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Introduction

In this chapter, an overview of soft-switching technology for three-phase power electronics converters and its evolution are briefly introduced, and the challenges and trends in the soft-switching three-phase converters are discussed.

1.1 Requirement of Three-phase Power Conversions

Three-phase converters are widely used as grid connecting inverters for renewable energy systems, rectifiers, or inverters for uninterruptible power supply (UPS) for data centers, rectifiers for electrical vehicle (EV) fast charging stations, inverters for EV, inverters for industrial motor drives, etc. For these applications, power flow is quickly and accurately controlled because the power converter is composed of power semiconductor devices, which can be turn on or off within less than a microsecond. With the application of the converters, we can realize high efficiency power conversion between sources and loads or vice versa. In addition, if a converter system operates at high frequency, its volume or weight is reduced due to size reduction of passive components such as inductors, capacitor, electric motors, etc. The higher the switching frequency, the smaller are the passive components. Thus the power density, processing power per liter, of the converter is increased [1, 2]. In addition, the dynamics of converter systems are enhanced with increased switching frequency.

1.1.1 Three-phase Converters

Three-phase converters are used as either grid converters to connect the utility or inverters to drive a motor or supply high-quality alternating current (AC) power to the load as shown in Figure 1.1. When a grid converter is used to convert the utility AC voltage into direct current (DC) voltage, it is usually called a rectifier. When it converts DC voltage to the grid AC voltage, it is usually called an inverter. Actually, it is the same entity, but it has two names. It is sometimes confusing for new learners. In most applications such as battery storage systems, the grid converter is required to control power flow bidirectionally. It can operate in either rectifier mode or inverter mode according to the system requirement. When a three-phase converter is used to drive a motor or supply AC power to a load, it is usually called as an inverter since it converts the DC bus voltage into three-phase AC voltages. In the book, a general name "converter" is used, which covers names such as rectifier, inverter, bidirectional converter that swaps between the inverter mode and the rectifier mode according to operation requirement.

Soft-Switching Technology for Three-phase Power Electronics Converters, First Edition.
Dehong Xu, Rui Li, Ning He, Jinyi Deng, and Yuying Wu.

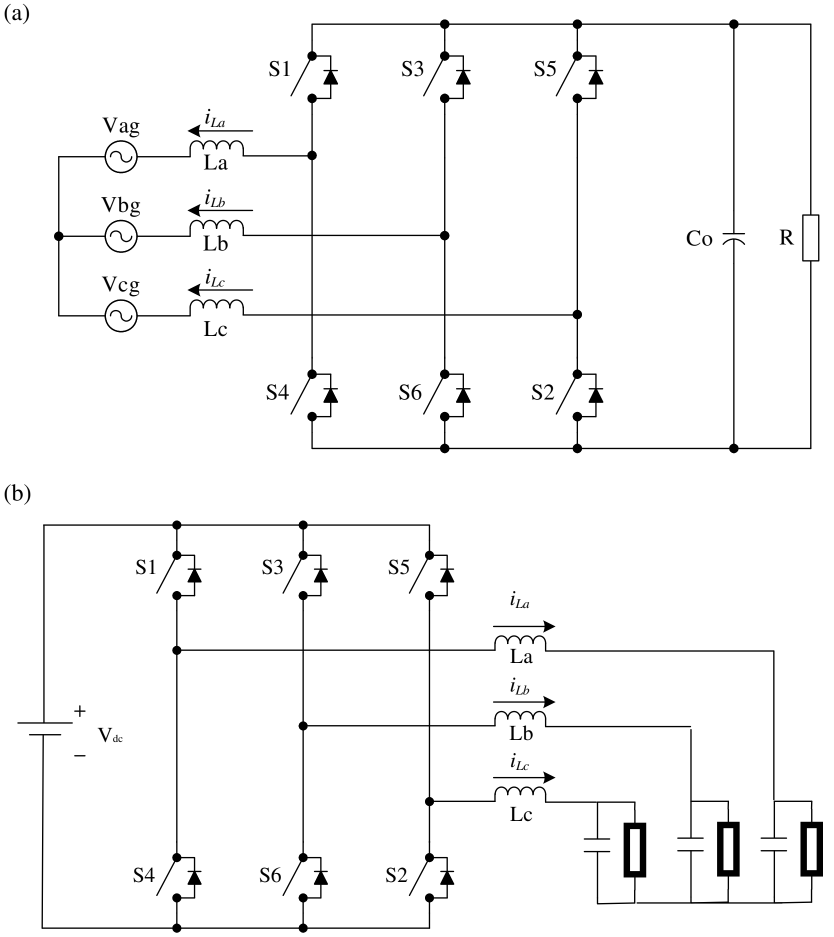


Figure 1.1 Three-phase converters: (a) grid converters; (b) inverter.

