AC–AC POWER CONVERTERS

Ac-to-ac converters transform electrical power from one ac source to another. Theoretically, each ac source can have a different number of phases and operate at different or variable voltage and frequency. Figure 1 shows the basic block diagram of an ac-to-ac converter where the converter links two different ac sources together.

In fact, a very large number of power electronic converters sold today are ac-to-ac converters because electrical power is distributed mainly via three-phase or single-phase ac networks at a fixed voltage and frequency (50 or 60 Hz) whereas most electrical loads require single- or three-phase power at variable voltage and frequency. Examples are adjustable speed ac motor drives; frequency converters between 50 Hz, 60 Hz, and 400 Hz networks; interties between three-phase

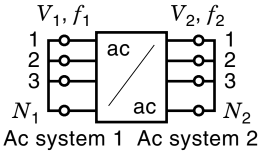

Figure 1. Basic block diagram of an ac-to-ac converter.

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50 Hz and 60 Hz power grids; and interties between three-phase 50 Hz systems and single-phase $16\frac{2}{3}$ Hz systems.

Most ac-to-ac converters provide only unidirectional power flow because their circuitry and control are less complicated and more economical. Typically, these low-cost converters operate with a two-stage conversion method. First, they transform the ac power into dc power creating an intermediate dc link by using a diode rectifier (ac-to-dc converter). The second conversion stage is accomplished with an inverter (dc-to-ac converter), which generates the variable ac voltage for the load (1–5). Typical examples are motor drives for pumps, blowers, and compressors, which do not regenerate power back to the ac grid. To connect ac sources together and to exchange power in both directions, bidirectional topologies are needed. Three distinctively different converter circuits have been developed to this end:

ac-to-ac bidirectional converters with an intermediate dc link;
cycloconverters; and
matrix converters.

Whereas dc-link converters use a two-stage power conversion method (by a rectifier and an inverter), the cycloconverter and the matrix converter transform ac power in a single-stage avoiding dc energy storage devices (capacitors or inductors). All three circuits transform power between ac sources and loads that operate at different or variable voltage and frequency. In addition, several bidirectional power electronic circuits have been developed specifically to transform only the ac voltage amplitude or phase of the ac power system. Direct frequency control of the ac power is not possible with the following dedicated low-cost systems:

ac voltage regulators;
ac voltage or tap regulating transformers; and
ac phase controllers.

AC-TO-AC CONVERTERS WITH AN INTERMEDIATE DC LINK

Three basic types of dc-link systems can be realized depending on the energy storage device used in the dc link. These systems are illustrated in Fig. 2. Large capacitors that store electrostatic energy are used to realize a relatively stable dc-link voltage [Fig. 2(a)]. This type of converter comprises two *voltage-source converters* because the dc-link voltage is impressed sequentially on both ac systems. Alternatively, it is possible to use inductors to maintain a stable dc link current. In these current-source systems the energy is stored electromagnetically, and current is impressed on the ac systems by the converters [Fig. 2(b)]. Both systems have dual properties, whereby the properties and characteristics that are true for the voltage quantities in the voltage-source converter are often valid for the currents in the *current-source converter*. Furthermore, it is possible to combine voltage- and current-source converters to construct mixed-dc-link converters as shown in Fig. 2(c).

Currently, costs and technology developments have led users to prefer voltage-source systems in the lower power range from 1 kVA up to 100 MVA, whereas current-source systems and mixed-dc-link converters are often used at higher power levels ranging from 1 MVA up to 1 GVA.

Voltage-Source ac-to-ac Converters

Typical voltage-source ac-to-ac converter configurations are detailed in Fig. 3. Two converters are linked in parallel to a common dc-link voltage. Usually, these converters are single-phase or three-phase inverters (normal operating mode is from dc to ac). The sign and amplitude of the dc voltage are critical for operating the ac-to-ac converter. The dc voltage must remain positive for both inverters and must be larger than the amplitude of the line-to-line voltage of either ac supply. The dc current of each inverter can be positive or negative. To limit current peaks, the source impedance ought to be inductive because the inverters impress the dc voltage on the ac sources. This property is usually fulfilled in practice because most ac sources have transformers whose leakage inductances are significant. Freewheeling diodes, placed antiparallel across each power switch, are necessary to provide a current path for the inductive source current to flow whenever a switch turns off. The voltage across each power semiconductor device at turn-off will be clamped to the dc voltage through the freewheeling diodes of the complementary switches.

Modern power devices used in inverter phase legs are power transistors, such as power MOSFETs (up to 1 kV) and insulated gate bipolar transistors (IGBTs). IGBTs are available with blocking voltages ranging from 600 V up to 3.3 kV. At higher power levels gate turn-off (GTO) thyristors up to 9 kV are used. Standard GTO devices require snubbers to limit

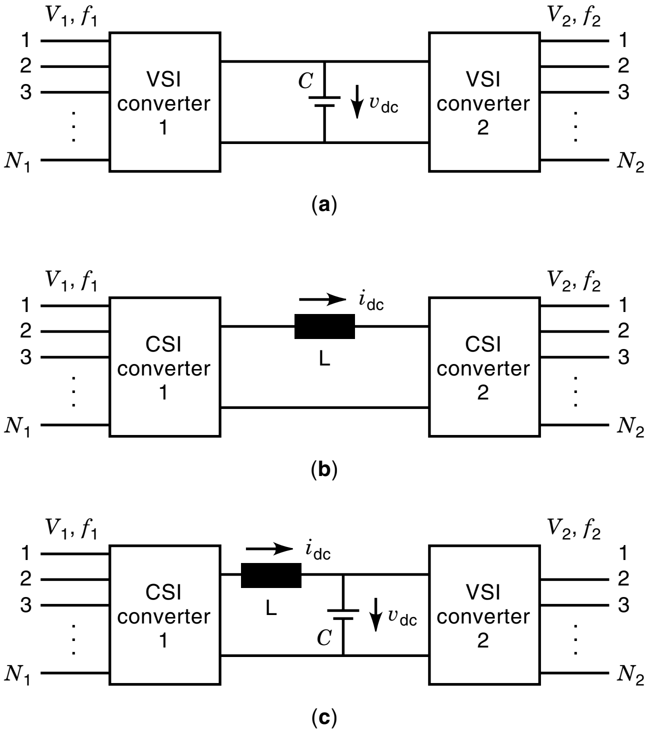


Figure 2. Intermediate dc-link systems. Voltage-source converters (a) use capacitors. Current-source converters (b) use inductors to store dc energy. Mixed-dc-link systems (c) combine voltage- and current-source dc links.

