Power Electronic Circuit Topology

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Invited Paper

A generalized concept of "sources" embracing both power generators and power consumers simplifies the basic topological aspects of power electronic converter circuits, which are reduced to an array of switches for selectively interconnecting two source systems. Capacitive and inductive filters can modify the nature of the systems, because they act as short-time sources and effectively determine whether the converter sees a voltage source or a current source at its terminals. These differing source qualities require different types of switching devices and have extensive ramifications in the mode of operation of the equipment. This paper presents some basic configurations and describes their significant properties, with emphasis on the most widely used circuits in high-power equipment, particularly ac/dc converters.

INTRODUCTION

Electrical loads often require, or would prefer, a power supply having characteristics different from the available source. The function of power electronic converters is to perform this desired transformation with minimum losses and acceptable cost. Low loss demands a switching mode of operation, and many types of semiconductor devices have been optimized for this purpose. However, switching results in discontinuous power flow through the devices, and temporary energy storage or filtering is necessary to render the overall power flow smooth enough to be acceptable to the source and to the load, and not to impose undue stress on the switches.

The interconnection of switching devices with inductive and capacitive filter elements between the source and load terminals forms the topology of the converter circuit. Certain basic rules must be observed in making the interconnections, depending on the type of power conversion desired but not on the power level. Switching changes the effective topology of the circuit, so the operation of a power converter can be regarded as a sequence of different topological states or modes which are repeated cyclically. There are usually restrictions on the allowable state of the circuit (polarity of voltages and currents of the sources and reactive elements) at the instants of switching, depending on the characteristics of the switching devices. Control of the converter, fundamentally, reduces to controlling the on/off state of the switches in the proper sequence to perform the desired conversion function while observing these restrictions. The normal control may need to be modified for protection against overloads and faults.

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The selection of topology for a converter must consider the following factors:

- The basic conversion function required.
- The properties of the switching devices that are available in the necessary size.
- The number, size, and cost of filter elements and other accessories.
- The losses and stresses involved in switching.
- Ease of control and protection.

As in any other field of engineering, there are many tradeoffs. Certain circuit arrangements have a combination of characteristics that meet the needs of many applications and are widely used. Other arrangements have special characteristics that are needed in a more limited range of applications. Some topologies are not yet practical, but have desirable features that may be realized with future development of components.

BASIC PRINCIPLES

This section discusses the various classifications and operating mechanisms of converter power circuits. A generalized concept of "source" is introduced, including both power generators and power consumers, regarding the latter as negative sources. Capacitance and inductance, often added as filters to suppress unwanted frequency components or for temporary energy storage, are considered to be short-time sources. This viewpoint simplifies the basic topological aspects of converter circuits, which are reduced to an array of switches for selectively interconnecting two source systems. The inherent regenerative capability of many converters is stressed by avoiding restrictive terms such as input/output or supply/load when referencing to the two sources. Brief discussions of semiconductor power devices and the principles of switching-mode conversion are presented. Finally, the effects of minor topological elements such as snubbers and parasitic impedances are mentioned.

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Voltage and Current Sources (Supplies) or Sinks (Loads)

The links between a power converter and the outside world are its power supply or source and its load or power sink, which may be perceived as a negative source. In some systems, the direction of power flow can reverse, so the roles of "source" and "sink" are interchanged. It is, therefore, convenient to regard both as "sources." Obviously, the nature of these sources and the desired interchange of power between them specifies the duty of the converter and imposes certain topological conditions on the circuit. An electrical source implies a conversion of energy from some other form to electromagnetic. Examples of dc sources are batteries, solar cells, and dc machines, while ac sources are rotating machines or oscillating tuned circuits. Resistive sources (sinks) are heaters or loads where most of the energy is ultimately converted to heat.

It is important to clearly define the terms "voltage source" and "current source" as applied to converters, since these differing modes of operation have extensive ramifications in the operation of the equipment. These terms derive from mathematical circuit analysis, as follows:

- A voltage source maintains a prescribed voltage across its terminals, irrespective of the magnitude or polarity of the current flowing through the source. The prescribed voltage may be constant dc, sinusoidal ac, a series of pulses, etc. The current depends on the impedance connected across the terminals.
- A current source maintains a prescribed current flowing between its terminals, irrespective of the magnitude or polarity of the voltage applied across these terminals. The prescribed current may be constant dc, sinusoidal ac, a series of pulses, etc. The voltage depends on the impedance connected across the terminals.

While no practical source has these ideal properties, approximate voltage sources are familiar: a battery approximates a dc voltage source, and the EMF induced in conductors by rotation of a magnetic field is an approximate ac voltage source. For many applications, the source imperfections are reduced by feedback regulation: a utility system endeavors to maintain the appearance of an ac voltage source, as seen by its customers. One of the major applications of power converters is to provide an "artificial" source for other equipment. DC power supplies and ac uninterruptible power supplies are familiar examples, and tight regulation to mimic a voltage source is usually specified. There seem to be no natural current sources, but a large superconducting coil approaches this ideal. Approximate current sources can be obtained from voltage-source supplies by appropriately regulated conversion equipment. For example, electrochemical power supplies and field exciters for machines are usually current-regulated.

