Self-Commutating Converters for High Power Applications

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Contents

Preface

The characteristics of power semiconductors have reached the stage at which they can be used to control the operation of generation, transmission and utilization systems of all types and ratings.

For very high-voltage or very high-current applications, the industry still relies on thyristor-based line-commutated conversion (LCC), which lacks reactive power controllability. However, the ratings of self-commutating switches, such as the IGBT and IGCT, are reaching levels that make the self-commutating technology possible for very high power applications.

The term ‘high’ requires a reference for its interpretation. In this respect, three rating components are involved, namely voltage, current and power. Of course, high power ratings can only be achieved by correspondingly high current and/or voltage ratings, but not necessarily both. While high power transmission uses high voltage and relatively low current in order to reduce power losses, some industry processes (such as aluminium smelting) require very high current and very low voltage.

Currently, there is a high level of interest in countries such as China, India, Brazil and parts of Africa in generating power from large renewable resource (mainly hydro) plants at remote locations and transmitting this power using ultra high voltage (UHV) to national and/or international load centres. The powers and distances under consideration are typically 6000 MW and 2000 km respectively and the voltage selected by the planners for these projects is ±800 kV DC. Although there is no experience of operating at such voltage level, the general opinion is that they do not represent an unreasonable risk and the manufacturers are ready for the task.

This book reviews the present state and future prospects of self-commutating static power converters for applications requiring either UHV DC (over ±600 kVs), such as required by very large long-distance transmission or ultra high currents (in hundreds of kA), such as those used in aluminium smelters and large energy storing plants.

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1

Introduction

1.1 Early developments

A variety of electronic valves was tried in the first part of the twentieth century for the conversion of power from AC to DC and vice versa. The mercury-arc valve was the most suitable option for handling large currents, and thus, multiphase grid-controlled mercury-pool cathode valves were developed for industrial and railway applications.

Efficient bulk power transmission, however, requires high voltage rather than current and, thus, the development of a high-voltage DC transmission technology only became possible in the early 1950s, with the invention (by Uno Lamm of ASEA) of the graded-electrode mercury-arc valve [1]. Soon after, with the appearance of the thyristor or silicon controlled rectifier (SCR), the use of power conversion progressed rapidly to higher voltage and power ratings.

The source forcing the commutation process between the converter valves (either mercury-arc or thyristor) was the AC system voltage and thus the converter was said to be line-commutated (LCC). LCC relies on the natural current zeros created by the external circuit for the transfer of current from valve to valve. The commutation is not instantaneous, because of the presence of AC system reactance, which reduces the rate of change of current and, therefore, lengthens the commutation time in proportion to the reactance and the magnitude of the current to be commutated; the duration of the commutation also depends on the magnitude of the instantaneous value of the commutating voltage, which changes with the position of the firing angle. All these variables depend on the operating conditions and, as a result, the prediction and minimization of the commutation angle becomes a difficult problem. This is an important issue for inverter operation, which requires a large firing advance for safe operation, with an increasing demand of reactive power.

By the late 1960s, the successful development of the series-connected thyristor chain had displaced the mercury-arc valve in new high-voltage direct current (HVDC) schemes [2].

SCR-based power conversion technology continues to be used extensively in power transmission (in the form of static VAR compensation (SVC) and HVDC) and in a variety of industry applications. In fact, the power rating capability of present SCR converters is

Self-Commutating Converters for High Power Applications J. Arrillaga, Y. H. Liu, N. R. Watson and N. J. Murray

only limited by the external components attached to the converter, such as the interface transformers.

1.2 State of the large power semiconductor technology

Progress in power semiconductor types and ratings has been such that a review of their current state, important as it is to the subject of this book, will be short lived, and any recommendations on their specific application must be looked at in this context.

Historically, the application of semiconductors to high-voltage applications started with the silicon controlled rectifier (SCR) in the late 1950s. Despite its age, the SCR, though with highly improved current and voltage ratings, is still the most widely used semiconductor in HVDC conversion. However the restricted controllability of the SCR has encouraged the development of alternative power semiconductors of the thyristor and transistor families.

At present the power semiconductor devices available for large power conversion applications are based on the silicon technology and they can be broadly classified in two groups [3].

The first group includes devices with four-layer three-junction monolithic structures, the two early devices in this category being the SCR (silicon controlled rectifier) and GTO (gate turn off thyristor). The devices in this group have low conduction losses and high surge and current carrying capabilities; they operate only as on/off switches with bidirectional voltage blocking capability.

Recent developments in this group are the MCT (MOSFET (metal oxide semiconductor field-effect transistor) controlled thyristor), ETO (emitter turn-off thyristor), MTO (MOS (metal oxide semiconductor) turn-off thyristor) and GCT or IGCT (integrated gate-commutated thyristor). These recent devices were developed to provide fast turn-off capability and low turn-off switching losses.