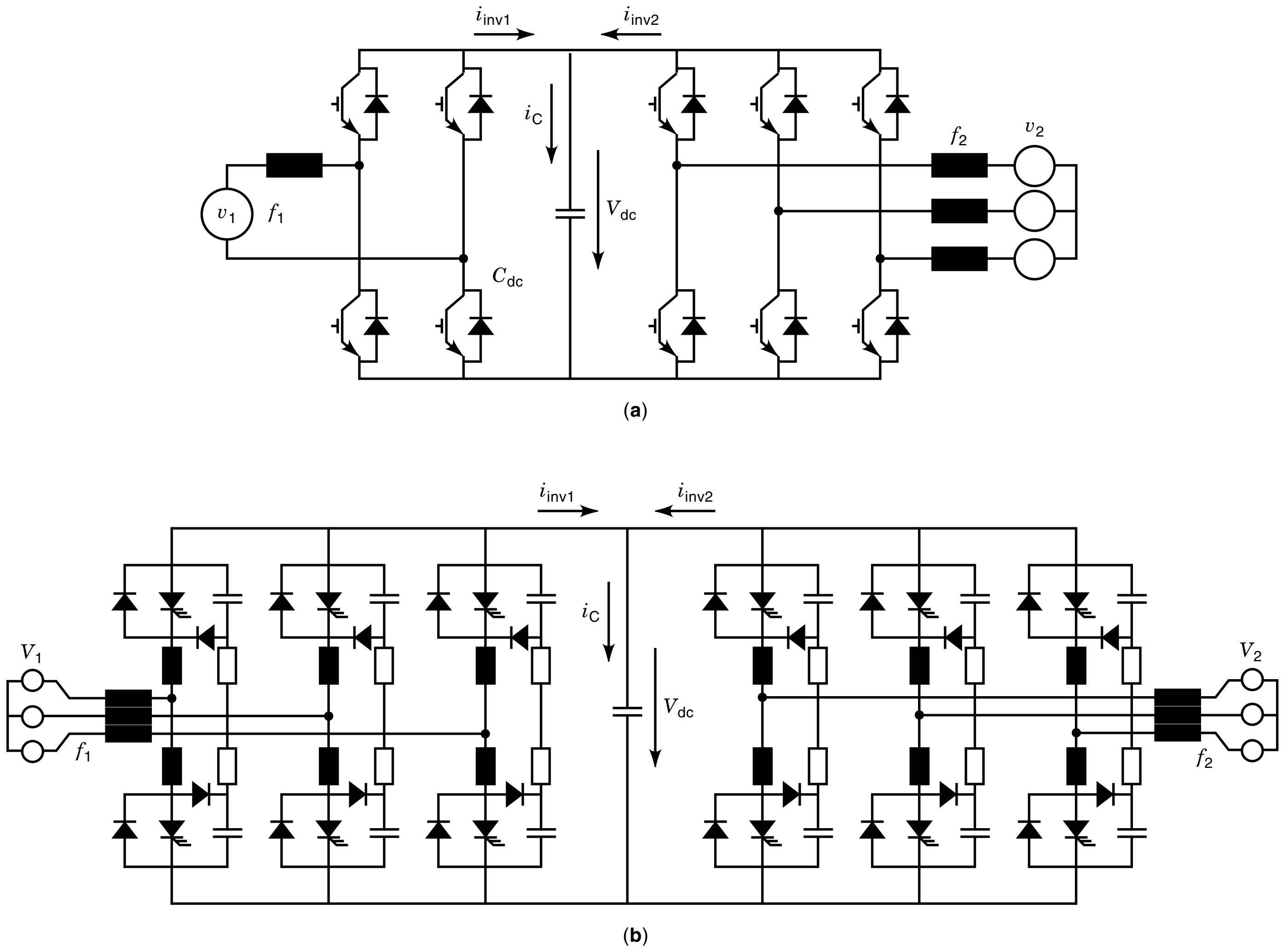


Figure 3. Voltage-source converters. A single-phase to three-phase IGBT converter (a) requires no snubbers. At high power levels, three-phase GTO converters with snubbers (b) are used.

peak power during turn-off. However, recent developments indicate that operation of a GTO without a snubber is possible when special low-inductance gate drivers are used (9).

The converter shown in Fig. 3(a) is a bidirectional converter that uses IGBT devices. Figure 3(a) also illustrates how single-phase ac power is converted to three-phase ac power. The circuit diagram of a high-power, three-phase ac-to-ac converter based on GTO devices is shown in Fig. 3(b). Snubber circuits consisting of capacitors, inductors, and resistors are used to limit the switching stress on the GTO devices.

Each voltage source inverter (VSI) shown in Fig. 3 controls ac voltage amplitude and frequency independently of each other by pulse-width modulation (PWM) control. Several PWM methods have been developed, such as sine-triangle PWM and space-vector modulation (6). With PWM, the peak amplitude of the sinusoidal ac phase voltage of a three-phase system can be controlled linearly as a function of the voltage command up to 50% of the dc-link voltage.

The power flow in and out the dc link must be controlled precisely because, in practice, the energy storage capacity of the dc link is limited. The smaller the dc capacitor, the higher the control bandwidth should be for regulating the dc voltage. For stability reasons, cascaded *current regulation* loops are added to the PWM controller. This current regulator decouples the ac filter inductors from the dc-link capacitor. As a result, the current-regulated, voltage-source converter with the output filter inductors acts as a controlled current source. Hence, this type of control is called current-regulated PWM (CRPWM) control. The complete ac-to-ac control configuration is detailed in Fig. 4.

When the converter is connected to an ac source, the PWM modulator needs to synchronize its pattern with the ac source voltage. Whenever the converter is feeding a passive load, this synchronization is not necessary. A phase-locked loop (PLL) is often used to provide synchronization signals to the zero voltage crossings of the ac source voltages. In Fig. 4, it is assumed that converter 1 (input side) is connected to a three-phase ac system whereas converter 2 (output) is feeding a passive load.

The current commands of converter 2 are generated by an outer control loop that controls external (load side) variables, such as the output ac voltages or, in the case of a machine drive, the torque of an ac machine. The current commands of the input side converter are set by the dc-link voltage regula-

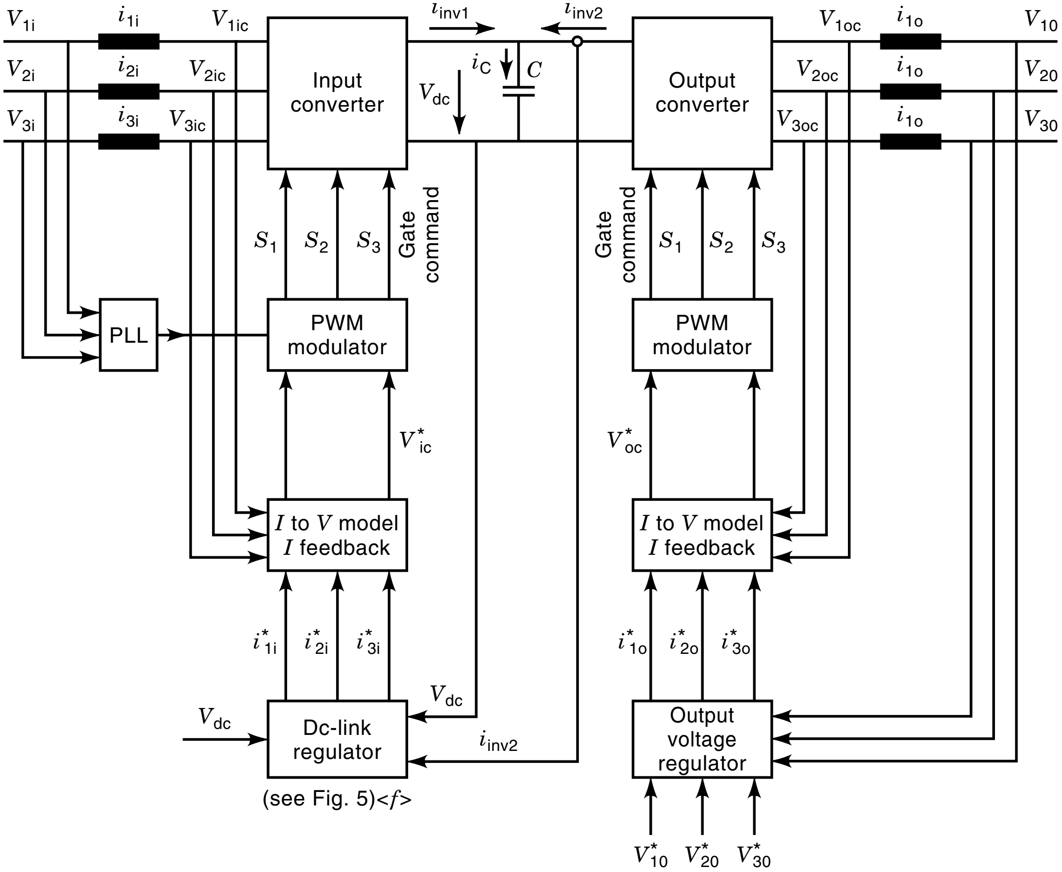


Figure 4. Control diagram of a voltage-source, dc-link, ac-to-ac converter.

tor, shown in Fig. 5. The required dc-link current for converter 1 is calculated by two control loops. A fast acting feedforward control loop is implemented using the dc capacitor state equation:

$$C\,dv_{\mathrm{dc}}/dt = i_{\mathrm{inv1}} - i_{\mathrm{inv2}}$$

The dc-link current i_{inv2} of the load-side converter is measured or calculated from the current signals and the converter state of converter 2. Adding this dc current i_{inv2} to the derivative of the dc voltage command v^*_{dc} leads to a command value for the dc current i^*_{inv1}. Obviously, this feedforward loop is extremely fast and is limited only by the sample delays of the converter controller. However, the exact knowledge of the dc capacitor value C is essential to guarantee high accuracy in the feedforward control loop. To compensate for possible detuning errors of C^* in the feedforward path, a feedback loop is added. In this case, to eliminate steady-state error, the feedback can be a simple proportional gain because the capacitor represents a first-order system, that is, an integrator.

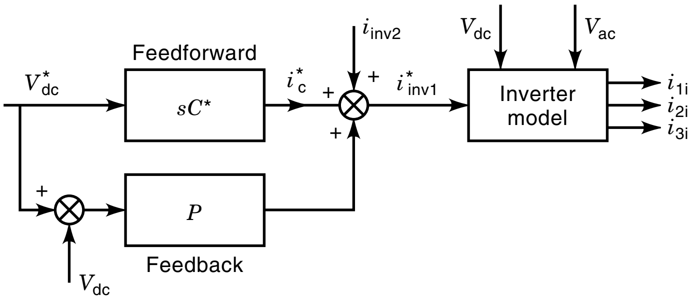


Figure 5. Control block diagram to control the dc-link voltage using feedforward and feedback control.