Capacitance and Inductance as Short-Time Sources (Filters)

For short-time transients, a capacitor can be regulated as a voltage source, and an inductor can be regarded as a current source. This makes these components useful as filters for artificial sources, maintaining the desired source properties for times shorter than the response time of the controlling equipment. For example, a voltage-source dc power supply can be regarded as capacitor provided with a controller to replenish its charge at the same rate as it is withdrawn by the load, as closely as possible. Similarly, a current-source dc supply can be regarded as an inductor with controlled means to match the average voltage of its input terminal to the voltage of its output terminal as closely as possible. Most conversion equipment employs filters of both types and often includes both types of control loop. For example, a dc motor drive usually has an inner current/torque control loop and an outer voltage/speed regulator.

Converters are often classified to distinguish between "voltage-source" and "current-source" inverters (or converters), abbreviated as "VSI" and "CSI," respectively. *Note that the "source" classification of an ac/dc converter depends on the type of filter and control that is most immediate to the dc terminals of the network of switching devices.* In general, a voltage-source ac/dc or dc/ac converter has a capacitor connected directly across the dc terminals, with no intervening impedance apart from snubbers and wiring. Conversely, a current-source converter has an inductance in series with the dc terminals, preceded by no shunt impedance apart from snubbers and stray capacitance. The switching devices are controlled to interconnect the dc and ac terminals in a time sequence such that an ac source of the same type as the dc source is produced. Thus, one type of voltage-source converter produces a quasi-square-wave ac voltage and the corresponding dual type of current-source converter generates a quasi-square-wave ac current.

For ease of explanation and elementary analysis, it is often assumed that the dc inductance or capacitance is "infinite," equivalent to an ideal current or voltage source, respectively. However, a major objective of the designer is to minimize these filter components. Often, this is accomplished by employing more complex topologies, such as multiphase transformer connections [1]. Another method of reducing filter size is to raise the operating frequency, particularly favored in the case of low power dc/dc converters.

Classification of Converter Circuits

Besides their "source" nature, there are many other criteria by which power converter circuits can be classified. For example, the type of conversion performed: ac/dc (rectifier), dc/ac (inverter), dc/dc (chopper), or ac/ac (voltage controller or frequency changer). Some circuits can transmit power in only the one direction implied by this source/load ordering, while others are capable of transmitting power in both directions, that is, they can operate in a regenerative mode. The difference is not critical if the application requires only one direction of conversion.

Often, conversion systems employ two stages, where a pair of converters are cascaded via an intermediate link. AC motor drives from a utility supply usually consist of a rectifier, dc link, and adjustable-frequency inverter [2], [3]. For isolation or shifting voltage level through a wide range, dc/dc converters frequently include an inverter-rectifier cascade with an ac transformer link. If system regeneration is required, both converters in the chain must be reversible.

Another classification is according to the type of switching or "commutation" employed by the circuit. While commutation is generally synonymous with switching, referring to either turn-on or turn-off of a switching device, it is more often employed when turn-off is under discussion, since this is generally more difficult for the device, and is impossible for diode and ordinary thyristor devices without external assistance. Such external assistance may be the cyclic voltage reversal of an ac source or an ac load (including the counter EMF of a motor or an oscillating tuned circuit). The terms "natural commutation," "line commutation," "load commutation," or "external commutation" are often used to describe this mode of circuit operation [1], [4].

A converter in which turn-off commutation of the switching devices is provided by means internal to the equipment is termed "self-commutated" or "force-commutated" [5]. Current extinction or turn-off may be accomplished by base/gate control of the devices themselves, or by auxiliary circuit means in the case of ordinary thyristors [6]. The mode of commutation of converter may depend on the "quadrant" of operation, as determined by the four possible combinations of voltage and current polarities where these can vary. A circuit that is self-commutated in one quadrant may be externally-commutated in another quadrant. However, since self-commutation is a necessary feature, the equipment will be classified as a "self-commutated converter."

In some converters, the action of a resonant L-C circuit provides relatively low-stress on- and off-commutation for the switching devices. This mode of commutation could be regarded as a particular case of self-commutation if the resonant circuit is contained within the converter or a particular case of external-commutation if the resonant circuit is located outside of the converter. However, the operational behavior is sufficiently different to justify a special category. In essence, forced oscillations are maintained by switching, and the oscillations return the circuit state to conditions favorable for operation of the switches. Control is obtained by adjusting the frequency below or above resonance. Various topologies employing series or parallel resonance have been developed [7]–[9] but, for brevity, further discussion will be omitted.

Power Electronic Switching Devices

Switching devices are the essential components of a power converter and their properties are reflected in the properties of the equipment. The ideal switch would be a fully controllable impedance of infinite range in both directions of voltage and current. Practical devices have limited range, of course, and are restricted to some combination of the following alternative capabilities:

- unidirectional/bidirectional current,
- unidirectional/bidirectional voltage,
- controlled/uncontrolled turn-on,
- controlled/uncontrolled turn-off,
- proportionally controllable/latching.

Diodes, for example, are limited to unidirectional current and voltage, uncontrolled turn-on and turn-off, and are latching. Ordinary thyristors can withstand bidirectional voltage but are limited to unidirectional current (TRIAC types excepted), have controlled turn-on but uncontrolled turn-off, and are latching. Gate turn-off thyristors (GTOs) add the capability of controlled turn-off, but some types are asymmetrical and cannot withstand reverse voltage. Reverse-conducting thyristors cannot withstand reverse voltage but, instead, are designed to conduct reverse current without controllability.