The majority of commercially available GTOs for providing free current path in voltage source conversion are of the asymmetrical type; they are reversed connected to a fast recovery diode, such that the GTO does not require reverse voltage capability. Asymmetrical GTOs have been used extensively in pulse width modulation (PWM) two- and three-level voltage source converters, active filters and custom power supplies. However, there is little further development of the GTO technology, the interest focusing instead on the GCT, which differs from the GTO by having a turn-off current gain close to unity. This means that, at turn-off, practically all the load current is commutated to the gate circuit for a few microseconds (thus the name gate commutated thyristor). This is achieved by the application of a very strong pulse with a *di/dt* of the order of 3000 A per microsecond. A further development of the GCT is the IGCT (integrated gate commutated thyristor), which, instead of the separate gate drive connected via a lead, uses a gate drive circuit integrated with the semiconductor device, thus achieving very low values of gate inductance. This device has a very short storage time (of about 1 μs), which permits small tolerances (under 0.2 μs) in turn-off times of the different devices, and therefore provides very good voltage sharing as required by the series connection in high-voltage applications.

The IGCT can also be used as an asymmetrical device, in which case a free-wheeling diode with a soft recovery turn-off is needed. IGCTs with blocking voltages up to 6.5 kV are available on the market and IGCTs with 10 kV are under development.

Although the IGCT has overcome many of the problems of the conventional GTO, the gate driver is still complex and a large linear *di/dt* limiting inductor is needed for the anti-parallel diode.

The second group contains devices of three-layer two-junction structure which operate in switching and linear modes; they have good turn-off capability. These are: the BJT (bipolar junction transistor), Darlington transistor, MOSFET, IEGT (injection enhanced transistor), CSTBT (carrier stored trench-gate bipolar transistor), SIT (static induction transistor), FCT (field controlled transistor) and IGBT (insulated-gate bipolar transistor).

There is little manufacturing enthusiasm for developing further some of the devices in the second group, because of the perceived advantages of the IGBT; at present the voltage and peak turn-off currents of the silicon based IGBTs are 6.5 kV and 2 kA.

These devices are mainly designed for use at high PWM frequencies and therefore the switching time must be minimized to reduce losses. This causes high *dv/dt* and *di/dt* and thus requires snubber networks, which result in further losses. Recent advances in the IGBT technology involve the modular and press-pack designs.

A new type of IGBT (referred to as IEGT) has become available that takes advantage of the effect of electron injection from emitter to achieve a low saturation voltage similar to that of the GTO.

1.2.1 Power ratings

As already mentioned, the ratings are changing fast and therefore any comparisons made must indicate the date and source of the information. For instance a 1999 published IEE review [4] of typical maximum ratings (Figure 1.1), showed that the GTO offered the best maximum blocking voltage and turn-off current ratings; these were 6 kV and 4 kA respectively, the switching frequency being typically under 1 kHz. More recently, however, the industry has

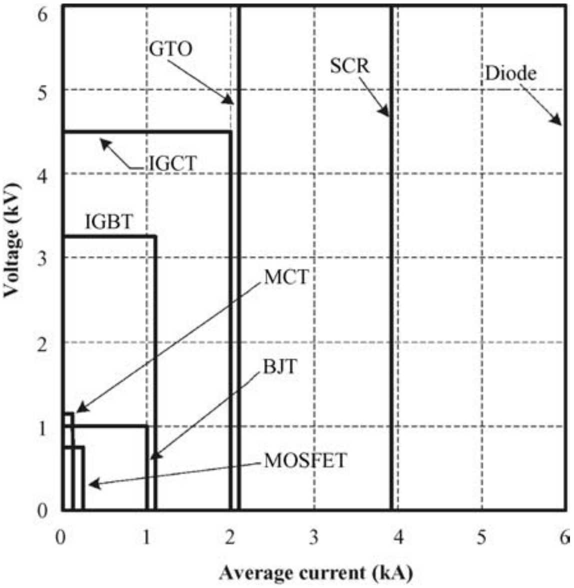

Figure 1.1 Voltage and current ratings of the main power semiconductors. (Reproduced by permission of the IET.)

concentrated in the IGCT development, for which the maximum ratings have already reached 6.5 kV and 6 kA.

The thyristor remains by far the most cost-efficient device for very high power application. The thyristor ratings presently available are typically (12 kV/1.5 kA and 8.5 kV/5 kA).

1.2.2 Losses

The IGBT turn-off losses are lower than those of the SCR and IGCT and so are the turn-on losses in the case of soft-switched IGBTs. The forward voltage drop of the IGBT is, however, much higher than that of a thyristor of comparable voltage rating.

In the assessment of the energy loss of a converter, the most important factor is the frequency used for the switching of the valves, which depends on the type of configuration and control. To illustrate this point a comparison between different alternative converters of the LCC and voltage source conversion (VSC) types has shown the following figures for the power loss of the complete converter station [5]:

- An IGBT based two-level voltage source converter with a PWM frequency of 1950 Hz has a power loss of approximately 3%.
- An IGBT based three-level voltage source converter with a PWM frequency of 1260 Hz has a power loss of approximately 1.8%.
- The loss figure for an SCR based LCC (line-commutated converter) station (including valves, filters and transformers) is 0.8%.