Next, the three-phase current commands for the ac converter 1 are computed by using the equality between ac real power and dc power. In addition, reactive components may be superimposed on the input converter current commands if the converter needs to provide reactive power compensation.

Fast-acting feedforward control of the dc-link voltage is necessary when the dc-link voltage changes rapidly, for example, when few dc film type capacitors are used. When the dc capacitor is large, for example, when electrolytic capacitors are used, a simple voltage feedback control loop is adequate to regulate v_{dc}.

Typical applications are adjustable speed drives (ASDs) for ac asynchronous and synchronous machines (Fig. 6) that provide bidirectional power flow for centrifuges, elevators, and rolling mills. The output converter controls the torque of the ac machine. The input converter (converter 1 in Fig. 6) is connected to the ac supply and controls the dc bus voltage while maintaining unity power factor at the ac supply.

Modern ac traction systems (Fig. 7) fed by a single-phase, medium-voltage, ac catenary use a single-phase input converter that provides unity power factor at the ac input and

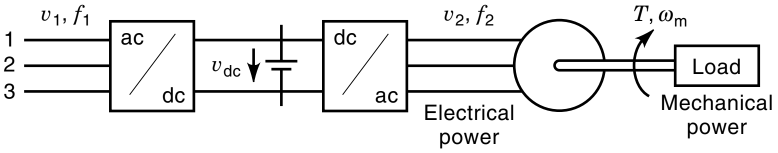


Figure 6. Adjustable speed drives use ac-to-ac converters when power flow can reverse.

regulates the dc voltage in the locomotive. Three-phase output inverters control the torque of the traction machines. While braking, the locomotive feeds energy back into the single-phase ac grid (regenerative braking). In new high-speed locomotives, the trend is to distribute the traction drives over many axles to improve weight distribution and enhance the maximum achievable tractive effort under all weather conditions.

In the United States, large 100 MVA ac-to-ac VSI systems have been commissioned in utility systems to support the voltage of long transmission lines. These static compensators regulate voltage by compensating reactive power demand independent of fast load changes (flicker). Figure 8 illustrates a utility type compensator which compensates for reactive power by injecting current into the ac line with a "shunt" converter. This shunt converter also regulates the dc voltage by drawing current in phase with the ac voltage. An ac voltage in series with the line is induced by using a "boost" converter to compensate for source voltage dips. The boost converter may need to exchange active power with the dc bus when the induced voltage is in phase with the load current. The complete system provides a high degree of controllability against ac voltage sags and swells caused by dynamic reactive load changes and sags in the source voltages. This unified power factor compensator (UPFC) will become a key device in flexible ac transmission systems (FACTS) when voltage and power flow control become more decentralized.

Ac-to-ac Converters with Current-Source dc Link

A simple current-source ac-to-ac converter is obtained by connecting two multiphase thyristor or GTO converter bridges in series with a dc-link inductor as illustrated in Fig. 9. A typical configuration consists of single-phase or three-phase thyristor converter bridges that can operate in rectifier mode or inverter mode. Figure 9(a) shows a single-phase to three-phase current-source converter based on line-commutated thyristor circuits (snubbers not shown). Figure 9(b) shows a three-phase to three-phase current-source converter. The converter on the left is a forced-commutated thyristor converter whereas the converter on the right uses GTOs to control the output current i_{ac}.

Note that the sign of the circulating dc link current i_{dc} of the circuits shown in Fig. 9 has to be positive. The amplitude of the dc-link current should be equal to the maximum line current of either ac system. When thyristors without commutation circuits are used [Fig. 9(a)], the turn-on instant of the thyristors always lags with respect to the ac supply voltage because thyristors cannot turn off current. As a result, the ac supply needs to provide this reactive power. Hence, as illustrated in the vector diagram of Fig. 9(a), the line-commutated thyristor converter operates only in two quadrants of the voltage-current vector diagram. However, the dc voltage of each converter can be controlled continuously proportional to cos α by controlling the firing angle α. This firing angle α is measured between the instant where the voltage across the thyristor becomes positive (the device would conduct if a diode were used instead) and the turn-on instant of the thyristor (determined by the gate driver control). Negative dc voltages are obtained whenever the firing angle exceeds 90°. As a result, the converter of Fig. 8(a) is bidirectional for real power as long as i_{dc} remains constant. Assuming no losses in the dc

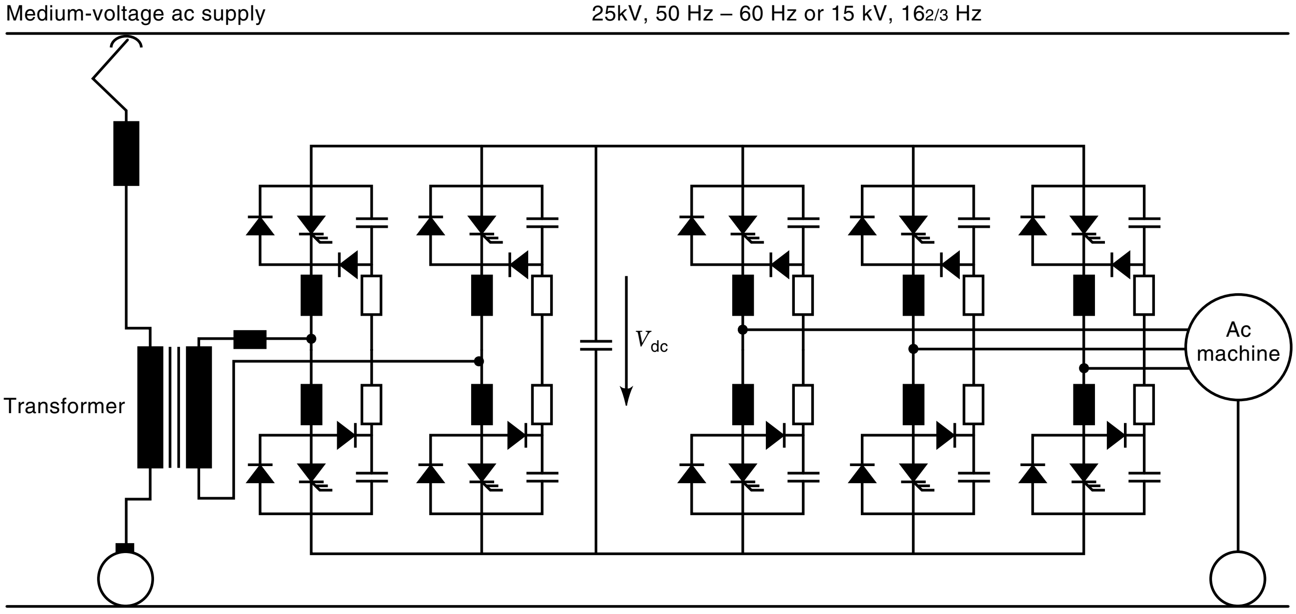


Figure 7. Diagram of a modern traction drive fed by ac catenary.

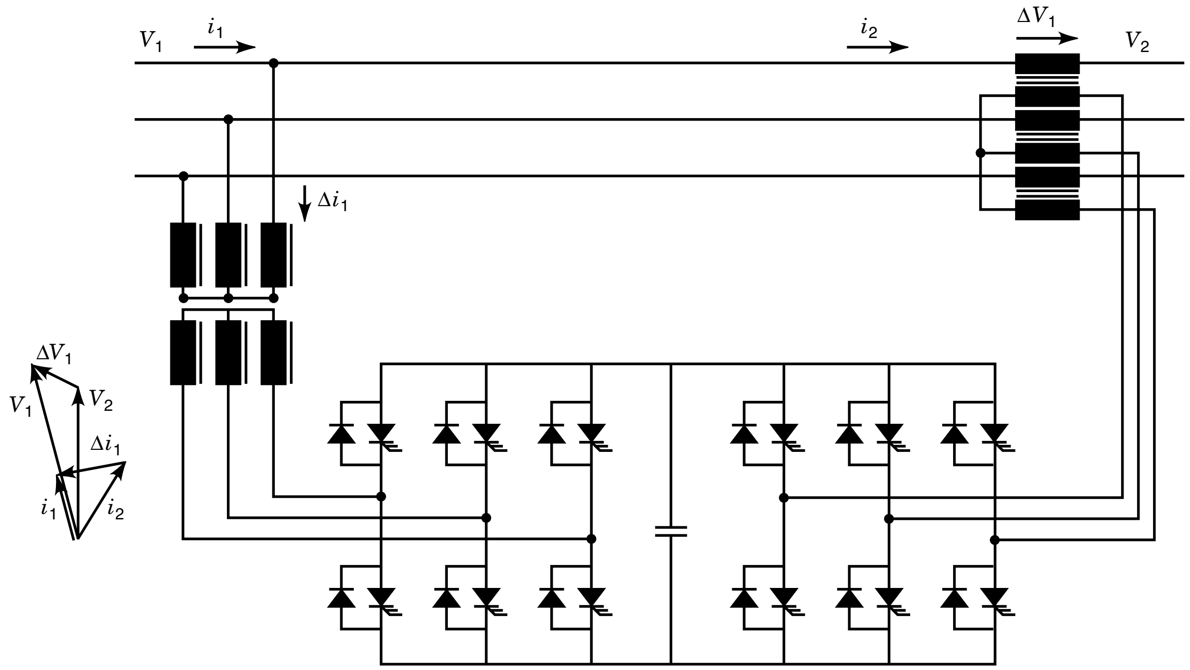


Figure 8. The unified power factor compensator uses a voltage-source ac-to-ac converter to compensate for input line-voltage disturbances and load-side reactive power (including harmonics).