Transistors are generally limited to unidirectional current and voltage, but can control both turn-on and turn-off, and are proportionally controllable. Proportional control is useful in limiting the rate of switching and the resulting transients generated by parasitic impedances, particularly if no snubbers are employed. However, switching transistors are driven into or near saturation during the on-state, so they operate in a fashion similar to latching devices at normal current levels. There is an advantage over latching devices in that, above a certain current level, they come out of saturation and proportional control is regained, allowing faults to be more easily limited. This description of transistors applies to bipolar junction devices (BJTs) and field effect devices such as MOSFETs, as well as many specialized variations that have been developed.

Viewed from the power circuit topology and type of conversion required, the quadrants of operation and controllability of the switches are the critical factors, and not the particular internal construction of the devices. Sometimes, composite switches of two or more devices are employed where a single device having the desired characteristics may not be available. For example, inverse diodes are often connected across transistors or thyristors to provide reverse conduction capability. However, the availability and cost of suitable devices largely determines what types of converter are practical. Integrated packages of multiple power devices and associated drivers are being intensively developed, primarily to reduce cost and size.

Switching-Mode Conversion: Time-Average Voltage Control

Fundamentally, a power converter is a device for interconnecting two sources. In performing this function, the converter should consume a minimum of power, so the connection should not intentionally be resistive. This goal is achieved by employing a switching mode of operation. The great majority of converters operate upon the following basic principle: *A current-source terminal is selectively connected or switched between two or more voltage-source terminals.*

This is illustrated in Fig. 1, which also serves to define the

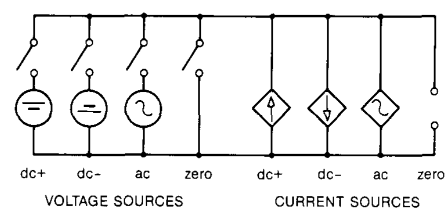

Fig. 1. Switching-mode converter: basic topology.

source symbols that will be used here. The voltage sources may be dc of either polarity, ac of any amplitude, phase or frequency, and one switch terminal may be a zero-voltage source, or ground. Similarly, the current source may be dc of either polarity or ac of any amplitude, phase or frequency. While it is unusual, several current sources may be connected together, as indicated in Fig. 1. However, at any time, one and only one of the switches must be closed to connect a single voltage source to the current-source terminal. (Except that, in most converter circuits, there is a discontinuous-current mode of operation where all switches are open; the prevailing topology includes an inductance carrying no current, equivalent to a zero-current source or open circuit.)

In a diode rectifier, the switch selection is automatic: the diode switches "on" whenever the voltage across its terminals becomes positive and turns "off" when the current attempts to go negative. In this case, the power flow is entirely determined by the state of the two sources, and is restricted to one direction.

To obtain control over the power flow, the switching devices must be able to control their time of turn-on or their time of turn-off, or both. With control of the switching times between terminals, the average voltage at the current-source terminal is determined by the fraction of time it dwells at each voltage-source terminal and the average source voltage during the dwell time. This time-average voltage control is the major means of adjusting the power to achieve the desired performance. Note that the voltage at the current-source terminal cannot exceed the maximum of the voltage sources. That is, power from the voltage sources is "stepped down" in voltage level, or power from the current source is "stepped up" in voltage level. With multiple voltage sources and a given desired voltage at the current-source terminal, the switches should be operated to time-share its connection between the "closest higher" and "closet lower" of the available voltage sources.

The voltage and current polarities at the instant of switching determine the mode of commutation and the type of devices required. Suppose, in Fig. 2, that the switches *S*1

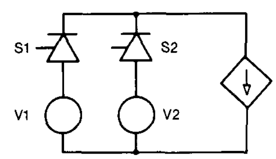

Fig. 2. Commutation between voltage sources.

and *S*2 are unidirectional current devices, as indicated, and *S*1 is initially conducting to connect voltage source *V*1 to the dc current source. When it is desired to reconnect the current source to voltage source *V*2 by turning *S*1 off and *S*2 on, the required sequence of switching depends on the voltage difference between *V*1 and *V*2. If *V*2 is instantaneously more positive than *V*1, then switch *S*2 is forward biased and can be turned on, which will cause the current to commutate "naturally" from *S*1 to *S*2, driven by the external voltage (*V*2-*V*1) which will now appear as reverse voltage across *S*1.

However, if *V*1 is more positive than *V*2, switch *S*2 will be reverse biased and cannot turn on. Or, if *S*2 were a bidirectional current switch, turning *S*2 on would short circuit the voltage *V*2 to *V*1. Therefore, switch *S*1 must be turned off first by self-commutation, forcing its voltage to rise. This will bring *S*2 into forward bias, so it can now be turned on and limit the forward voltage on *S*1 to (*V*1-*V*2).

For a return commutation from *S*2 back to *S*1 again, the situation has now reversed, unless and until the difference voltage (*V*2-*V*1) changes polarity. That is, an external commutation from *S*1 to *S*2 must be followed by self-commutation of *S*2 to *S*1, and vice versa. With dc sources, the voltage never changes polarity, so at least one of the switches must be self-commutated. A converter employing only externally-commutated switches must rely on ac sources to provide cyclic voltage reversals, and the switching frequency is limited to the ac source frequency.

Commutation Aids: Snubbers

Snubbers are relatively small auxiliary circuit elements that are added to the basic circuit topology in order to reduce the transient voltage or current stresses on the semiconductor switching devices. Shunt snubber capacitors are connected across the devices to limit the rate of rise of voltage (*dv/dt*) or the peak voltage (or both) during turn-off [10], [11]. They also may serve to limit the effects of externally imposed voltage transients. Series snubber inductances are connected in series with the devices to limit the rate of rise or fall of current (*di/dt*) through the device when turning on or off, respectively. A typical arrangement is illustrated in Fig. 3 [12]. In the various converter topologies to be presented, it should be understood that snubbers may be included in the location of the switching devices.

