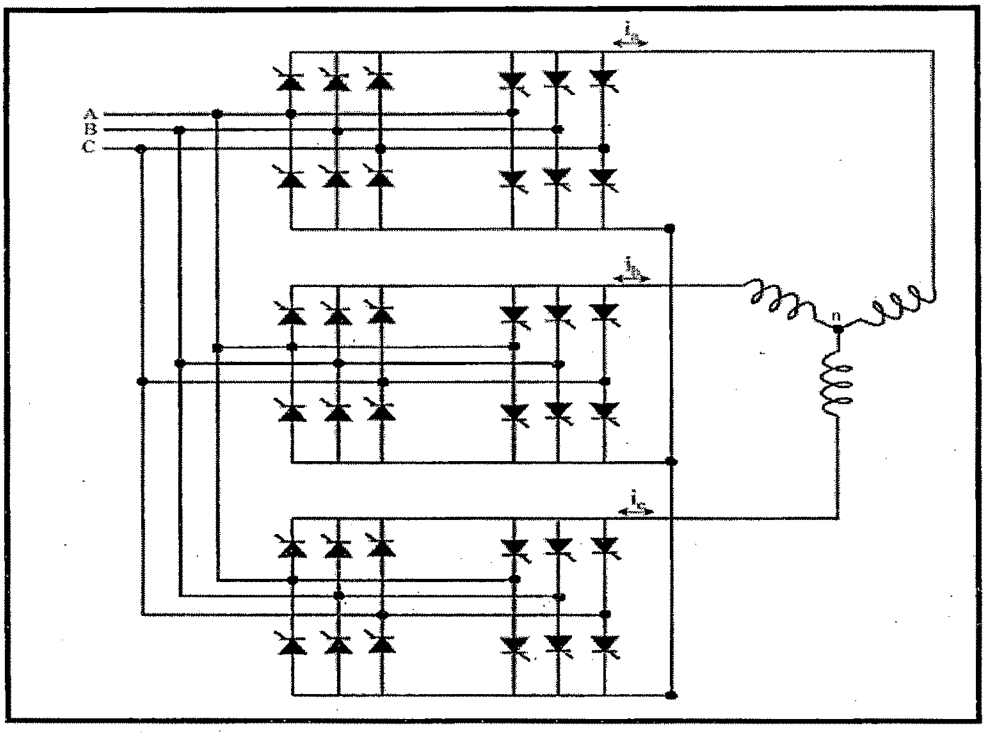


Fig. 1.16 3ϕ-3ϕ half-wave cycloconverter

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.

1.3.3.2.c) 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 fewer harmonic. 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 affecting 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 affects the harmonic content. A greater number of pulses have less harmonic content. Therefore, a 6-pulse (bridge) cycloconverter produces fewer harmonic 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±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 ± 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 correspond to frequencies below f_i. These are called sub-harmonics. 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 sub-harmonics expected. According to calculations done in [1], sub-harmonics in this mode exist for $f_o/f_i > 0.6$. For the blocking mode, [1] states that the sub-harmonics 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 "$(pn+1) f_i \pm M f_o$" 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, $f_i \pm 6f_o$, $f_i \pm 12f_o$, ...

n=1 $2f_i \pm 3f_o$, $2f_i \pm 9f_o$, $2f_i \pm 15f_o$ ...

$4f_i \pm 3f_o$, $4f_i \pm 9f_o$, $4f_i \pm 15f_o$,...

n=2, 3,...

1.4 Modern trends of AC - AC conversion

Increasing proliferation of conventional AC-DC-AC converter employing diode bridge configuration results in increase of power quality problems like harmonics, low power factor, etc. of utility distribution systems.

Researchers have implemented various solutions including passive filters, multi-pulse rectifiers, high performance converters etc to improve the power quality.