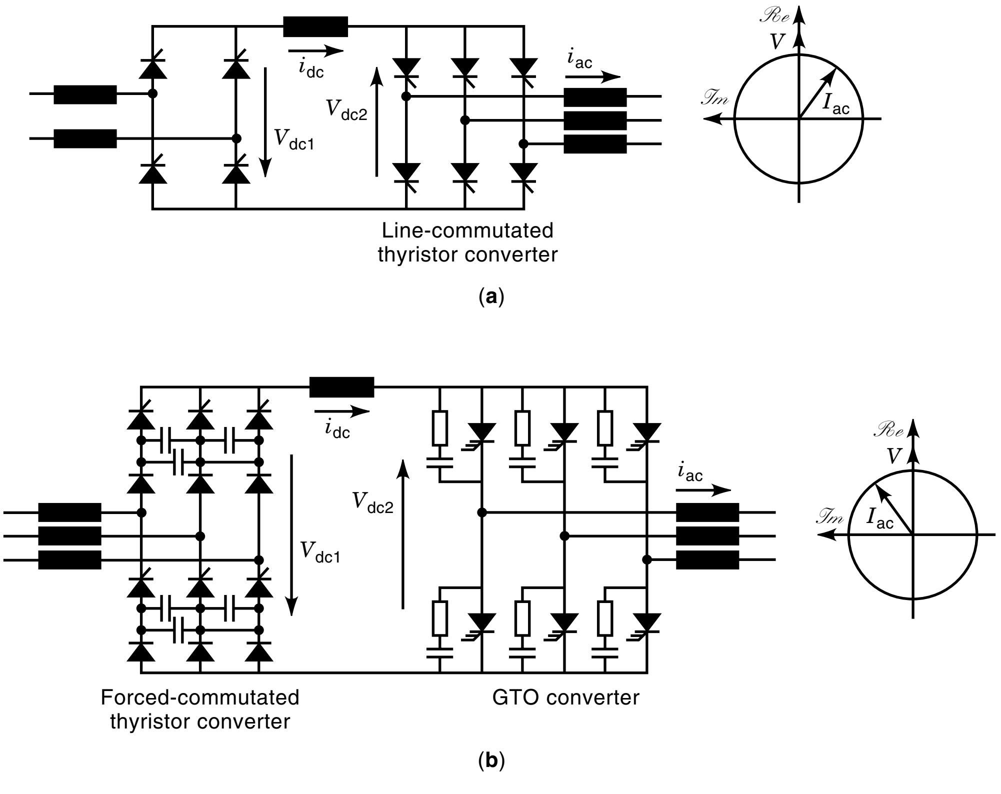


Figure 9. Current-source converters. (a) A single-phase to three-phase converter with line-commutated thyristor bridges operates only in two quadrants (lagging power). (b) The three-phase forced-commutated thyristor converter or the GTO converter operates in all four quadrants.

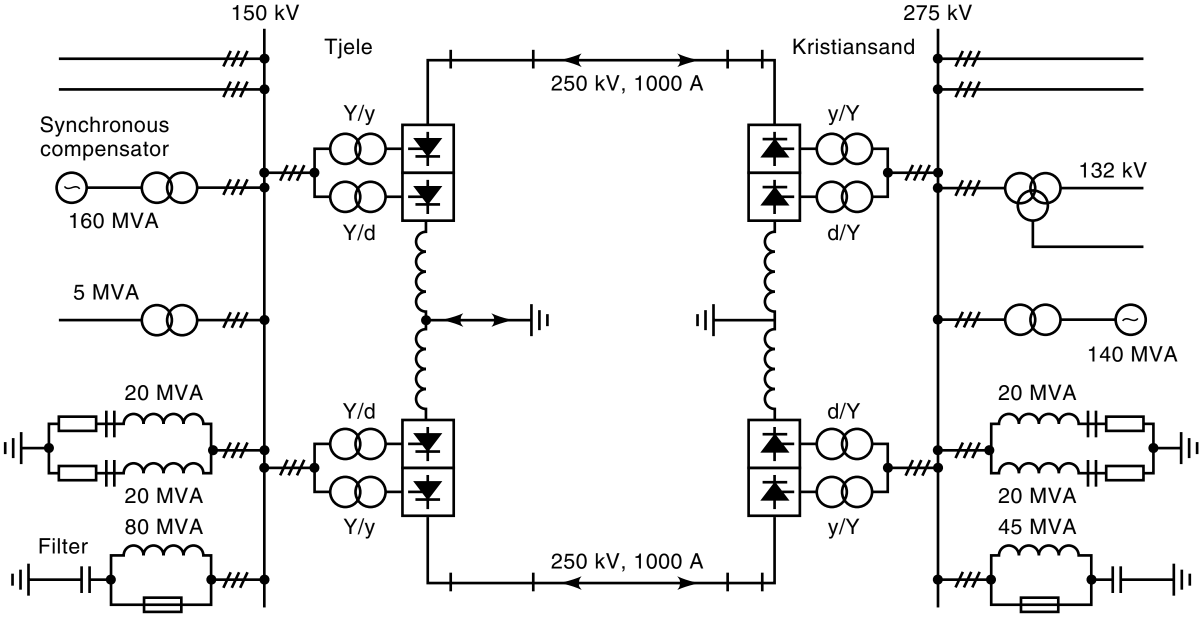


Figure 10. The Skagerrak HVDC system is a classical example of a high-power (500 MW), thyristor-controlled, current-source system (8).

link and neglecting commutation overlap delays, the steady-state voltage v_{dc1} is opposite to the voltage v_{dc2}. In other words, the sum of the firing angles $\alpha_1 + \alpha_2$ equals 180°.

Most dc-link ac-to-ac converters use thyristor devices because thyristors are relatively inexpensive and are available over a wide voltage range (600 V to 9000 V) and current range (10 A to 6000 A). Thyristors converters can be realized from 10 kVA to 10 MVA. In this case, rotating or static VAR compensators are needed because thyristor converters draw lagging currents whenever the firing angle varies between 0° and 180°. Modern current-source converters use GTOs or forced-commutated thyristor circuits [Fig. 9(b)] and turn off current at any instant, enabling full control of the ac line displacement factor cos φ.

All current-source converters need capacitive snubbers across the devices because, in practice, ac systems are inductive. This inductive characteristic would induce large voltage spikes across the devices whenever current is turned off. In some cases large ac capacitors are placed at the converter terminals to decouple the ac line inductance and to clamp the voltages across the devices. In addition, these capacitors filter the higher switching harmonics of the converter.

Current-source ac-to-ac converters have been used since 1972 in high voltage dc (HVDC) transmission systems and interties. Figure 10 illustrates the HVDC system built between Norway and Denmark in 1976 (8). On each side large current-source converters using line commutated thyristor bridges were installed. Each switch (also called a valve) of the thyristor bridge consists of hundreds of thyristors connected in series. The three-phase voltages of each thyristor converter are phase-shifted by using “wye-delta” and “wye-wye” transformers. This leads to a higher switching pulse rate at the ac side, canceling low frequency harmonics in the ac line current. This harmonic cancellation makes the ac line filters smaller and less expensive. Notice the VAR compensation systems shown in Fig. 10. They are essential to compensate for the reactive power demand of the two-quadrant thyristor converters which can draw only lagging reactive power.

Today, very large HVDC systems are being built that reach power levels of 2 GW. Transport of electrical power over long distances (more than 500 km) is possible via HVDC lines because the reactance of the line does not cause voltage drops in dc transmission systems. Actually, the dc line reactance adds to the dc-link reactance and helps maintain a constant dc current. Most HVDC systems operate at voltages higher than 300 kV. To block this high voltage, many hundreds of thyristors (up to 500) are connected in series to produce one switch. A complete system may consist of more than 30,000 thyristors. To provide galvanic isolation, these thyristors are optically triggered. To this end, glass fibers are used which carry the light of powerful infrared lasers toward the thyristors.

