

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.

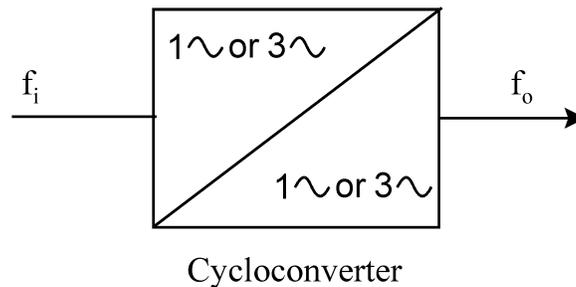


Fig.1 Block diagram of a cycloconverter

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 ($1\phi-1\phi$) cycloconverter.

1.1. Single-phase to Single-phase ($1\phi-1\phi$) 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 $\alpha=0^\circ$ 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.

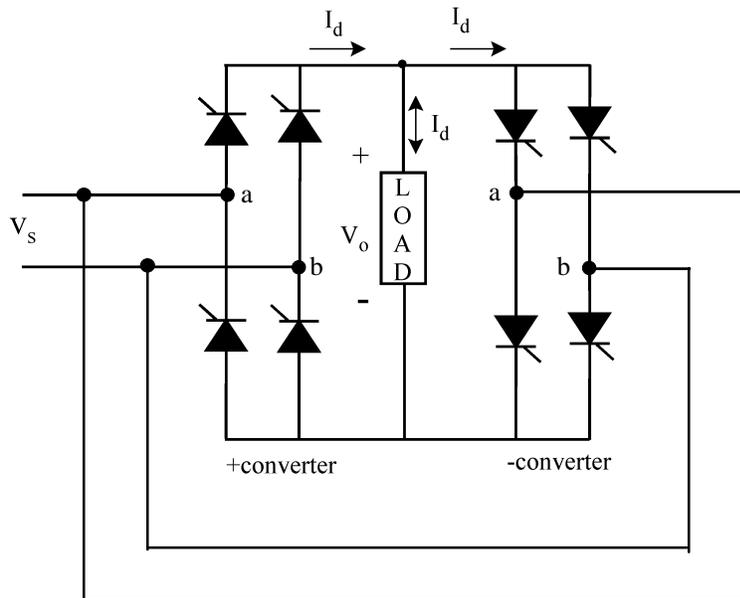


Fig. 2 Single-phase to single-phase cycloconverter

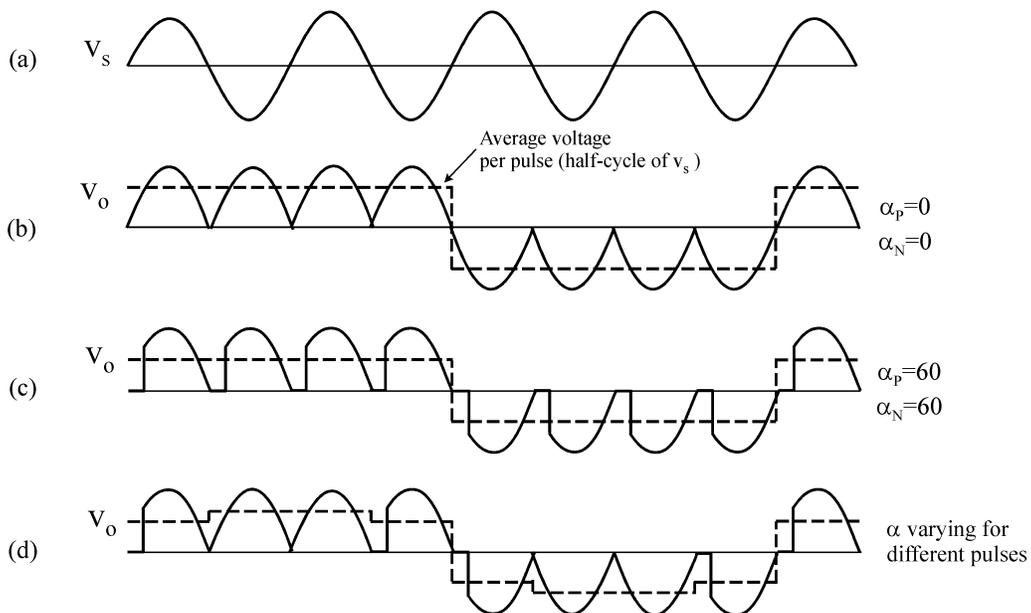


Fig. 3 Single-phase to single-phase cycloconverter waveforms

- a) input voltage
- b) output voltage for zero firing angle
- c) output voltage with firing angle $\pi/3$ 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:

$$V_d = \frac{2\sqrt{2}}{p} V \cos \alpha \quad (1)$$

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

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

Equation 2 implies that the fundamental output voltage depends on α . For $\alpha=0^\circ$,

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

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 (3 ϕ -1 ϕ) Cycloconverter:

There are two kinds of three-phase to single-phase (3 ϕ -1 ϕ) cycloconverters: 3 ϕ -1 ϕ half-wave cycloconverter (Fig. 4) and 3 ϕ -1 ϕ bridge cycloconverter (Fig. 5). Like the 1 ϕ -1 ϕ case, the 3 ϕ -1 ϕ 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.