1.4.1 Other Static Converters

With the recent advancement in development of gate turn off devices and digital signal processing, implementation of complex control algorithm having no of commutations per cycle has been possible. This has resulted in development of forced commutated converters for utility interface achieving a harmonic free power with an active approach to shape the supply currents to the converters. Advantages of forced commutated converters are as follows:

- The current or voltage can be modulated generating less harmonic contamination.
- Power factor can be controlled, and operation with leading PF also possible.
- Two topologies are possible one is voltage source and other is a current source rectifier.
- The reversal of power in thyristorized rectifiers is by reversal of voltage at the *dc* link.

Instead, force commutated rectifiers can be implemented for both, reversal of voltage or reversal of current.

One of the forced commutated converters is a PWM based voltage source rectifier (commonly known as PWM-VSR) as shown in figure 1.16. PWM-VSR acts as an active front-end converter that draws sinusoidal currents from the utility source.

The basic operation principle of the voltage source rectifier consists on keeping the *dc* link voltage at a desired reference value, using a feedback control loop as shown in figure 1.17. To accomplish this task, the *dc* link voltage is measured and compared with a reference V_{REF}. The error signal generated from this comparison is used to switch *ON* and *OFF* the six devices of the rectifier. In this way, power can come or return to the *ac* source according with the *dc* link voltage requirements. The voltage V_D is measured at the capacitor C_D.

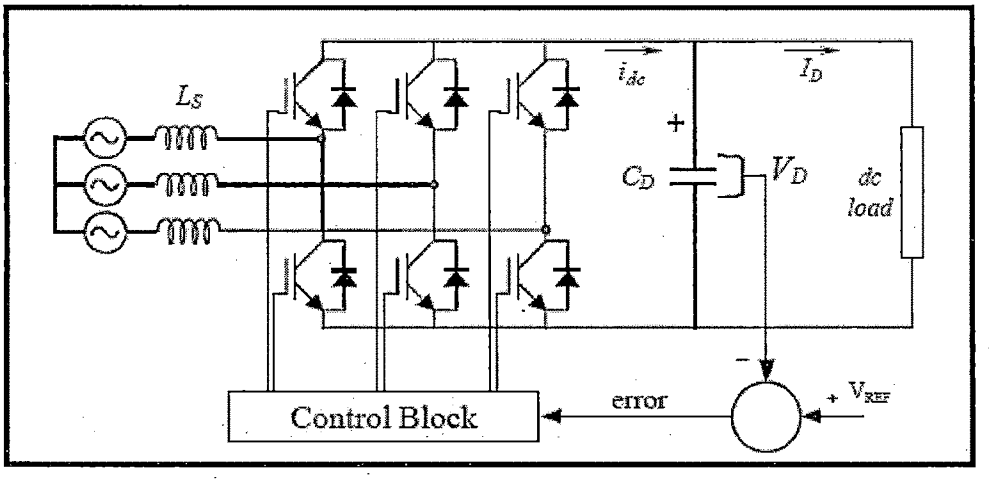


Fig 1.17 Block representation of voltage source inverters

When the current I_D is positive (rectifier operation), the capacitor C_D is discharged, and the error signal commands the control Block for more power from the *ac* supply. The Control Block takes the power from the supply by generating the appropriate PWM signals for the six devices. In this way, more current flows from the *ac* to the *dc* side, and the capacitor voltage is recovered. Inversely, when I_D becomes negative (inverter operation), the capacitor C_D is overcharged, and the error signal ask the control to discharge the capacitor and return power to the *ac* mains. The PWM Control not only can manage the active power, but reactive power also, allowing this type of rectifier to correct power factor. Besides, the ac current waveforms can be maintained almost sinusoidal, reducing harmonic contamination to the mains supply.