Current-source converters have been used to recover rotor-slip energy in high-power wound-rotor induction motor drives. Figure 11 illustrates the so-called static *Kramer drive.* The converter is handling only the slip energy that is small compared with the total rating of the machine when speed is varied over a narrow range around the synchronous speed.

Despite their simple operating principles, current-source converters have some drawbacks compared with voltage-source converters, such as slower response time for current regulation, higher no-load losses and, in case of thyristors, poor power factor. In the case of back-to-back interties, the dc-link inductor is costly and bulky. Furthermore, current-source converters need symmetrical blocking power devices which have higher conduction losses than asymmetrical devices. Consequently, as the current turn-off capability of GTOs steadily improves, voltage-source ac-to-ac converters are starting to replace current-link converters (except in HVDC systems).

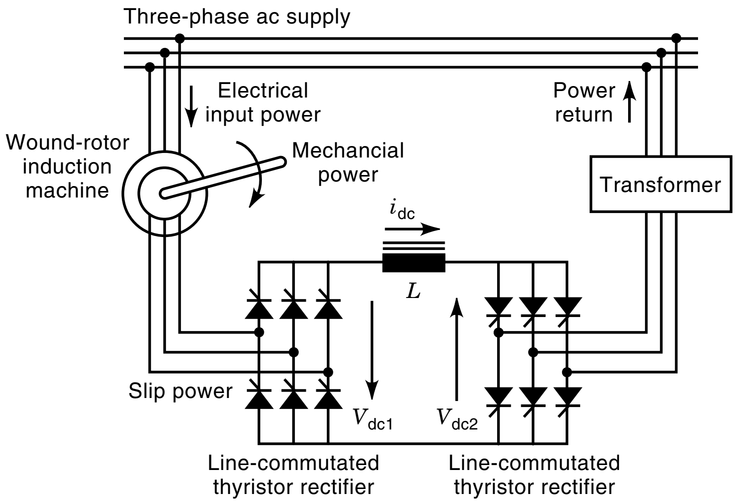


Figure 11. A Kramer drive uses a current-source ac-to-ac converter to recover the slip energy of a wound-rotor induction motor enabling an efficient speed control mechanism.

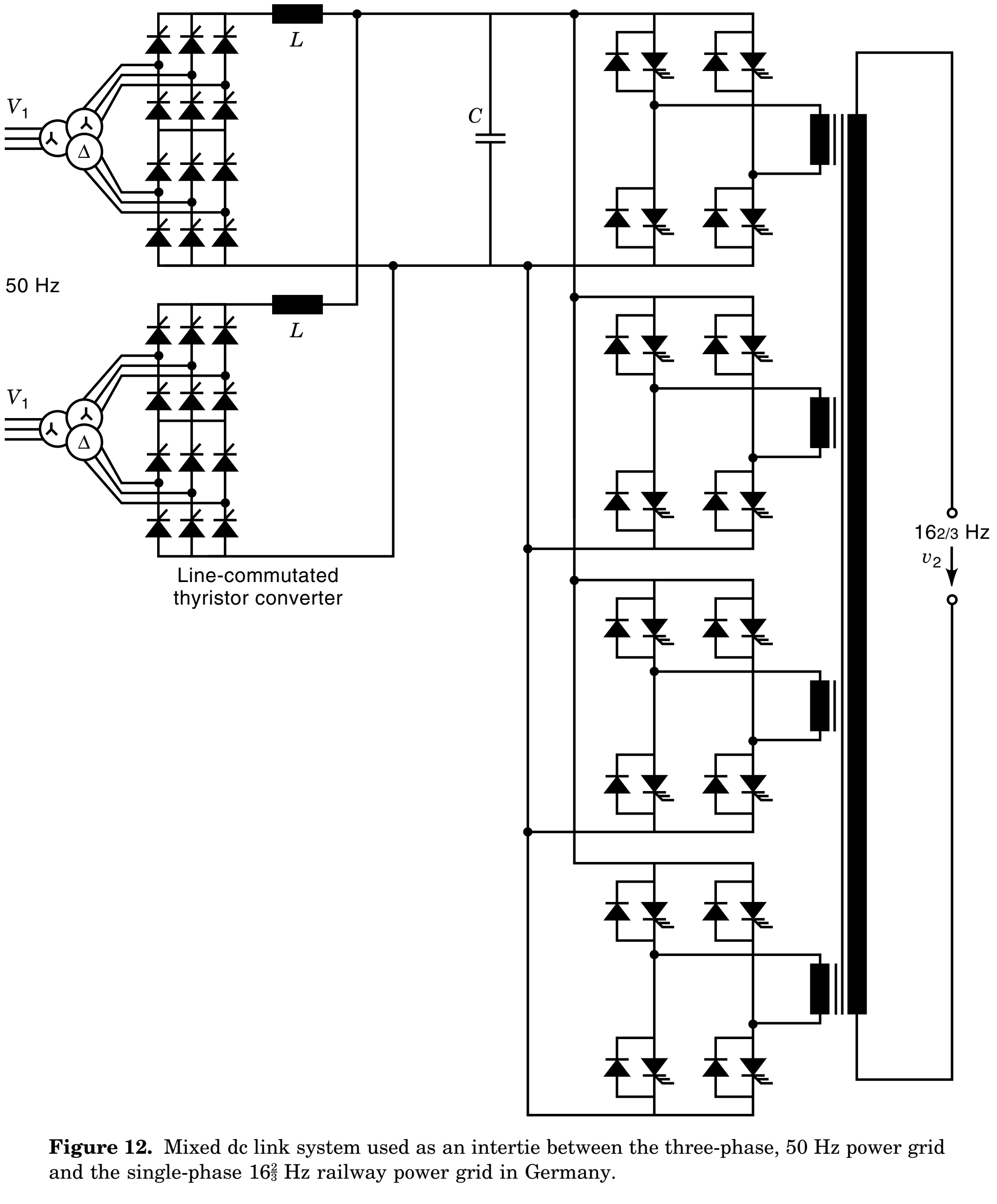


Figure 12. Mixed dc link system used as an intertie between the three-phase, 50 Hz power grid and the single-phase $16\frac{2}{3}$ Hz railway power grid in Germany.

Ac-to-ac Converters with Voltage-Source and Current-Source dc Link

Very high-power 100 MVA mixed-voltage-source and current-source converters have been built to link 50 Hz power systems to the low-frequency $16\frac{2}{3}$ Hz train network in Germany (Fig. 12). These converters typically consist of multiple current-source and voltage-source converters linked together (9). To minimize cost, the three-phase, line-side converter is typically based on standard 12-pulse thyristor rectifier bridges, as shown in Fig. 9(a). However, to allow the dc current to reverse sign, additional thyristor converter bridges are placed in anti-parallel. The sign reversal of the dc-link current is needed when power flow reverses because the voltage-source output converter requires a positive dc bus voltage. The voltage-source, railway-side inverter consists of many inverters placed in parallel. Each inverter switch is realized by connecting multiple GTOs in series. Each GTO inverter module feeds power into a primary winding of the railway-side transformer. The secondary windings of this transformer are placed in series. Switching patterns of each GTO inverter module are shifted to generate a multilevel output pattern that contains few harmonics. This voltage-control method is called harmonic cancellation and features excellent waveform quality, which avoids installing expensive filters on the ac railway