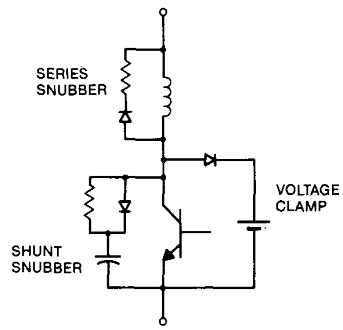

Fig. 3. Typical snubber and clamp arrangement for a switching transistor.

The action of a series snubber tends to interfere with the action of a shunt snubber and vice versa, so diodes are often used to polarize the action and limit the interference. In both types of snubber, energy is stored in the reactive elements and is usually "trapped," that is, not easily recoverable and must be dissipated by discharge through a resistor. This offsets the reduction of switching losses in the semiconductor devices. A great many different arrangements have been developed to reduce or avoid snubber losses, but at the expense of complexity [13]. It is desirable to extend the safe operating area of the devices and increase their switching speed to reduce the energy absorbed, so that they can be operated without snubbers. This has been accomplished with low and medium power devices.

Clamps are auxiliary circuit elements similar to snubbers except that they do not limit the rate of change, but only the peak value, of voltage or current. They are often needed to absorb the energy trapped in parasitic impedances, particularly when high *di/dt* switching generates inductive spikes. To avoid this, in snubberless operation the switching rate should be carefully controlled, if the devices allow it.

Parasitic Impedances

Parasitic impedances appear in locations where they are not desired, and are usually neglected in idealized analysis and omitted from circuit diagrams. The series resistance of windings, wiring, and on-state switches is the major cause of losses, but otherwise has little effect. Since inductance and capacitance have a dimension of length, they cannot be eliminated from physical equipment. Both can be important, because they impose ultimate limits on switching speed. The most significant stray element in many converters is series inductance, in the form of transformer or machine winding leakage inductance. While it is often desirable to minimize parasitic impedances, they may provide some "free" benefits.

The ac system or load connected to a converter should appear to be a source of the opposite type, at least transiently, since it is not permissible to connect voltage sources in parallel or current sources in series. Thus, a quasi-square-wave voltage-source converter must be connected to a sine-wave voltage-source utility (or motor) via series inductance, which might be simply the leakage reactance of windings. This reactance represents an imperfection of the ideal utility source which is advantageous in the above instance and acceptable for an ordinary thyristor current-source converter, where it assists natural commutation by acting as a large series snubber. Furthermore, ac system reactance is of prime importance in limiting fault currents. However, inductance hinders self-commutation in a current-source converter, and filter capacitors must be connected across the ac terminals to improve the voltage-source quality.

In high-voltage equipment, the shunt capacitance of transformer windings and stray capacitance to ground become significant, because the capacitance is reflected to the low-voltage side by the square of the turns ratio. In a self-commutated current-source converter, the stray capacitances can be regarded as a small addition to the ac filter and snubber capacitors. In an ordinary thyristor converter, the stray capacitances must be discharged when the devices turn on, and leg reactors (series snubbers) are required to limit *di/dt*. While these reactors are relatively small and can be allowed to saturate, they are not necessary in low-voltage systems where stray capacitance is negligible.

For a self-commutated voltage-source converter, the stray capacitances are an impediment to generation of the "ideal" waveform. However, the switching devices require snubbers which affect this waveform in a similar manner; stray capacitance has an effect akin to shunt snubber capacitance, for which *di/dt* limiting inductance is provided in any case. If the energy stored in stray capacitance were as large as the energy stored in leakage inductance, then the effect on voltage-source converters would be more serious.

AC/DC Converters

This class includes both rectifiers and inverters; since the equipment is inherently regenerative when controlled switches are employed, the generic term "converter" will be used. In the general description of topologies, the use of self-commutated switches is assumed; the restrictions of external commutation are discussed later.

Voltage-Source Converter Topologies

The basic single-phase arrangements are presented in Figs. 4–6. In a voltage-source converter, the switching devices do not have to block reverse voltage, as indicated by omission of the "blocking bar" from the device symbols

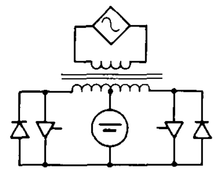

Fig. 4. Single-phase voltage-source converter: center-tapped ac source.

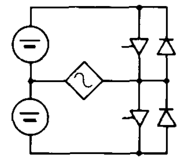

Fig. 5. Single-phase voltage-source converter: center-tapped dc source.

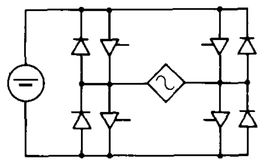

Fig. 6. Single-phase bridge voltage-source converter.

in the figures. Instead, the switches must be reverse conducting or employ antiparallel diodes. Devices of this type can be better optimized for fast switching. The full bridge, Fig. 6, is more common because the half-bridge, Fig. 5, requires a center-tapped dc source that must carry large ac currents and Fig. 4 requires a center-tapped transformer. The leakage inductance between the center-tapped windings impairs the switching performance. However, there is only one device in the loop through the dc source, giving the advantage of lower forward conduction drop, which is significant when the dc voltage is low.