1.4.2 Active Filter Topology

Force-commutated PWM rectifiers can work as active power filters. The voltage source current controlled rectifier has the capability to eliminate harmonics produced by other polluting loads. It only needs to be connected as shown in figure 1.18

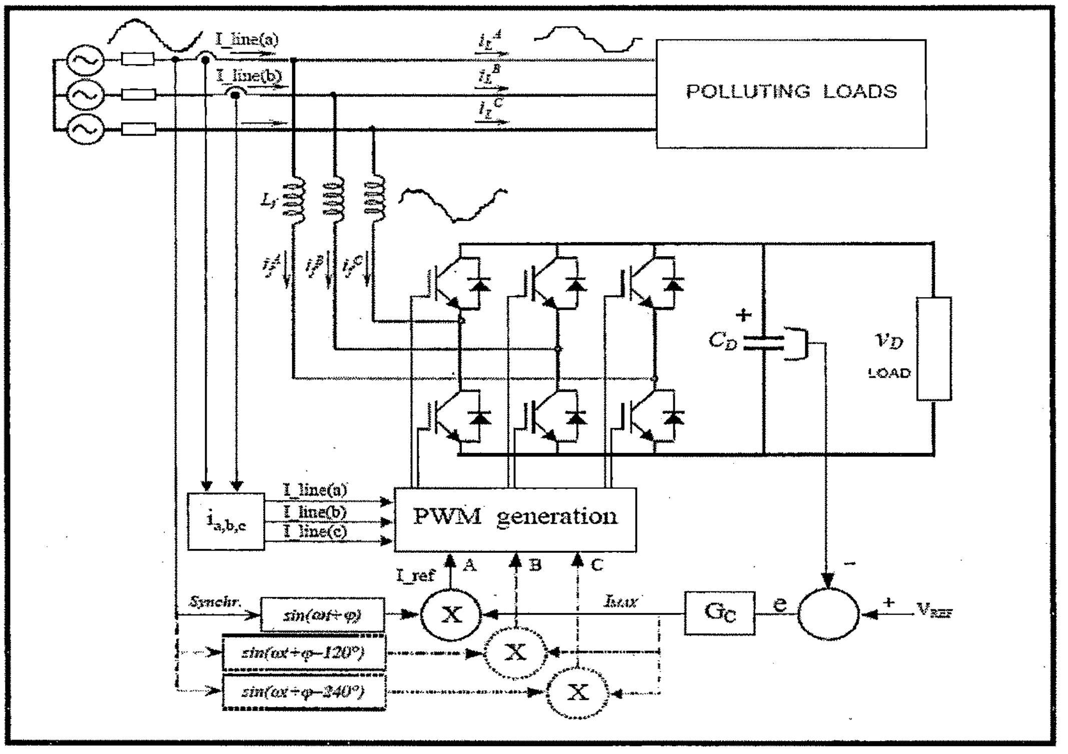


Fig 1.18 Active filter topology for compensation of harmonic currents

The current sensors are located at the input terminals of the power source, and these currents (instead of the rectifier currents) are forced to be sinusoidal.

As they are polluting the utility system, the rectifier is forced to deliver the harmonics that loads need, because the current sensors do not allow the harmonics going to the mains. As a result, the rectifier currents become distorted, but an adequate dc capacitor C_D can keep the *dc* link voltage in good shape. In this way the rectifier can do its duty, and also eliminate harmonics fed to the source. Besides, it also can compensate power factor and unbalanced problems.

1.4.3 Matrix Converters

Recently, with the decrease in the size and the price of power electronics switches, matrix converter started drawing more research interest. It is most versatile configuration without any limits on the output frequency and amplitude. It replaces the multiple conversion stages and the intermediate energy storage element by a single power conversion stage, and uses a matrix of semiconductor bidirectional switches, with a switch connected between each input terminal to each output terminal as shown in Fig 1.19.