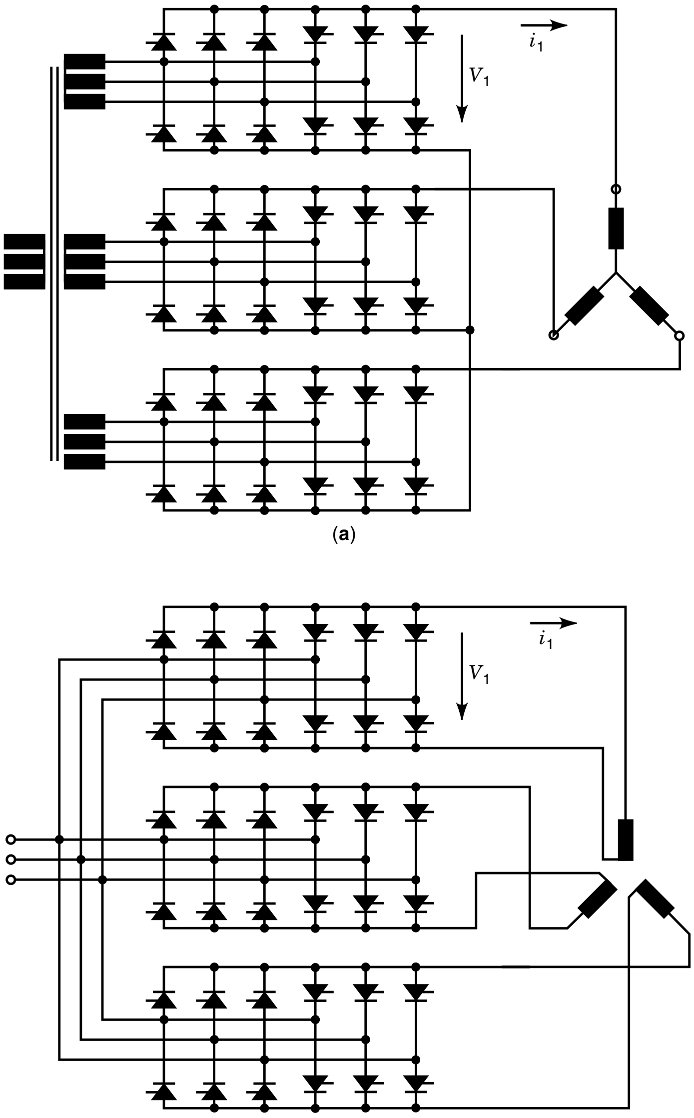


Figure 13. Cycloconverters for three-phase systems. (a) Loads connected in a "wye" configuration require isolation between each set of three phases. (b) The isolation transformer is avoided when using an open, delta-connected load.

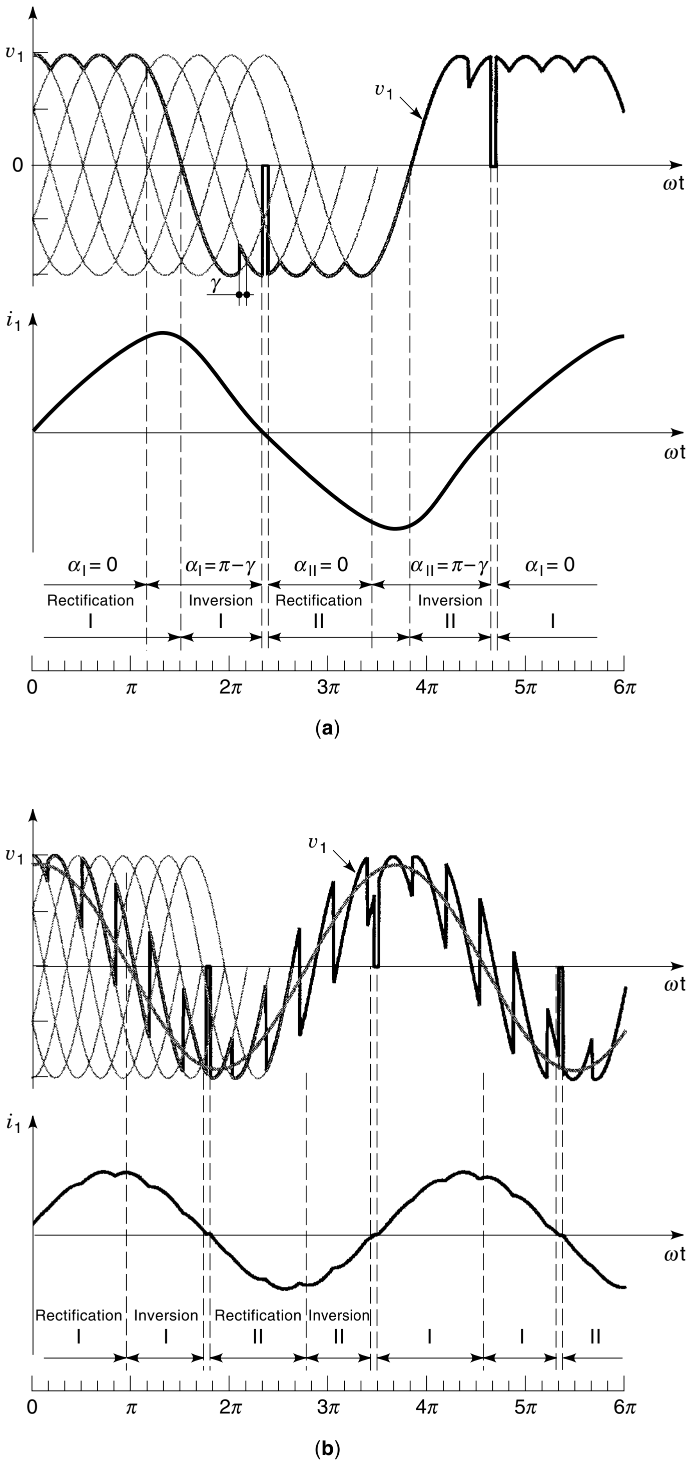


Figure 14. (a) Discrete control of the firing angle leads to trapezoidal output voltage waveforms, which can be frequency controlled. (b) Continuous control of the firing angle enables voltage and frequency control of the cylcoconverter.

line. These mixed-source interties are replacing older cycloconverter systems (see later) because external power factor compensators and filters are reduced or eliminated.

CYCLOCONVERTER

The topologies shown in Fig. 9 can be controlled so that little or no circulating dc-link current flows. The firing angle α of the converters can be controlled to vary proportionally with time, leading to a sinusoidal output voltage variation. As a result, a converter is created that has no intermediate dc link because the dc link itself becomes a low-frequency ac output that changes cyclically. This cycloconverter technique was developed in Germany with mercury arc tubes in the early 1930s to produce a single-phase $16\frac{2}{3}$ Hz fixed-frequency power system for the railways.

By repeating this configuration for each phase of the second ac grid, a multiphase cycloconverter system is realized. Three-phase versions of cycloconverters with no circulating current are shown in Fig. 13.

Cycloconverters have mostly been built using line-commutated thyristor circuits. Hence, a three-phase ac-to-ac cycloconverter requires 18 thyristors when using half-bridge converters or 36 thyristors when using full-bridge converters. Control of a cycloconverter is illustrated in Fig. 14(a) and 14(b). A simple control method [Fig. 14(a)] is realized when the firing angle α alternates only between the maximum values of 0° and 180°. Each thyristor bridge operates in the rectifier mode when the load current has the same sign as the voltage. When the firing angle α shifts to 180°, a negative voltage is produced by the rectifier. As long as the current remains positive, the converter feeds power back in the input ac source and operates in the inverter mode. As soon as the current crosses zero, the converter is turned off and the second thyristor rectifier is turned on with a firing angle at 0°, repeating the cycle. Figure 14(a) illustrates that a trapezoidal voltage waveform is obtained at a frequency lower than the input ac line frequency. The frequency can be changed only in discrete steps because each period consists of a fixed number of 60° intervals. Variable frequency control with reasonable resolution is realized only when the frequency is very low (below one-third of the fundamental frequency). Voltage control is not possible with this simple discrete control of the firing angle. To overcome this problem, the cycloconverter firing angle α can be programmed to vary proportionally with time to change the output voltage sinusoidally and control output frequency as shown in Fig. 14(b).

Both methods (discrete and continuous firing-angle control) have found application in low-speed, high-power motor drives used in rolling mills and direct-drive (without gearbox) cement mills. Cycloconverters have been used to recover the rotor slip energy in large doubly fed, wound-rotor induction motor drives. Similar to the CSI in the static Kramer drive, the cycloconverter makes speed control possible. This type of drive is also called the static *Scherbius drive* (7). A Scherbius drive is shown in Fig. 15 which uses half-bridge thyristor converters. Whenever the cycloconverter extracts power from the wound rotor, the machine operates at lower speed (subsynchronous mode). Feeding ac power to the rotor forces the machine to run above the synchronous speed (supersynchronous). The cycloconverter has to be rated at 50% of the rated machine power to enable a ±50% speed variation around the synchronous speed of the drive. In many high-power application, such as pumps, blowers, and wind turbines, this speed variation is adequate because the power demand of these loads varies with the cube of the speed.

Cycloconverters are also used to generate 400 Hz ac power onboard airplanes. A high-speed synchronous generator, driven by the jet engine, delivers three-phase power at high frequency (2 kHz to 3 kHz). Voltage and frequency for the 400 Hz system are controlled by the cycloconverter firing angle.

In general, cycloconverters produce relatively sinusoidal voltage waveforms. However, their disadvantage is the relative high reactive power demand from the input ac supply, especially when the output voltage is low. Furthermore, low-frequency harmonics are generated into the ac source. Bulky filters often need to be installed to compensate for these undesirable effects.