The IGCT has low on-state voltage and low total power losses (about one half of those of the conventional GTO) as shown in Figure 1.2. The IGCT has the lowest total loss (including both device and peripheral circuits) of all present power semiconductors.

1.2.3 Suitability for large power conversion

The main candidates for high power conversion appear to be the IGCT and IGBT. The previous section has already explained that the IGCT offers the best power ratings and lower overall losses, two important factors favouring its use in large power applications.

On the other hand, the IGBT requires much less gate power and has considerably superior switching speed capability, therefore permitting the use of higher switching frequencies (these can be typically 3 kHz for soft-switched devices as compared with 500 Hz for the IGCT). While high switching frequencies have some disadvantages (like switching and snubber losses), they help to reduce the harmonic content and therefore filtering arrangements, reduce machine losses and improve the converter dynamic performance.

The IGBT is more reliable than the IGCT under short-circuit conditions. It is designed to sustain a current surge during conduction and also during turn-on. However, short-circuit faults need to be detected quickly so that turn-off is achieved within 10 μs. The IGCT on the other hand has no inherent current-limiting capability and must be protected externally. The overall reliability of the IGCT for high-power and -voltage application is very impressive, given the reduced voltage stress achieved by the series connection and its potential to eliminate the need for snubbers.

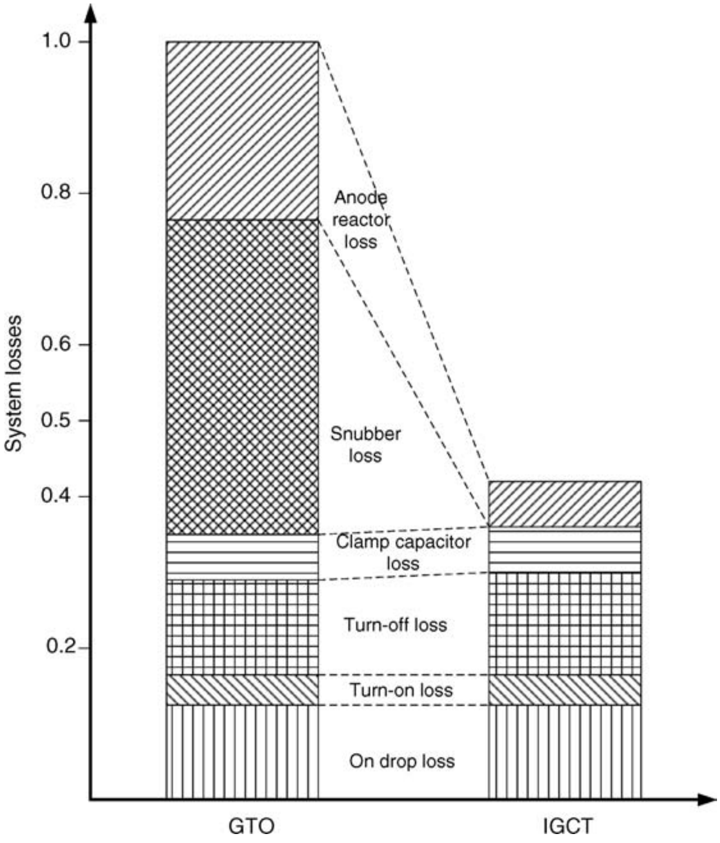

Figure 1.2 Comparison of system loss for a converter using GTO or IGCT (GCT).

For high-voltage applications the converters require high blocking voltage switches, which can only be achieved by the series connection of individual units. Both the IGBT and IGCT are suitable for series connection as the turn-on and turn-off times are relatively small and the switching speeds high. Reliable static and dynamic voltage sharing techniques are now available for thyristor chains (in LCC conversion) and transistor-type switching devices. Parallel sharing resistors are perfectly adequate for static balancing. In the case of the IGBT good dynamic voltage sharing can also be achieved by means of adaptive gate control of the individual units.

The current ratings of present switching devices are sufficiently large for high-voltage application and the use of device paralleling is rarely required. The IGBT technology is also suited for parallel operation, since the high-current IGBT modules themselves consist of many parallel chips.

Heavy investment in the IGBT technology is favouring this device at the expense of the GTO and IGCT alternatives. The availability of press-pack IGBTs at high voltages and currents is strengthening their position in high-voltage applications, where series operation and redundancy of power switches are required.

However, there are still problems with the IGBT for high-voltage applications, due to stray inductances and diode reverse recoveries and, thus, at this stage it is not clear to what extent the fast switching capability should be exploited, as the resulting voltage spikes may exceed the allowable limits.