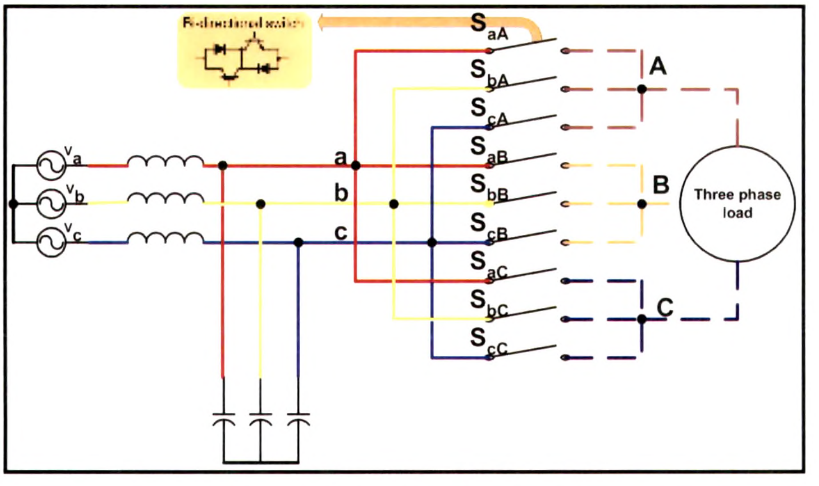


Fig. 1.19 Matrix converter

With this general arrangement of switches, the power flow through the converter can reverse. Because of the absence of any energy storage element, the instantaneous power input must be equal to the power output, assuming idealized zero-loss switches. However, the reactive power input does not have to equal the reactive power output. It can be said again that the phase angle between the voltages and currents at the input can be controlled and does not have to be the same as at the output. Also, the form and the frequency at the two sides are independent, in other words, the input may be three-phase ac and the output dc, or both may be dc, or both may be ac. Therefore, the matrix converter topology is promising for universal power conversion such as: ac to dc, dc to ac, dc to dc or ac to ac.

1.5 Review of the previous work

The first static transformer characterized by variable frequency ratio and the bidirectional flow of power was proposed by Hazeltine [9]. He established the fundamental principle of constructing the output voltage of the required frequency from the segments of the multiphase input voltages. He then proposed of usage of electric valves and its arrangements for switching the load sequentially, thus obtaining the output voltage of required frequency. Though, Hazeltine proposed a simple control technique, it was difficult to implement the theory at that time due to non availability of suitable switching devices at that time. In early nineteen thirties, Schenkel [10] and Van Issendorf [11] had proposed the principle of phase controlled mercury arc converters capable of generating variable output frequency that is lower than input frequency. These techniques were practically feasible and were capable of phase transformation from three phase to single-phase system. They find applications in traction systems [12], [13]. Rissik carried out thorough review and introduced the term cycloconversion for the process by which an alternating voltage wave having lower frequency is synthesized from multiphase high frequency input [14], [15]. Thus the popular name of cycloconverter was designated to static converters.

After the invention of SCR, frequency changers gained lot of attention and importance due to enormous potential of the converter. Books by Pelly and Gyugi give a unified treatment to this family of converters [16], [17]. Out of the various topologies discussed here, the most promising one is the unrestricted frequency changer. There are many other advantages of unrestricted frequency changers along with bidirectional flow of power such as unlimited output frequency range, good input voltage utilization, no sub-harmonic generation, less device count. The main drawback of these unrestricted frequency converters [16] is that they contain high percentage of lower order harmonic in output voltage and input current. This is particularly true in case of low voltage conditions where the amplitude of unwanted harmonics can even exceed the amplitude of the fundamental voltage/current components. As a result the advantage gained over the removal of DC link filter is offset by presence of large AC filters.

A method of direct frequency conversion using 18(or 12) transistor-diode pairs for three-phase controlled current output operation was proposed by Daniels et. Al [18], [19]. This converter allows bidirectional power flow and is of unrestricted frequency type. The control technique uses continuous monitoring and controlling of load current using slit-width modulation.