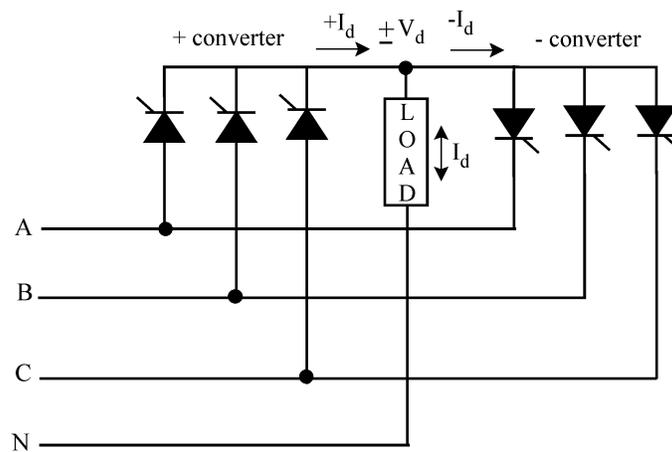


Fig. 4 3 ϕ -1 ϕ half-wave cycloconverter

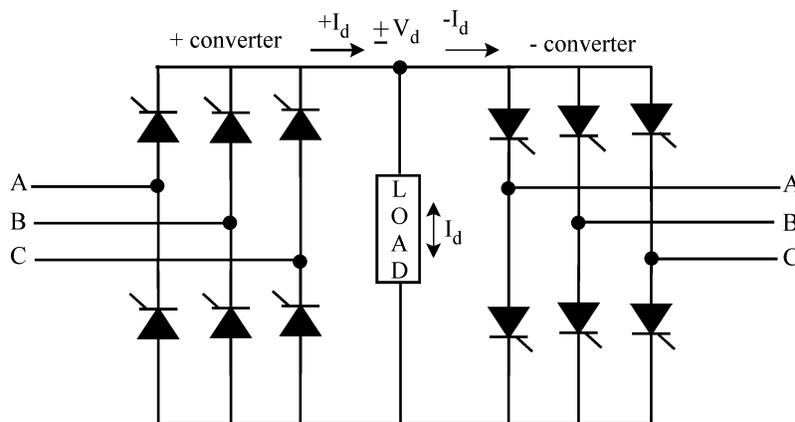


Fig. 5 3 ϕ -1 ϕ bridge cycloconverter

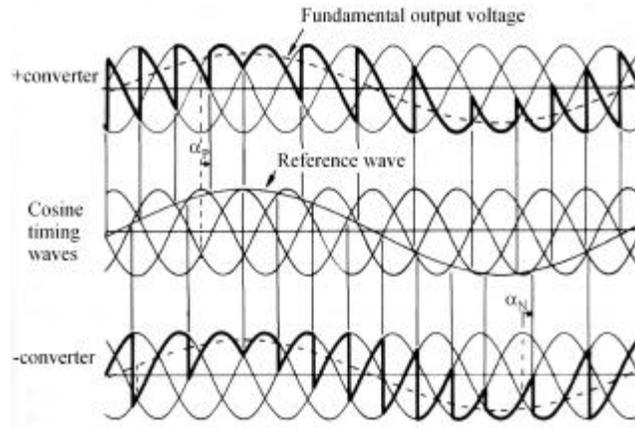


Fig. 6 3 ϕ -1 ϕ half-wave cycloconverter waveforms
a) + converter output voltage
b) cosine timing waves
c) – converter output voltage

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.

$$\mathbf{a}_p + \mathbf{a}_n = \mathbf{p} \quad (3)$$

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

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

where V_o is the rms value of the fundamental voltage

At a time t_o the output fundamental voltage is

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

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

$$v_{o_1}(t_o) = \sqrt{2}V_o \sin \omega_o t_o = V_{do} \cos \mathbf{a}_p \quad (6)$$

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)

$$v_{o_1} = V_{do} \cos \alpha_p = -V_{do} \sin \alpha_N \quad (7)$$

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

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

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

If the outputs of 3 3 ϕ -1 ϕ converters of the same kind are connected in wye or delta and if the output voltages are $2\pi/3$ radians phase shifted from each other, the resulting converter is a three-phase to three-phase (3 ϕ -3 ϕ) 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 3 ϕ -3 ϕ half-wave cycloconverter. If instead, bridge converters are used, then the result is a 3 ϕ -3 ϕ bridge cycloconverter. 3 ϕ -3 ϕ half-wave cycloconverter is also called a 3-pulse cycloconverter or an 18-thyristor cycloconverter. On the other hand, the 3 ϕ -3 ϕ 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.