In its simplest form, a voltage-source converter switches at the ac fundamental frequency and generates a square wave of voltage. With alternate conduction of the pair of switches in Figs. 4 and 5, a square-wave voltage is impressed across the ac current source. The same waveform is produced by Fig. 6 if the two legs are switched simultaneously. However, by introducing a phase displacement in the switching times, the quasi-square waveform in Fig. 7 can be generated. This is one common method of adjusting the ac/dc voltage ratio, and can also reduce the harmonic content of voltage on the ac side and ripple current on the dc side. Note that when the voltage in Fig. 7 is zero, the ac current

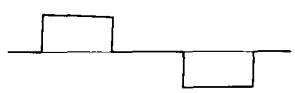

Fig. 7. Quasi-square waveform.

coasts through the pair of switches connected to the same dc rail (positive or negative), so there is no current in the dc source.

For three-phase ac systems, the bridge circuit in Fig. 8 is widely employed. When the three component half-bridge

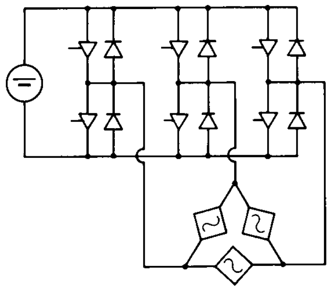

Fig. 8. Three-phase bridge voltage-source converter.

phase legs in Fig. 8 have symmetrical 120° phase displacement, the square waves at each ac terminal combine to produce the so-called "six-step" waveform seen in Fig. 9. A better waveform can be obtained with a multi-phase converter

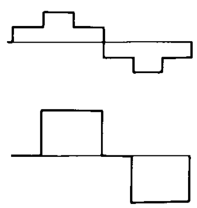

Fig. 9. Six-step voltage waveform produced by three-phase bridge circuit. (a) Line to neutral. (b) Line to line.

composed of two or more three-phase bridges in parallel across the dc source. The ac outputs are combined in special transformer connections to produce a stepped wave having low harmonic content, such as depicted in Fig. 10.

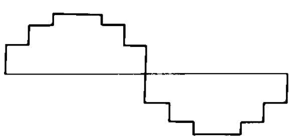

Fig. 10. Stepped waveform.

This is a popular arrangement for uninterruptible power supplies, but not for applications such as motor drives where an output transformer is generally not necessary.

In any of these circuits, one may exercise the option of operating the pair of switching elements in each phase leg many times during each fundamental ac cycle. A switching pattern of pulse-width modulation (PWM) can be chosen to reduce objectionable ac harmonics or otherwise shape the voltage waveform, at the same time adjusting the ac/dc voltage ratio. Many different patterns of PWM have been proposed, frequently with claims of "optimum" in respect of some criterion; a typical example is shown in Fig. 11. The

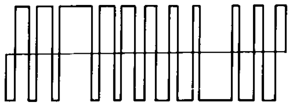

Fig. 11. AC voltage waveform produced by pulse-width modulation (PWM).

high-frequency harmonics can be suppressed with a relatively small series inductance and shunt capacitance. PWM control is favored because it does not require complex topology. The major design tradeoff involves the PWM switching frequency, with corresponding losses, and the size of the filters, both dc and ac. The disadvantage of higher switching losses is being overcome by the development of faster high-power semiconductor devices. A small electrolytic dc capacitor can be used, except where the application requires high voltage, high or low operating temperatures, or very high reliability.

Another method of adjusting the ac voltage is regulation of the dc voltage by means of another converter, such as a rectifier or dc chopper. For regeneration in dc-linked systems, it is desirable that both converters be of the same type; in this case, a second voltage-source converter should be used. Optimum system performance might be obtained with a combined system, in which the amplitude of the ac voltage is regulated by adjusting the dc link voltage, while a PWM control is devoted to harmonic suppression.

Current-Source Converter Topologies

A current-source converter is, essentially, the dual of a voltage-source converter. The switching devices must block reverse voltage, or else have series diodes instead of antiparallel diodes. Instead of a shunt capacitor, the dc side is filtered by a series inductance. Generally, a set of ac filter capacitors must be connected directly across the ac terminals of the converter if self-commutation is to be employed. For example, by interchanging the ac and dc nature of the sources in Fig. 5 and replacing the reverse-conducting switches with reverse-blocking devices, the arrangement of Fig. 12 is obtained. The center-tapped ac

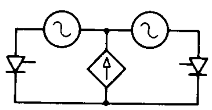

Fig. 12. Single-phase current-source converter: center-tapped ac source.

voltage source is usually a transformer, as in Fig. 4. The leakage inductance between the windings is not critical for external commutation, but addition of capacitors is necessary for self-commutation. With alternate conduction of the pair of switches in Fig. 12, a square-wave current is forced through the ac voltage source.

The single-phase full bridge circuit in Fig. 13 is obtained

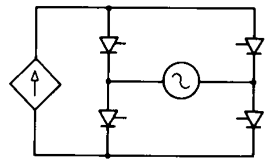

Fig. 13. Single-phase bridge current-source converter.

from Fig. 6 by interchanging the voltage/current nature of the sources and substituting appropriate switches. Again, a square waveform is produced by Fig. 13 if the two legs are switched simultaneously but a quasi-square current waveform like Fig. 7 is obtained by introducing a phase displacement in the switching times. This provides a method of adjusting the ac/dc current ratio, and can also reduce the harmonic content of current on the ac side and ripple voltage on the dc side. Note that when the ac current in Fig. 13 is zero, the dc current is bypassed through a pair of switches that short-circuit the dc current source, while the switches in the other leg are both open.