1.2.4 Future developments

In the future, new wide-band gap (WBG) semiconductor materials such as silicon carbide (SiC) and gallium nitride (GaN), instead of silicon, are likely to increase the power handling capability and switching speed. The best candidate at the moment seems to be the SiC, a device that provides low on-state voltage, low recovery charge, fast turn-on and turn-off, high blocking voltage, higher junction temperature and high power density. In particular this material permits substantial increase in the allowable peak junction temperature, thus improving the device surge capability and reducing the complexity of the cooling system. With the utilization of SiC unipolar power switches it is possible to reduce the power losses by a factor of ten. At present only small chip sizes of SiC are available on the market, but a recent forecast of the future voltage ratings achievable with SiC switching devices (in relation to those of present silicon technology) is shown in Figure 1.3.

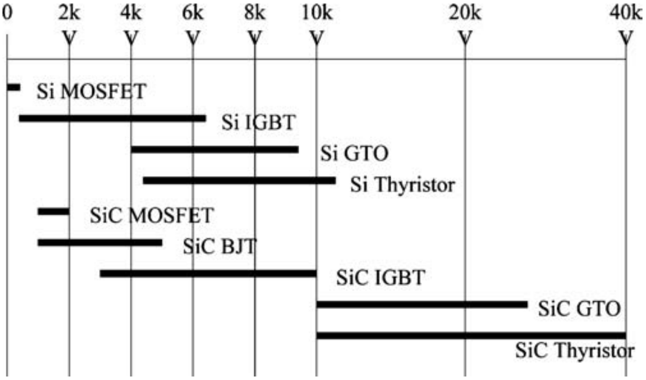

Figure 1.3 Silicon carbide (SiC) switches compared to silicon (Si) switches. (Reproduced by permission of CIGRE.)

Most of the reported development concentrates in raising the device voltage withstand level. There is, however, a place for a low-voltage, high-current device in applications such as aluminium smelters and in superconductive magnetic coils (for fusion reactors and energy storage).

1.3 Voltage and current source conversion

The first consideration in the process of static power conversion is how to achieve instantaneous matching of the AC and DC voltage levels, given the limited number of phases and switching devices that are economically viable. The following circuit restrictions are imposed on a static power converter by the characteristics of the external circuit and of the switching components:

- If one set of nodes (input or output) of the matrix of switches is inductive, the other set must be capacitive so as not to create a loop consisting of voltage sources (or capacitors and voltage sources) when the switches are closed or a cut set consisting of current sources when the switches are opened.
- The combination of open and closed switches should not open-circuit an inductor (except at zero current) or short-circuit a capacitor (except at zero voltage).

For stable conversion some impedance must, therefore, be added to the switching circuit of Figure 1.4(a) to absorb the continuous voltage mismatch that inevitably exists between the two sides.

When the inductance is exclusively located on the AC side (as shown in Figure 1.4(b)), the switching devices transfer the instantaneous direct voltage level to the AC side and, thus, the circuit configuration is basically a voltage converter, with the possibility of altering the DC current by controlling the turn-on and -off instants of the switching devices. A DC capacitor on the DC side and an AC interface inductance on the AC side are the essential components of a

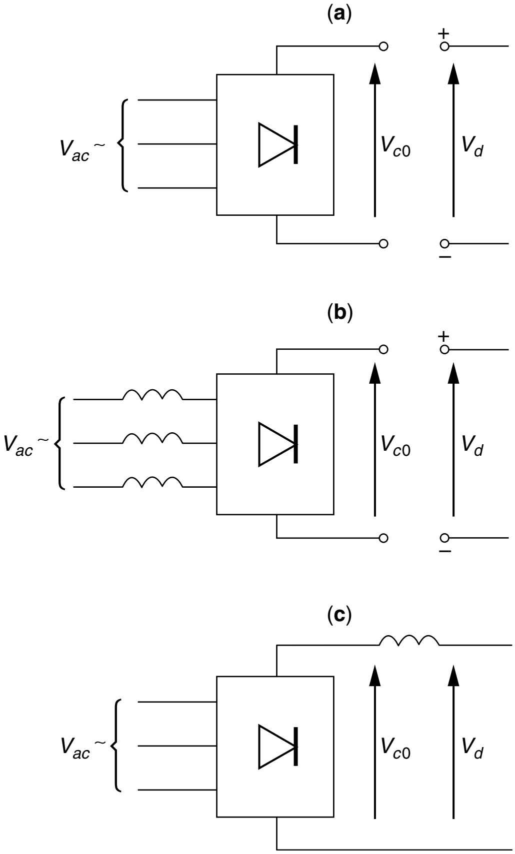

Figure 1.4 AC–DC voltage matching: (a) unmatched circuit; (b) circuit for voltage conversion; (c) circuit for current conversion.

voltage source converter. The designation voltage source converter is used because the function of the voltage source converter is explained by the connection of a voltage source on the DC side in the form of a large capacitor appropriately charged to maintain the required voltage. The AC side inductance serves two purposes: first, it stabilizes the AC current and, second, it enables the control of active and reactive output power from the voltage source converter. The switches must provide free path of bidirectional current, but they are only required to block voltage in one direction. This naturally suits asymmetrical devices like the IGBT or the thyristor type symmetrical ones paralleled with a reverse diode.