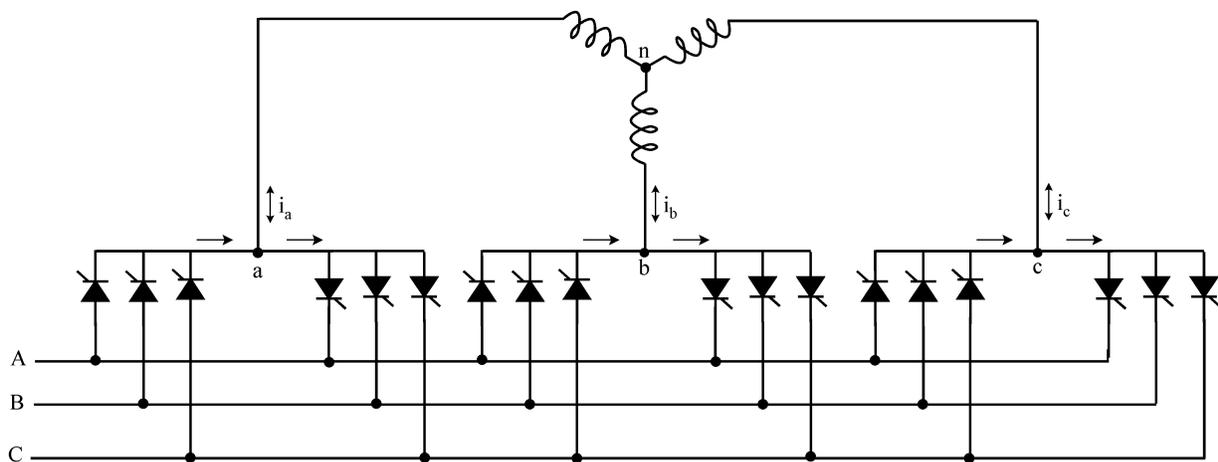


Fig. 7 3 ϕ -3 ϕ half-wave cycloconverter

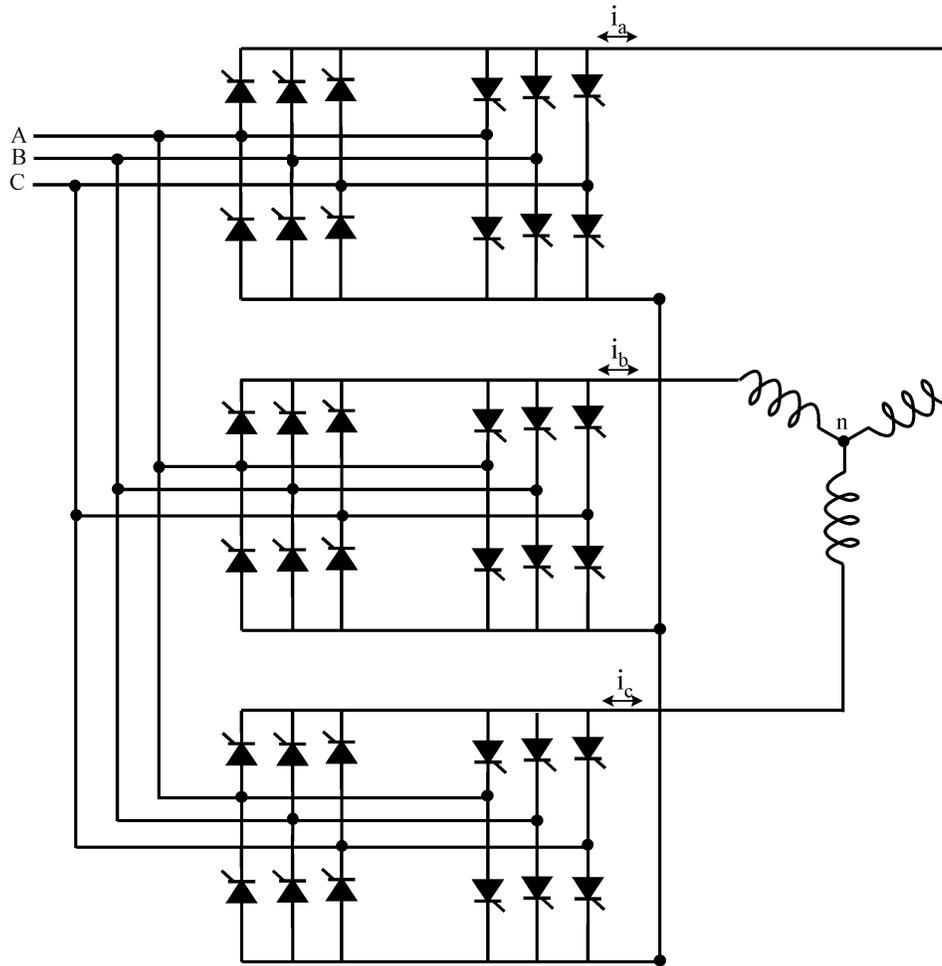


Fig. 8 3 ϕ -3 ϕ bridge cycloconverter

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.

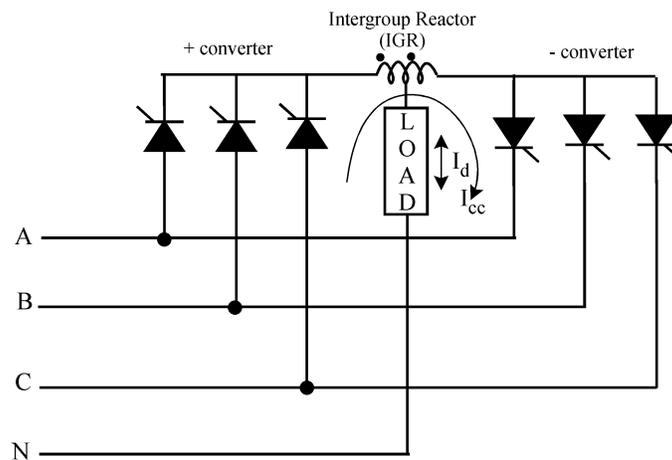


Fig. 9 Circulating current and IGR

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.