For three-phase ac systems, the arrangement in Fig. 14 is a basic building block, forming what is called a 3-pulse commutating group. The zero-voltage bypass arm, indicated by dashed lines, is an optional addition. When the three main switches are operated in sequence with symmetrical 120° phase displacement, the direct current is chopped into 120° blocks (pulses), forced through each ac voltage source in turn. This scheme was popular for mercury-arc rectifiers having a common cathode, but has lost favor today because a dc component of current flows through the ac sources (usually, polyphase transformer windings). However, two 3-pulse groups can be combined to form the 6-pulse three-phase bridge circuit in Fig. 15 (dual of Fig. 8), which is the most common converter circuit for high-power equipment. When the six switches in Fig. 15 are operated with symmetrical 60° phase displacement, quasi-square waves of current are forced into each ac terminal, producing a "six-step" current waveform like the voltage waveform seen in Fig. 10. The main method of adjusting the ac current is usually regulation of the dc current by means of another current-source converter.

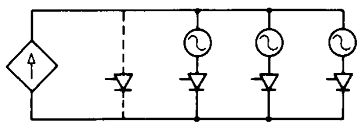

Fig. 14. Three-phase current-source converter.

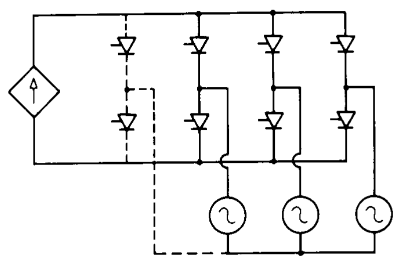

Fig. 15. Three-phase bridge current-source converter.

As in the case of voltage-source converters, with self-commutation it is possible to operate the switching elements many times during each fundamental ac cycle. A switching pattern of pulse-width modulation (PWM) can be chosen to reduce objectionable harmonics or otherwise shape the current waveform, at the same time adjusting the ac/dc current ratio [14]. Just as the dc voltage must exceed the peak ac voltage in a voltage-source converter, the dc current must exceed the peak value of the ac current envelope for the three phase in a current-source converter. The margin of dc current excess must be bypassed through the converter, that is, the PWM pattern must include modes that short-circuit the dc link for certain intervals. These modes may be programmed to occur through a neutral leg, such as indicated by dashed lines in Fig. 15. This can be considered as storage of reserve energy in the dc filter inductance, just as reserve energy is stored in the dc filter capacitance of a voltage-source converter.

Since inductive storage of energy is lossier than capacitive storage, the current-source converter is at a disadvantage. To minimize the losses, the dc link current must be modulated to closely match the load demand. This requires a very fast response current regulator for the controlling converter. One advantage of current-source converters pertains to the regenerative mode of operation. In a current-linked two-stage ac/ac converter system, reversal of power flow is obtained by reversing the dc voltage instead of the dc current. This allows an ordinary thyristor rectifier to operate as a load-commutated inverter, where external commutation of the thyristors is provided by the counter-EMF of a synchronous machine or ac system.

Externally-Commutated Converters

Historically, the first high-power electronic switches were mercury-arc rectifiers and similar devices having characteristics much like thyristors, with which they were replaced. In particular, they shared the requirement of external commutation. Ordinary thyristors are turned on by application of forward gate current, but cannot be turned off by reverse gate current. Instead, the anode current must be extinguished by external means. In the classical natural- or line-commutated phase-controlled rectifier, which may be classified as a current-source ac/dc converter, this is accomplished by turning on the thyristor in the next phase of the commutating group, which connects the line voltage to produce the desired switching. However, this mode of operation is restricted to the half-cycle in which the line voltage has the proper polarity. The only method of control is to delay the time (or phase angle) of turn-on in this half-cycle. As a result, the converter always draws lagging current from the supply.

The displacement angle between the source voltage and the fundamental component of current is proportional to the turn-on delay angle, so the reactive power is greatest when operating near 90° to produce a low dc voltage. By including a switched connection to a source of zero voltage (ground) in the topology of the circuit, such as indicated by dashed lines in Figs. 14 and 15, a level closer to the desired dc voltage may be selected. When the freewheeling switch in Fig. 14 is closed, the dc current bypasses the ac sources, reducing the reactive power. A freewheeling diode rectifier is often employed, but a thyristor is needed if regeneration is required. The fourth leg in the bridge circuit of Fig. 15, connected to the neutral point of the ac voltage sources, operates in similar fashion [15]. The power factor can also be improved by methods that do not require a change in topology, such as by asymmetrical control of commutating groups, or by sequential control of groups in converters where two or more commutating groups are connected in series (as in Fig. 15) [16].

The ordinary thyristors employed in externally-commutated converters need only simple pulse turn-on control and can withstand high surge currents. Because a relatively large ac source reactance is permissible, overloads and faults, including the effects of miscommutation, can be limited by relatively simple control techniques. Rapid recovery is possible, so the equipment is rugged and reliable. These features are difficult to duplicate with self-commutated converters, where the switching devices must be able to turn off the peak fault current or special, complex arrangements are necessary to limit the current and the normal performance of the converter may be compromised.