Rodriguez proposed and presented a simulation of control technique for direct frequency conversion using bidirectional switches [20]. The converter is operated with fixed switching frequency and the modulation is performed by using a high frequency carrier signal superimposed to a low frequency modulating voltage. The proposed control topology is based on the concept of fictitious bipolar source. Neither experimental results are given nor the analysis of the results is presented. Daniels and Rodriguez's control technique contains no harmonics in input current. But their control system has the inherent problems of

- High switching frequency
- Low utilization as switching is controlled by monitoring the output current at all time.
- Loss of control if one or more phases remain open as current monitoring is used.

Finally a generalized transformer electronic circuit capable of frequency, voltage and power factor change has been proposed and demonstrated by Venturini [21]. This direct frequency converter is characterized by sinusoidal waveforms both at input and output ports, bi-directionality, independent control over input and output frequency, amplitude and phase displacement. This 3-phase frequency transformer constitutes of nine bidirectional switches. A prototype was successfully implemented as new semiconductor switches become available in the market. Although the output voltage and input current are free of low order harmonics, the voltage utilization of this converter is low. Maximum attainable output voltage is 50% of respective input voltage. However by addition of few components [22] in the modulation function the maximum attainable output can be increased to 86.6% of the input voltage.

The indirect space vector modulation (indirect SVM), which was proposed by Borojevic in 1989, has been considered a standard modulation strategy of the matrix converter.

1.6 Objective of the thesis:

The main disadvantages of the existing direct AC-AC converters are as follows:

- Unrestricted frequency changers contain low order harmonics of considerable amplitude.
- Implementation of the complex control logics
- Gain of the converter proposed so far is very low.

With the fast development in the Semiconductor field, more efficient and cheaper devices in integrated form are available in the market. Also with the availability of high-speed controllers and processors, the implementation of complex control logic has become easier. Exploitation of the above-mentioned developments towards the production of cheaper and compact converters for variable frequency applications is showing considerable promise.

However due to the aforementioned disadvantages, the implementation of the existing direct AC-AC converter structures has been quite difficult and impractical.

The objective of the thesis is to provide the solutions for the above mentioned problems with the prime goal to provide a simple control for direct AC-AC converter. The second objective is to achieve high percentage ratio of output to input voltages i.e high utilization factor. To. provide with a practically feasible topology for direct AC-AC converter having low percentage of harmonics, high input power factor with bidirectional power flow capability.

1.7 Outline of the thesis:

Introduction to the various techniques for generation of variable voltage variable frequency outputs; starting from the heavy and bulky electromechanical methods to the sophisticated direct AC-AC converters topologies is outlined in chapter 1 with all corresponding advantages and disadvantages.

A generalized direct AC-AC transformer model having M-phase inputs and N-phase outputs is presented in chapter 2. Different modes of operation are explained in details and transformation of Voltages, frequency and the phases is evaluated. Detailed simulation of each conversion is carried out and results are incorporated in the chapter 2.

Model for high frequency generation is proposed and various models with possibility of phase transformation alongwith low to high frequency conversion is depicted in the chapter 3. A novel topology for direct AC-AC conversion with unrestricted frequency conversion and high quality of waveforms with an added advantage of galvanic isolation is analyzed and modeled in chapter 3. A simple control technique is derived and implemented to achieve the arbitrary frequency at the output terminals. In depth simulation study of the proposed technique is carried out to support the mathematical model.

An attempt is made to reduce the device count of the circuit proposed in the chapter 3, at the cost of bidirectional flow of power and galvanic isolation between the input and output is outlined in the chapter 4. Various stages of device reduction are discussed and finally a nine-switch technique is analyzed and modeled.

Chapter 5 shows the practical implementation of the technique proposed in chapter 3 using both analog control and digital circuits. Experimental results are included in this chapter.

Practical implementation of the model proposed in chapter 3 applicable to variable frequency sources as well as loads is discussed in chapter 6. in this chapter the application of direct AC-AC converter to wind turbine is explained in detail.

Results and the outcome of all the research work carried is summarized and concluded in chapter 7. It also focuses on the future scope of research in the field of direct AC–AC converters and its behavior in transient modes.