If, instead, a large smoothing reactor is placed on the DC side (as shown in Figure 1.4(c)), pulses of constant direct current flow through the switching devices into the AC side. Then, basically a current source converter results. The AC side voltage is then the variable directly controlled by the conversion process. Since the AC system has significant line or load inductance, line-to-line capacitors must be placed on the AC side of the converter. The switches must block voltages of both polarities, but they are only required to conduct current in one direction. This naturally suits symmetrical devices of the thyristor type and, therefore, current source conversion (CSC) constitutes the basis of line-commutated conversion. The asymmetrical type switches are not suited for current source conversion as a diode for sustaining the reverse voltage has to be connected with the asymmetrical switch in series, which causes extra losses.

The valve conducting period in the basic voltage source converter configuration is 180°, i.e. the bridge AC voltage has two levels by the valves and by the AC current when both valves are in the off state (as in this case the AC terminal is floating); whereas in the CSC case the width of the pulse is 120° and, therefore, the output phase (the current in that case) is either $+I_d, 0$ or $-I_d$, i.e. the bridge AC phase current has three levels.

1.4 The pulse and level number concepts

The pulse number (p) is a term commonly used in line-commutated conversion (LCC) and indicates the ratio of the DC voltage ripple frequency to the AC system fundamental frequency. A large number of phases and switches would be needed to produce perfect rectification, that is, a ripple-free DC voltage. This, of course, is not a practical proposition because the AC system consists of three phases only, which limits the number of pulses to six. This pulse number can be derived by the use of a double-star (six-phase) converter transformer, each phase, in series with a single valve, providing one sixth of the DC voltage waveform. However a more efficient alternative in terms of transformer utilization is the three-phase bridge switching configuration, which is the preferred option for other than very low-voltage applications.

The idealized (i.e. with perfect AC and DC waveforms and zero commutation angle) conversion process in a three-phase bridge converter is shown in Figure 1.5.

If on the DC side the rectified voltage is connected to the load via a large smoothing inductor the current will contain practically no ripple (i.e. will be perfect DC) and the converter will inject rectangular shaped currents of 120° duration into the converter transformer secondary phases (positive when the common cathode switches conduct and negative when the common anode switches conduct). On the primary side of the converter transformer the phase current is the AC rectangular waveform shown in Figure 1.6(a). This three-level waveform only applies when there is no phase-shift between the transformer primary and

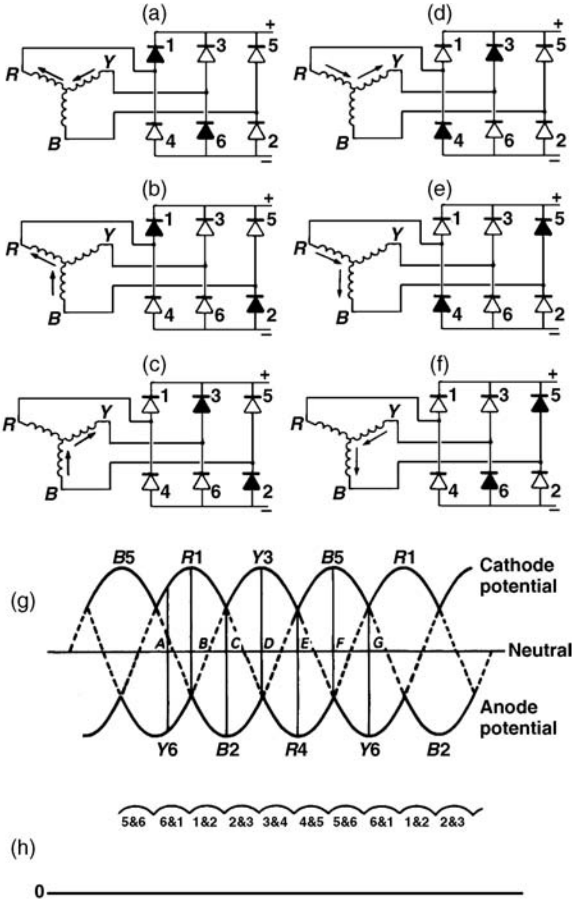

Figure 1.5 Conducting sequence and DC voltage waveforms in a three-phase bridge converter.

secondary phase voltages, i.e. a star–star transformer connection. If instead the converter transformer uses the star–delta or delta–star connection, the primary current, as shown in Figure 1.6(b), has four levels instead of three. So the use of the term level for this purpose is inconsistent.

Instead, the description of the conversion process is normally made in terms of sinusoidal frequency components (i.e. harmonics). In this respect, the three-phase bridge is referred to as a six-pulse configuration. producing *characteristic* voltage harmonics of orders $6k$ (for $k = 1,2,3\ldots$) on the DC side and *characteristic* current harmonics of orders $6k \pm 1$ on the AC side. In practice, any deviations from the assumed ideal AC or DC system parameters will result in other frequency components (though normally of greatly reduced magnitudes), which are referred to as *uncharacteristic* harmonics.