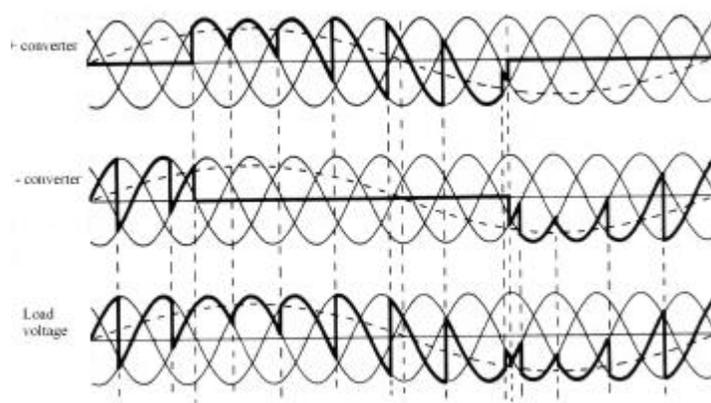


Fig. 10 Blocking mode operation waveforms

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.

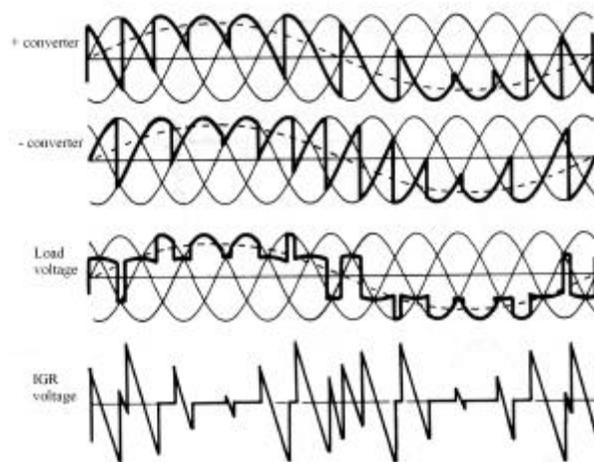


Fig. 11 Circulating mode operation waveforms
a) + converter output voltage
b) – converter output voltage
c) load voltage
d) IGR voltage

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 $pn \pm N = \text{odd}$ condition is satisfied. Then the output harmonics for a 3-pulse cycloconverter in blocking mode will be found at frequencies

$$\begin{aligned} n=1 & \quad 3f_i, 3f_i \pm 2f_o, 3f_i \pm 4f_o, 3f_i \pm 6f_o, 3f_i \pm 8f_o, 3f_i \pm 10f_o \dots \\ n=2 & \quad 6f_i, 6f_i \pm 1f_o, 6f_i \pm 3f_o, 6f_i \pm 5f_o, 6f_i \pm 7f_o, 6f_i \pm 9f_o \dots \\ n=3 & \quad 9f_i, 9f_i \pm 2f_o, 9f_i \pm 4f_o, 9f_i \pm 6f_o, 9f_i \pm 8f_o, 9f_i \pm 10f_o, \dots \\ n=4, 5, \dots & \end{aligned}$$

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

$$\begin{aligned} n=1 & \quad 3f_i, 3f_i \pm 2f_o, 3f_i \pm 4f_o \\ n=2 & \quad 6f_i \pm 1f_o, 6f_i \pm 3f_o, 6f_i \pm 5f_o, 6f_i \pm 7f_o \\ n=3 & \quad 9f_i, 9f_i \pm 2f_o, 9f_i \pm 4f_o, 9f_i \pm 6f_o, 9f_i \pm 8f_o, 9f_i \pm 10f_o \\ n=4, 5, \dots & \end{aligned}$$

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 " $(pn \pm 1)f_i \pm Mf_o$ " where M is an integer and $(pn+1) \pm M = \text{odd}$ condition is satisfied. Thus, a 3-pulse cycloconverter has input current harmonics at the following frequencies:

$$n=0 \quad f_i, f_i \pm 6f_o, f_i \pm 12f_o, \dots$$

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

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

$$n=2, 3, \dots$$

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.