MATRIX CONVERTER

The *matrix converter,* or *Venturini converter,* consists of a matrix of bidirectional current and voltage power devices connecting two multiphase ac sources together. Similar to the cycloconverter, the matrix converter has no internal dc link, thus avoiding bulky energy storage devices. The current and voltage waveforms of both ac systems can be controlled arbitrarily by using PWM control. The matrix converter controls the active power flow between both systems and is capable of individually controlling the reactive power of each ac system.

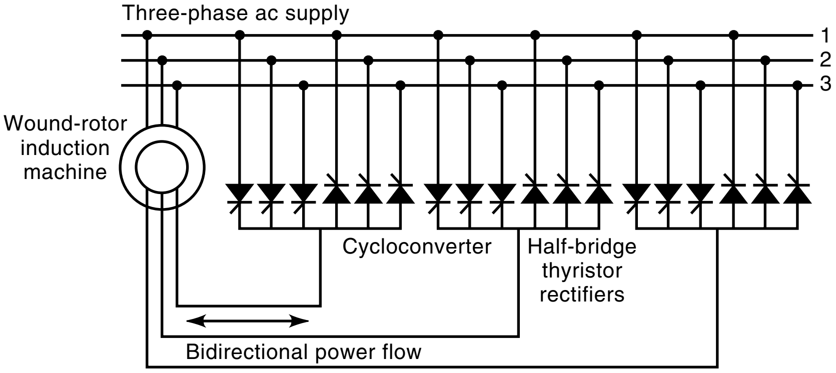


Figure 15. The Scherbius drive uses a cycloconverter to recover the slip energy of a wound-rotor induction machine to provide efficient speed control.

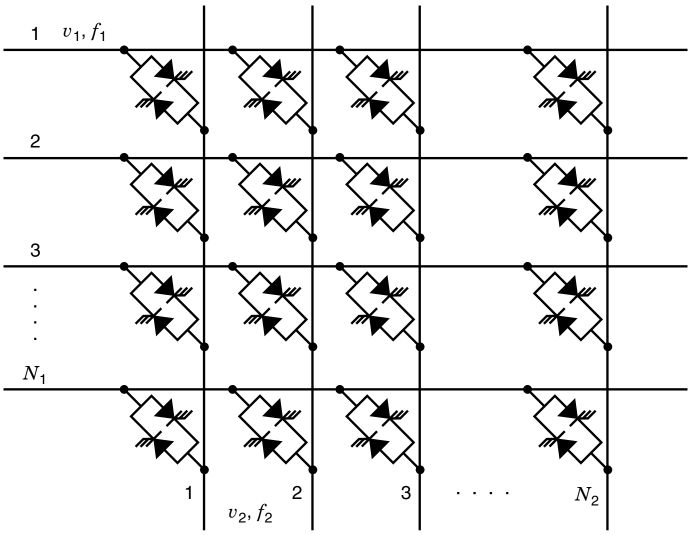


Figure 16. General block diagram of a matrix converter.

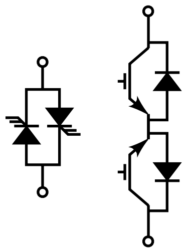


Figure 17. Practical implementation of bidirectional current and voltage switches.

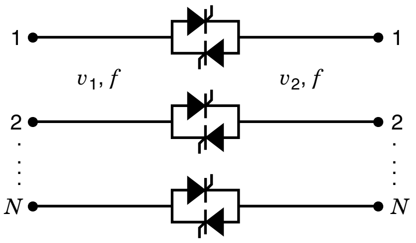


Figure 18. The ac voltage regulator uses antiparallel thyristor switches to regulate output-voltage amplitude.

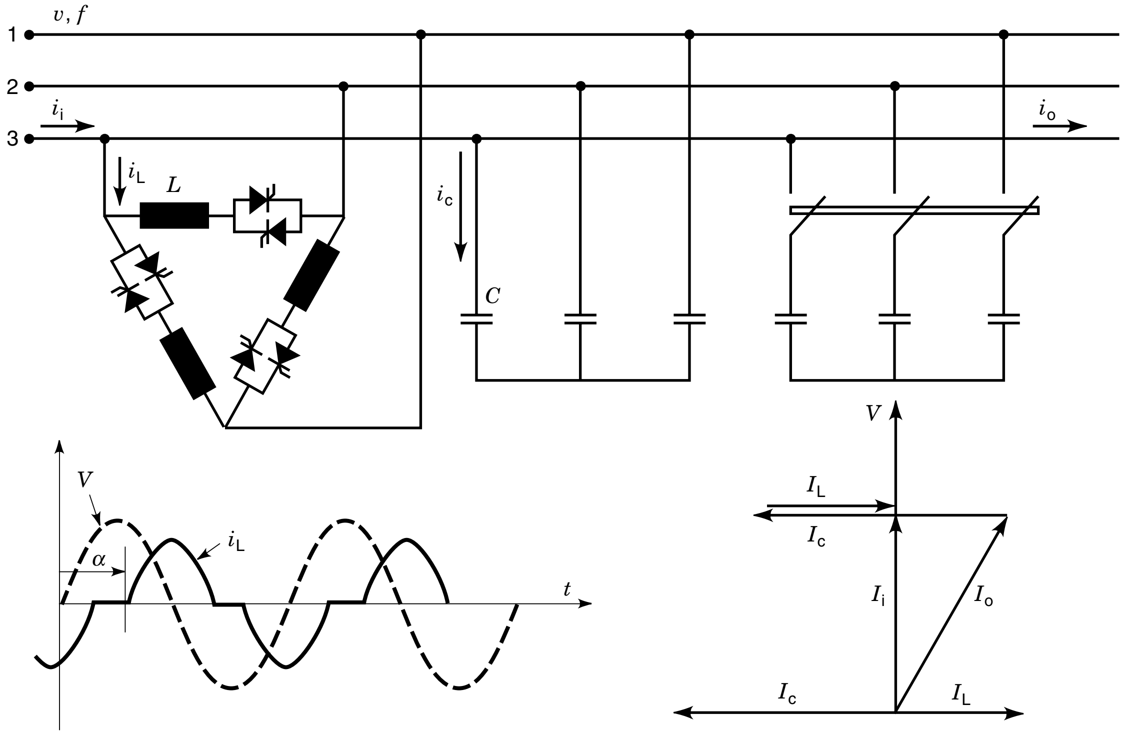


Figure 19. Typical configuration for a static VAR controller. The ac voltage regulator controls the reactive power that flows into the inductors (variable reactance). Fixed or switched capacitors deliver reactive power to offset the reactive power required by the load and the variable reactance.

As illustrated in Fig. 16, each phase of the input ac source can be connected to a phase of the output ac system. It is important that, while turning current on or off, the devices are not connecting solely inductive or capacitive systems together which would lead to uncontrollable current or voltage spikes. As a result, one ac system should have an inductive or current-source behavior while the other behaves as a capacitive or voltage source. As an example, in Fig. 16, the input side is made inductive by adding inductors to the ac supply. The output is made capacitive by adding filter capacitors.

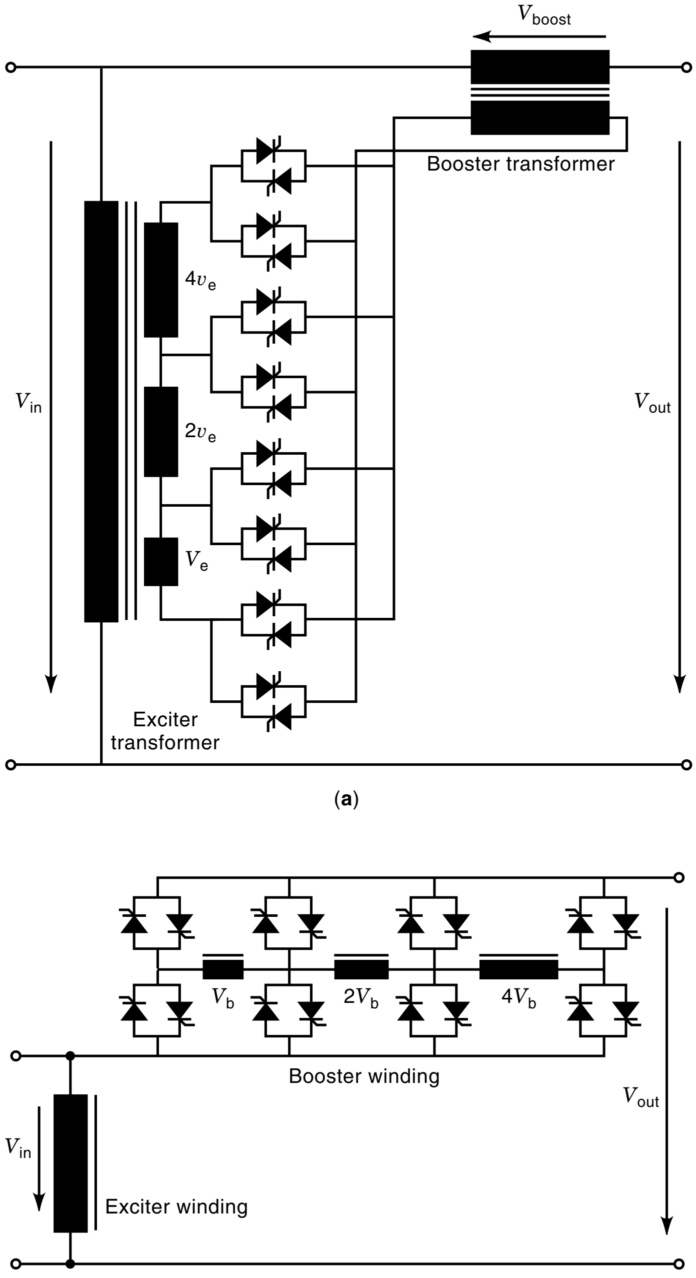
The size of the passive filter components depends on the switching frequency of the converter. The higher the switching frequency, the smaller these components become. At frequencies above 10 kHz, one can consider using the inherent impedance of the ac grid at the input side because the ac supply is typically inductive due to line and transformer leakage inductances.