The ‘level number’ is a term commonly used in self-commutating conversion and indicates the number of voltage levels used by the bridge phase arms. It is normally limited to two or three (in the case of PWM) while higher numbers are used in multilevel configurations.

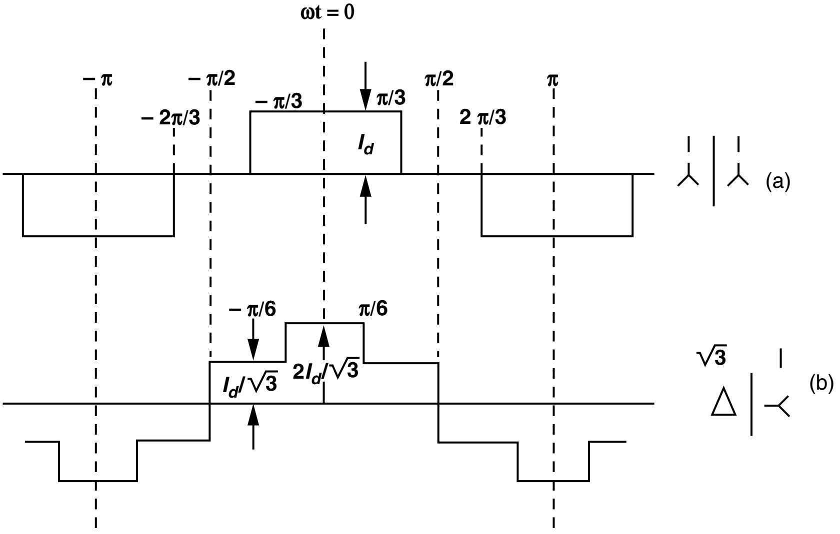

Figure 1.6 Idealized phase current waveforms on the primary side: (a) star–star transformer connection; (b) delta–star transformer connection.

1.5 Line-commutated conversion (LCC)

Three-phase AC–DC and DC–AC converters ratings in hundreds of MW, as required in power transmission and in the metal reduction industry, need to be of high-voltage and high-current designs respectively. These normally consist of complex structures of series or parallel connected power switches, as the ratings of the individual ones are far too low for these purposes. In the series connection the difficulty arises from the need to achieve equal voltage sharing, both during the dynamic and steady states, while in the parallel connection the switches must share the steady state and dynamic currents.

In line-commutated conversion the switchings take place under zero current conditions and snubber circuits are only used to slow down the speed of the individual switches to that of the slowest one in order to achieve good voltage sharing.

Diode rectification (the earliest conversion technology) has no controllability and makes the rectified voltage and current exclusively dependent on the external DC and AC system conditions.

The advent of the silicon controlled rectifier under LCC permited active power conversion control from full negative to full positive rating but at the expense of absorbing varying quantities of inductive reactive power. The DC voltage, however, can be controlled from full negative to full positive rating and the DC current from zero to full rated level. Lack of waveform quality, normally in the form of current harmonic content, is another important problem of SCR–LCC conversion.

The 12-pulse configuration has become the standard configuration in high-voltage thyristor conversion. Higher pulse numbers, such as 48, are commonly used by the metal reduction industry, but in practice they suffer from some low-order harmonic distortion problems. Shunt connected passive filters are, thus, an integral part of the LCC power conversion process and risk causing low-order harmonic resonances with the AC system.

Most of the present HVDC converters, being of the CSC–LCC type, require reactive power for their operation but possess full DC voltage and current controllability. The power and voltage ratings of existing schemes are already in GWs and a ± 800 kV DC technology is currently being introduced. The valves consist of a large number of series-connected thyristors, which are fired synchronously and they are naturally switched off when the current through them reduces to zero; the natural commutation process permits the use of low-cost voltage-balancing snubbers.

1.6 Self-commutating conversion (SCC)

Self-commutation takes place independently from the external circuit source and system parameters and is achieved practically instantaneously. It requires the use of switching devices with turn-on and turn-off capability and the position and frequency of the on and off switching instants can be altered to provide a specified voltage and/or current waveform.

With self-commutation, the switching action takes place under rated voltage and current conditions, and, therefore, a large amount of stored energy is involved that increases the rating and cost of the snubbers.

The following is a wish-list of items for an effective large power conversion:

1. Perfect balancing of the voltages across the series-connected individual switches of the high-voltage valves during the off-state and in the switching dynamic regions; or perfect balancing of the current in the shunt-connected individual switches of the high-current valves during the on-state and in the switching dynamic regions.
2. High-quality output waveforms.
3. Low dv/dt rate across the switches and other converter components to simplify insulation coordination and reduce RF interference.
4. Minimal on-state and switching losses (prefers relatively low switching frequency).
5. Simple structural topology to reduce component costs.
6. Flexibility in terms of active and reactive power controllability.

The self-commutating concepts advanced so far for large power conversion are pulse width modulation (PWM) and multilevel VSC for high-voltage applications and multipulse and multilevel CSC for high-current applications.