Most high-power externally-commutated converters are of the current-source type. However, some externally-commutated voltage-source converters have been developed [17], [18]. Also, rectifiers with capacitor-input filters, including voltage multiplier circuits, can be regarded as a special category within the class of voltage-source converters. A large number of such topologies have been used [19].

Self-Commutated Converters

Self-commutated power converters of many types have been developed extensively since the introduction of power semiconductors. While controllable turn-off semiconductor devices have always been preferred for this type of equipment, they have only recently (within the past ten years) become available in large sizes. A self-commutated converter using ordinary thyristors must be provided with an auxiliary commutating circuit including capacitors, inductors and, often, additional thyristors. This results in a quite complex and expensive arrangement, and the large number of different topological configurations that were developed for commutating circuits indicates that no one was entirely satisfactory.

As power transistors have increased in size, they have taken over applications at power levels originally restricted to ordinary thyristors with commutating circuits. As their name implies, gate turn-off thyristors (GTOs) can be turned off by reverse gate current and, as in the case of power transistors, major accessory components are not required. From the viewpoint of the power circuit, a GTO can be regarded as a very large power transistor with, perhaps, reverse blocking capability. The very high power GTOs now available are supplanting the remaining applications of ordinary thyristors in all self-commutated power converter equipment. The elimination of commutating circuits greatly enhances the practicality of high-power self-commutated converters and extends their range of application.

The controls required by a self-commutated converter are more complex and critical than for an externally-commutated converter, because turn-on of the incoming arm must be properly timed with respect to turn-off of the outgoing arm. Multiple switching within each cycle (PWM) may be used to adjust voltage or reduce harmonics, but requires careful timing to be effective. For protection, it is necessary to continuously monitor the current in each phase arm and override the normal control signals within a few microseconds after overcurrent is detected. Signals to produce appropriate action in the other phase arms should simultaneously be generated. With due care, these needs can be met reliably with integrated circuit and other techniques, and the generated signals can be transmitted from ground to each gate (or base) driver via optical links.

AC/AC Converters

Systems in which a pair of ac/dc converters (rectifier and inverter) are operated in cascade have been mentioned previously. These systems may be described as "dc link converters" or "indirect frequency changers." They have major applications as adjustable-speed ac motor drives and UPS systems, including a battery charger and inverter. Interaction between the input and output frequencies is buffered by the dc link filter. Cascaded voltage-source converters need only a common dc filter capacitor. Similarly, a pair of current-source converters can share a common dc filter inductor, and the rectifier can be an inexpensive circuit using externally-commutated thyristors. However, cascaded converters of the opposite type require both inductance and capacitance in the dc filter, and problems arise if regeneration is necessary. If regeneration is not required, then a diode rectifier followed by a voltage-source PWM inverter is an attractive system, because it operates close to unity power factor.

Cascaded systems involve two stages of power conversion, rectification and inversion, in which the load current must pass through at least two power switching devices in series. This increases the conduction losses. Direct frequency changers or cycloconverters have the advantage of only one stage of power conversion: current can flow from input to output through only one switching device so that conduction losses are minimized. However, reverse-blocking thyristor-type devices are required. If the only available devices having the desired high-frequency switching characteristics are of the forward-blocking transistor-type, then series diodes must be employed and the advantage is lost. Cycloconverters are inherently capable of reverse power flow without additional components, so that regenerative systems need only the appropriate control functions.

Externally-Commutated Cycloconverter

In concept, this type of frequency changer can be regarded as an inverse-parallel pair of phase-controlled rectifiers, one for each polarity of current, which are modulated to produce ac output [20], [21]. Commonly, a polyphase set of voltage sources feeds a single-phase current source at a lower frequency, as in the bridge arrangement of Fig. 16. This same configuration is popular for reversing

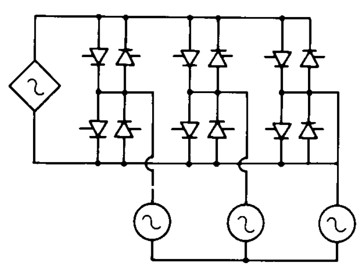

Fig. 16. Direct frequency changer: three-phase voltage source, one-phase current source.

dc motor drives, where it is known as a "dual converter." For three-phase output, three such converters are required. Externally-commutated cycloconverters can employ ordinary thyristors, but are limited to switching at the supply frequency. Ideally, the supply should act as a voltage source with only a small amount of series inductance to act as a "series snubber," limiting the *di*/*dt* in the devices.

The frequency at the current-source, inductively filtered output side can, theoretically, approach and possibly exceed the input frequency. However, the interaction between the asynchronous sources becomes excessive and the quality of the waveform deteriorates rapidly. For practical utilization, a relatively high ratio between the supply frequency and the output frequency must be maintained, often in combination with many input phases. That is, a high pulse number is beneficial, but the penalty is that a large number of thyristors is required. Another serious disadvantage of externally-commutated cycloconverters is the poor power factor imposed upon the supply, because of the phase control delay required for voltage regulation and waveshaping of the output. Various techniques for improving the power factor of externally-commutated cycloconverters have been proposed, but all provide only marginal improvement for greater complexity and introduce other problems.

Self-Commutated Cycloconverters

The basic concept and circuit configuration of a self-commutated cycloconverter is the same as the externally-commutated type, except that gate turn-off thyristors (GTOs) or similar devices are substituted for the ordinary thyristors [22]. As before, each device may switch at the supply frequency, but the option of operating in a PWM mode is added. While self-commutation, with suitable control, allows operation near unity power factor or with a leading power factor on the supply, there is generally no reduction in the number of switching devices or the output filter size.