The matrix converter requires bidirectional power devices that are not available now (as single integrated devices). As a result, *bidirectional power switches* are constructed by connecting symmetrical blocking devices (e.g., GTOs) antiparallel or by connecting asymmetrical devices in series with reverse voltage-blocking diodes (e.g., transistors) as illustrated in Fig. 17. As a result, a three-phase to three-phase matrix converter needs at least 18 power switches whereas a dc-link ac-to-ac converter needs only 12 devices. This increase in the number of components, combined with relatively complex control, makes the matrix converter less attractive in industrial applications. It is anticipated that the matrix converter will gain interest when fully integrated bidirectional ac switches become available, especially for applications that require a high level of integration, for example, integrated into the frame of an electrical machine to reduce volume. Matrix converters may also become attractive in high-temperature applications that require high reliability. Indeed, the maximum allowable ambient temperature of dc-link capacitors used in voltage-source converters is often a limiting factor that prevents voltage-source converters from operating beyond 75°C.

STATIC AC VOLTAGE REGULATORS AND PHASE SHIFTERS

The ac voltage regulator, shown in Fig. 18, is a simplified matrix converter that has only one bidirectional ac switch per phase. Hence, the ac voltage regulator links two ac systems together that have the same frequency and number of phases. In most applications, this low-cost ac-to-ac converter uses line-commutated thyristors. The thyristor firing angle α is controlled to regulate the amplitude of the output ac voltage.

The ac voltage regulator is used in many well-known applications in single-phase circuits, such as light dimmers, speed control of universal dc motors (fed by the ac supply) used in vacuum cleaners, kitchen appliances, blowers, and hand-held power tools (saws, drills). Low power factor and relatively high harmonic content of the current waveforms are negative aspects of this simple voltage converter. In high-power applications, three-phase ac voltage regulators are often used as "soft-starters" to limit the in-rush currents during the start-up of induction motors. As soon as the induction motor reaches its rated operating point, the solid-state soft-starter is bypassed by a mechanical switch to eliminate conduction losses in the thyristors.



(a)

(b)

Figure 20. Solid-state, tap changer, single-phase diagram. (a) The booster transformer injects a voltage in series with the ac line voltage and provides isolation for the power electronic circuit. (b) The autotransformer concept may offer a lower cost alternative. Both circuits increase and reduce the output line voltage.

Static VAR compensators are another important application for ac voltage regulators (see Fig. 19). Continuous control of reactive power is achieved by controlling the current in the inductors by phase control of the thyristors. The inductor current is lagging and is offset by the capacitive leading current of fixed or switchable capacitor banks.

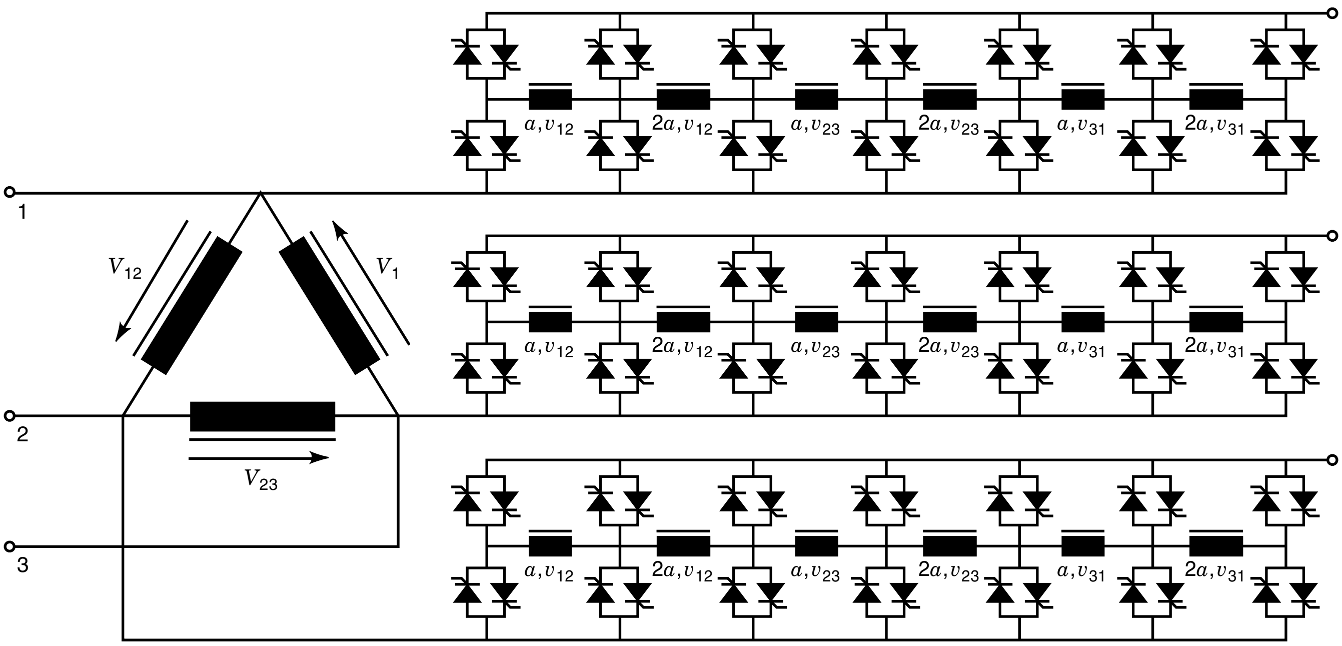


Figure 21. Solid-state voltage regulator and phase shifter.

Accurate control of ac voltages at high power without generating harmonics or creating excessive lagging power is realized by using solid-state transformer tap changers or "load tap changers." Figure 20 illustrates two tap changer concepts (single-phase diagram). The system shown in Fig. 20(a) uses a separate boost transformer to induce a voltage in series with the ac line. Although the boost transformer can be avoided, as illustrated by the autotransformer circuit shown in Fig. 20(b), it permits isolating the power electronic devices from the medium-voltage ac system, and makes the gate drive circuitry and sensors less expensive. The secondary windings of the exciter transformer are designed to produce voltages that form a binary sequence (1, 2, 4, 8, . . .) of the smallest voltage step that needs to be regulated. Using a matrix of bidirectional thyristor switches, it is possible to generate any (discrete) positive and negative voltage variation in phase with the input voltage. Normally, the thyristors are completely turned on or off, that is, no ac voltage regulation is performed by controlling the firing angle. As a result, the output voltage v_{out} contains no harmonics generated by the regulator. In future applications, the solid-state tap changer will be used as a fast-output voltage regulator whenever the line voltage v_{in} sags. In this case, the circuit can be simplified and fewer thyristors are needed because the secondary voltages are always added and not subtracted from the input voltage.

The solid state tap changer concept can be expanded to create *solid-state phase shifters* that combine phase-shift control and voltage regulation. Indeed, in three-phase systems it is possible to connect secondary windings of other phases of the transformer (which are shifted by 120°) in series with the primary voltage (see Fig. 21). The voltage produced per phase can be any discrete combination of the secondary voltages induced in the windings belonging to that phase. Unbalanced voltages and phase shifts between ac systems can be completely compensated for with these solid-state phase shifters.

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ACCELERATED AGING TESTS IN DIELECTRICS AND ELECTRICAL INSULATORS. See WATER TREEING.