1.6.1 Pulse width modulation (PWM) [6]

The ideal properties of the power transistor, in terms of voltage/current characteristics and high-frequency switching capability, permitted the development of PWM in the 1960s, and is still the most flexible power conversion control technique. The PWM principle is illustrated by the output voltage waveform shown in Figure 1.7. As well as providing fundamental voltage control, while maintaining the DC voltage constant, PWM eliminates the low harmonic orders and only requires small filter capacity to absorb the high-frequency components. Such level of flexibility is achieved by modulating the widths of high-frequency voltage pulses. A modulating carrier frequency is used to produce the required (normally

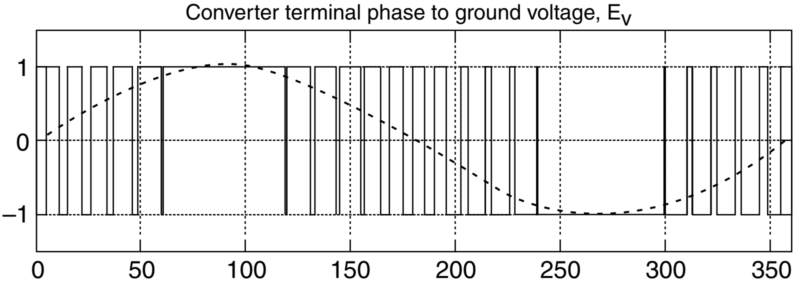

Figure 1.7 Voltage source converter PWM with optimum harmonic cancellation.

voltage) waveform. The PWM concept scores well on items (2), (5) and (6) of the ideal requirements but poorly on items (3) and (4).

PWM, originally used in relatively low-power applications such as the motor drive industry, has recently led to the development of series-connected valves capable of withstanding the high voltages used in power transmission. It was first used in flexible alternating current transmission systems (FACTS) applications, and more recently as the basis of self-commutating HVDC transmission systems. At the time of writing, however, it is uncertain whether this technology will continue developing to meet the needs of very large-power, long-distance transmission. In this respect there are important difficulties to overcome in terms of efficiency and reliability of operation. Besides the high switching losses, the use of two or three DC voltage levels subjects the valves and all the surrounding system components to very high *dv/dt*'s following every switching event, increasing the conversion losses and complicating the system insulation coordination.

The power rating capability of PWM is also limited at present by its reliance on cable transmission. To extend the use of VSC–PWM to overhead line transmission will also require improvements in the control of DC line fault recovery.

1.6.2 Multilevel voltage source conversion

The main object of multilevel conversion is to generate a good high-voltage waveform by stepping through several intermediate voltage levels, i.e. the series-connected devices are switched sequentially at the fundamental frequency, producing an output waveform in steps. This eliminates the low-order harmonics and reduces the *dv/dt* rating of the valves by forcing them to switch against a fraction of the DC voltage.

This concept scores well on items (2), (3) and (4) of the ideal requirements list but poorly on items (5) (the number of auxiliary switches increasing approximately with the square of the

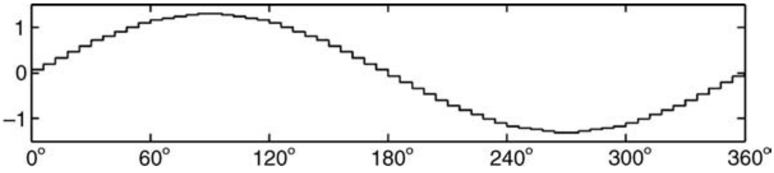

Figure 1.8 Typical output voltage waveforms of a multilevel VSC configuration.

level number in most of the proposed topologies) and (6) (lacking independent reactive power control at the terminals of DC interconnections).

The use of the robust thyristor-type switches (such as the GCT and IGCT), makes the multilevel alternative better suited to the needs of very large power conversion, but the structural complexity and limited control flexibility has so far discouraged the use of the multilevel configurations.

The original multilevel configurations are of the VSC type, which provides free current paths without the need to absorb substantial electromagnetic energy.

Modular multilevel converter (MMC) is a recent Siemens concept [7] that, in common with other multilevel configurations, provides a fine gradation of the output voltage, thus reducing the harmonic content, the emitted high-frequency radiation and the switching losses. The important advantage of this configuration over earlier multilevel proposals is that it permits four-quadrant power controllability. This alternative scores well on item (6).

Finally, a structurally simpler multilevel concept is multilevel reinjection [8,9], applicable to both VSC and CSC, suited to very large power ratings; this scores well in items (1) to (6).

1.6.3 High-current self-commutating conversion

At present most of the perceived application of large power self-commutating semiconductors appears to be in the high-voltage area. In comparison there seems to be little interest in the development of low-voltage, high-current self-commutating switching. However, the latter is important for applications such as aluminium smelters and superconductive magnetic energy storage, both of which are likely to benefit from a more flexible and cost-effective power electronic technology.