Ideally, the supply should act as a voltage source with zero series inductance because self-commutation abruptly interrupts the source current into the converter. Many theoretical treatments assume an ideal ac voltage source and neglect the effect of source reactance. In practice, a capacitive input filter is necessary to prevent loss of energy stored in the supply system reactance, particularly with transformer input, and to limit the overvoltages that must be produced in order to transfer the current with this associated stored energy from one supply phase to another. The capacitance itself may compensate for a substantial part of the poor power factor that the converter is intended to improve.

Pulse-Width-Modulated (PWM) Frequency Changer

This is a type of self-commutated frequency changer which attempts to overcome the deficiencies of the conventional type by operating the switching devices in a PWM mode at a frequency considerably higher than either the input or output frequencies. In the ideal minimum circuit topology, each phase of a polyphase set of voltage sources is connected directly to each phase of a polyphase set of current sources via a pair of antiparallel reverse-blocking devices such as GTOs, for a total of 18 devices in a three-phase system, as illustrated in Fig. 17. The switches are controlled in the manner proposed by Venturini, or some similar mode [23]–[25]. If the supply system inductance is sufficient to provide a current-source quality for voltage-averaging at the input and a set of small filter capacitors can provide a voltage-source quality for current-averaging at the output, the number of filters is reduced to a minimum.

While this "universal frequency changer" or "generalized transformer" is attractive in concept, there are many obstacles to its practical development. To maintain a reasonable efficiency, the switching loss must be reduced to a very low value. Conventional snubbers effective for both turn-on and turn-off of bidirectional device arrangements are inefficient, while "lossless" snubbers introduce considerable complexity. Alternatively, devices that can switch at very high frequencies without snubbers would have to be developed. Many analyses of this type of converter have been published, but most assume balanced load and do not address the problems of current limiting and protection. Because of strong interactions between phases at both input and output, the circuit behavior becomes very complicated. It is concluded that PWM changers are impractical at present, but may become important in the future.

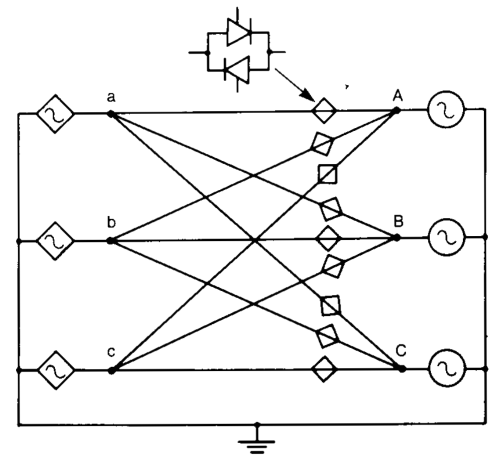

Fig. 17. Direct frequency changer: three-phase to three-phase using bidirectional self-commutated switches.

DC/DC Converters

Just as many ac/ac converters employ a dc link between a rectifier and an inverter, many dc/dc converters employ an ac link between an inverter and a rectifier, especially when a transformer is required to provide a large shift in voltage level. When a transformer is not needed, the single-phase bridge topology of Fig. 6, employing self-commutated switches, can be used to produce a reversible dc current source capable of regeneration. If only unidirectional current is needed, the topology can be simplified by eliminating certain of the switching devices. The reduced form in Fig. 18(a) is known as a voltage step-down chopper or buck converter, while the variant shown in Fig. 18(b) is called a step-up chopper or boost converter. From another viewpoint, the dc converters in Fig. 18 can be regarded as basic building blocks for reversible dc converters and inverters, which may be obtained by adding switching elements in suitable locations.

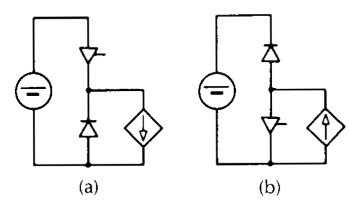

Fig. 18. Basic dc chopper circuits. (a) Voltage step-down (buck). (b) Voltage step-up (boost).

In both buck and boost types of direct dc converter, a dc form of pulse-width modulation or duty-ratio control produces a voltage waveform of the type shown in Fig. 19 at the current-source terminal. The current in the dc voltage

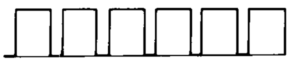

Fig. 19. DC waveform produced by pulse-width modulation (PWM).

source has a similar pulsed form. Many topological variations for dc switchmode converters have been developed, such as the "buck-boost" circuit, mainly in the low-power range of application. The thrust of development is towards topologies that are effective at very high frequencies and integration of accessory components with the switching devices, to achieve power supplies of very small size.

Conclusion

Historically, the field of power electronics has been divided into a high power range mainly concerned with externally-commutated ac/dc converters for industrial applications and a low power range where the main interest began with self-commutated dc/dc switchmode converters for aerospace applications. Previous studies of high-power self-commutated converters contained extensive discussions of the many topologies devised as auxiliary commutating circuits for ordinary thyristors [26], [27]. Development of high-power self-commutated switching devices has made the latter obsolete, allowing the circuit topologist to concentrate on the more basic aspects common to all types of converters. An approach based on a generalized concept of sources has been presented here. Also, an expanded concept of switchmode conversion encompasses external commutation, regarded as a switching mode limited to the ac source frequency. In these ways, the inherent common ground of power electronics is revealed.

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