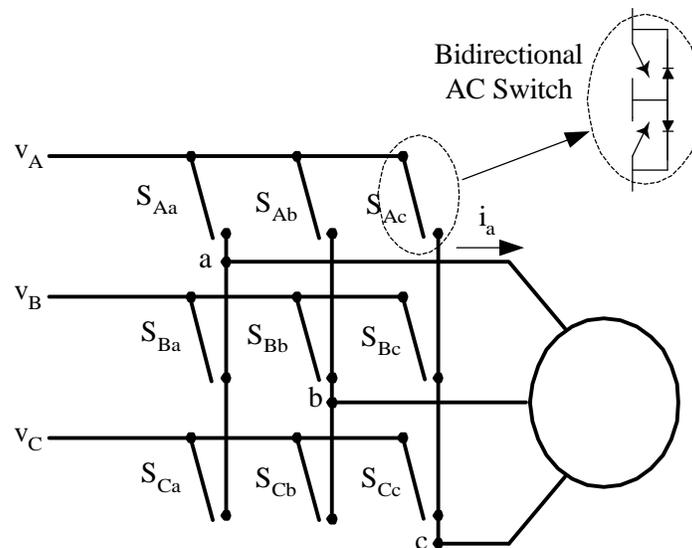


Fig. 12 Matrix converter

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 (1 ϕ -3 ϕ) Cycloconverters:

Recently, with the decrease in the size and the price of power electronics switches, single-phase to three-phase cycloconverters (1 ϕ -3 ϕ) 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 (1 ϕ -3 ϕ) 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.

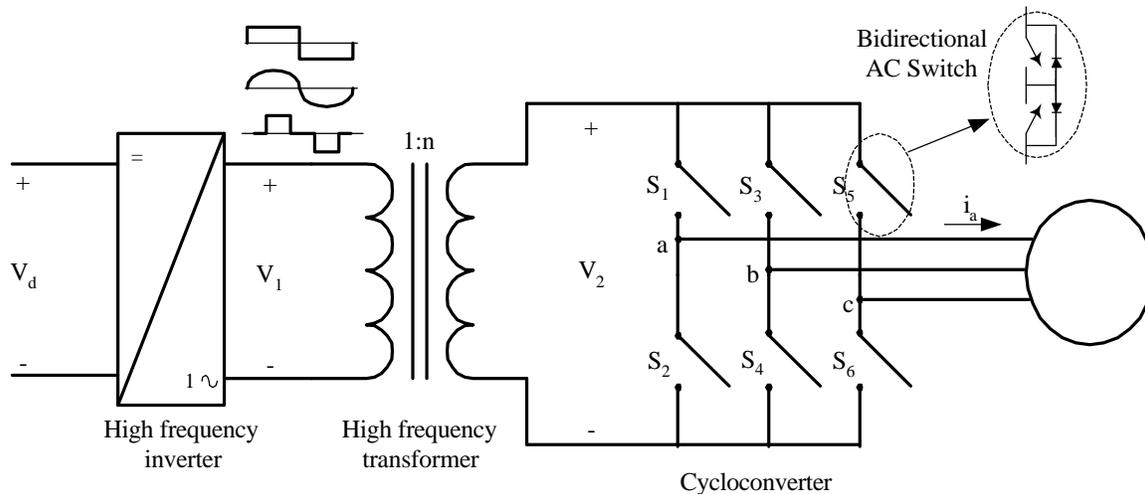


Fig. 13 High frequency ac link converter (1 ϕ hf inverter + (1 ϕ -3 ϕ) Cycloconverter)

4.2.2 Phase-Controlled (1 ϕ -3 ϕ) 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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