In self-commutating CSC the forced commutation from rated current to zero involves large electromagnetic energy (stored in the AC system inductance). Thus interfacing forced-commutated CSC with the AC system requires the provision of costly high capacitors. An acceptable self-commutated CSC configuration should be able to provide a continuously varying AC current. It will be shown that CSC multilevel current reinjection can achieve that target, as well as scoring well in the other items of the wish-list.

1.7 Concluding statement

Only two decades ago it would have been considered science fiction to talk about a transistor-based 300 MW HVDC transmission link, and yet this is now a reality. Trying to predict the final state of the static conversion technology is a very difficult task.

The next five chapters of the book describe the present state of the large power conversion technology and the concepts and configurations likely to influence the design of large static power converters in the next decade. These concepts and converter configurations are used in the last six chapters, with reference to the most likely applications requiring high power and/or current conversion.

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2

Principles of Self-Commutating Conversion

2.1 Introduction

The conventional line-commutated large power converters normally use the current source conversion principle. Both during rectification and inversion they absorb varying quantities of reactive power in their normal operation and inject substantial harmonic currents into the AC system. These conditions require complex and expensive converter stations and cause voltage and harmonic interactions with the AC system to which they are connected. Although the experience of many years has managed to reduce, if not completely eliminate, these problems, the extra cost involved is very substantial and the scheme's reliability is reduced by the number of components.

The progressive development of the self-commutated conversion techniques permits the design of high-power converter systems without the need of passive filters and shunt reactive power compensators; this results in substantial cost reduction and elimination of potential harmonic interactions between the converter and the power system.

Although the progress already made with self-commutation has been great, we are still speculating on the extent to which self-commutating based technologies should be developed to exploit the great potential available in the future.

For power transmission application, the voltage needs to be high to reduce losses and, thus, to match the high voltage rating the converter valves consist of many series-connected switches. Similarly, for industry applications requiring very high currents, many switching devices need to be connected in parallel to match the high current rating.

The dynamic and steady state voltages and currents of these configurations are now well understood and the design of very large power conversion systems presents no special problem.

This chapter introduces the principles of self-commutating conversion with emphasis on VSC, which is at present the preferred option. In later chapters, however, it will be

Self-Commutating Converters for High Power Applications J. Arrillaga, Y. H. Liu, N. R. Watson and N. J. Murray

shown that for high-power applications there is considerable potential for a self-commutating CSC technology.

2.2 Basic VSC operation

Figure 2.1 displays the switching circuit for one phase of the basic two-level converter and its corresponding voltage output waveform, with the midpoint of the DC capacitors used as a reference for the AC output voltage. The two switches are turned on–off in a complementary way (one on and the other off) to generate a certain output of discrete two voltage levels ($+V_{dc}/2$ or $-V_{dc}/2$).

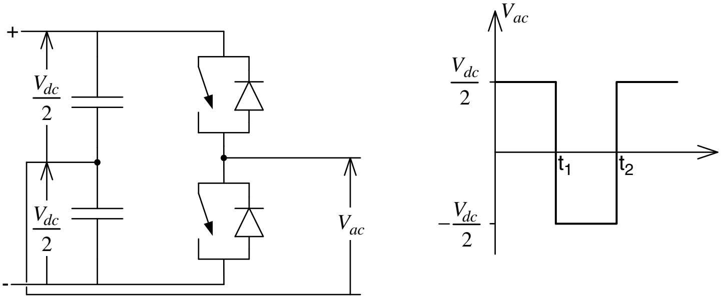

Figure 2.1 Two-level single phase voltage source converter. (Reproduced by permission of CIGRE.)

Since the conduction in a solid state switch is unidirectional, an anti-parallel diode needs to be connected across to form a switch pair, to ensure that the bridge voltage only has one polarity, while the current can flow through the pair in both directions.

When the two main switches are blocked, the anti-parallel diodes form an uncontrolled rectifier. In this condition the application of an external AC voltage charges the DC upper and lower capacitors, via the uncontrolled rectifiers, to the peak value of the AC voltage connected across them. Once the DC capacitor is charged and the external source connected, the voltage source converter is ready for operation.

The main switches can be switched on and off in any desired pattern; however, immediately before one switch is turned on, the opposite switch must be turned off, as their simultaneous conduction would create a short circuit of the DC capacitors. This action causes a small blanking period (of a few microseconds) where none of the switches are on and the current path is via the freewheeling diodes. To explain this condition let us start at a point, after $t = 0$ in Figure 2.1, where the upper switch is on and, thus, the AC terminal is connected to the plus terminal of the DC capacitors via the main switch and freewheeling diode pair; this allows the current to flow through the pair in either direction.

When the upper switch is turned off (at instant t_1), the reactance of the AC circuit maintains its present current and the diodes in parallel with the upper and lower switches provide the current path. If the current in the upper pair at instant t_1 is from the plus terminal of the DC capacitors to the AC terminal, the lower freewheeling diode turns on, and thus the AC output voltage changes from plus to minus $V_{dc}/2$, i.e. the polarity reversal has been initiated by