The three-phase converter is one of the most important power conversion building blocks in power electronic systems. It is widely used in various applications due to its distinct advantages as follows:

- It has the simplest converter topology that can realize DC/AC or AC/DC conversions with minimum number of power switches. It has lower cost.
- It has lower voltage stress on the power devices because the maximum voltage on them is capped by the DC bus. It has lower current stress on the device for AC loads/sources to operate at current continuous mode (CCM).
- There are well-established pulse-width-modulation (PWM) control methods such as sinusoidal PWM (SPWM), third harmonics injected SPWM, space vector modulation (SVM), etc.
- It has well-established system control methods for the converter under *abc* static frame, *αβ* static frame, and *dq* synchronous rotating frame.

Because of these advantages, the three-phase converters have been used almost everywhere from low power to high power such as disk drives, inverters for pumps, inverters for EV, drive inverters for bullet trains, solar inverters, wind turbines, UPS, etc. For these applications, there is an ever increasing demand for the performance of the converter. In addition to basic functions such as AC to DC or DC to AC conversion and output power quality, following demands are critical for the converter.

First, it is expected that the converter has higher efficiency, which has become a more stringent requirement than ever before due to increasing public concern of impact of energy consumption on the environment. Besides, high efficiency can also bring economic benefits to the users. A Photovoltaic (PV) inverter with high efficiency can harvest more electricity and also improves the utilization of the PV panel. A UPS with high efficiency can save the operating cost of data centers. It also can reduce the footprint of the power supply due to lower energy loss. An EV power train with high efficiency increases the utilization of the kWh of the battery and extends mileage at the same time.

Second, we hope that the converter has small size. It is especially critical for moving vehicles such as electric vehicles, electric railway, boats, and airplanes or aerospace applications. Smaller size means less use of material, copper, iron, isolation material, etc., which cuts down the cost. For users, it can reduce space, which is expensive in many large cities. Usually, you may hear the word *power density*. It means the ratio of power capacity to the volume or weight of the converter. It represents the ability of a converter to process the power at a given size. For a given power capacity of a converter, the higher the power density, the smaller is the size of the converter.

Third, the converter is required to have good dynamics. The dynamics of a converter mainly depends on bandwidth of the close loop control systems. It is mainly constrained by the switching frequency of the converter. Generally speaking, power electronic converters have high dynamics since they use power semiconductor devices as the switch. In many applications such as ultra-high-speed pumps and compressors in industrial applications, power generation for aeronautics, EV, etc., it is required that the converter drives the motor to reach ultra-high speed from tens to hundreds of thousands rpm. In some applications such as moving vehicles, the size of the electric machines can be reduced by increasing their operating frequency. To increase the fundamental frequency of the converter, it is natural to increase switching frequency. What is the limit of the switching? We will discuss it in detail later.

Another demand is lower cost. The cost of a converter or a converter system should be optimized. A converter system is generally composed of power semiconductor devices and passive components. Size of the passive components depends on operating frequency. If we can increase the frequency, their size can be reduced.

Actually, switching frequency is a critical parameter for the converter. It plays an important role in efficiency, power density, dynamics, and cost reduction.

1.1.2 Switching Frequency vs. Conversion Efficiency and Power Density

In this section, we will discuss the effects of the switching frequency on the converter. First, an inverter used for UPS is taken as an example. The main circuit of UPS is back to back (BTB) converter as shown in Figure 1.2. It is composed of three-phase grid converter as the rectifier cascaded with a three-phase converter as the inverter to provide high-quality power to the load. To satisfy the load requirement, output voltage of UPS needs to be an almost sinusoidal waveform. Its output voltage quality is usually described by total harmonic distortion (THD). Filters are installed in load sides. In addition, to satisfy the grid standard, filters in utility side are also installed. Filter cost ranges from 15 to 30% of total material expenditure in the UPS (excluding the battery cost). Besides, it also occupies a large footprint. Size of the passive components depends on operating switching frequency. If we can increase the switching frequency, their size will be reduced.

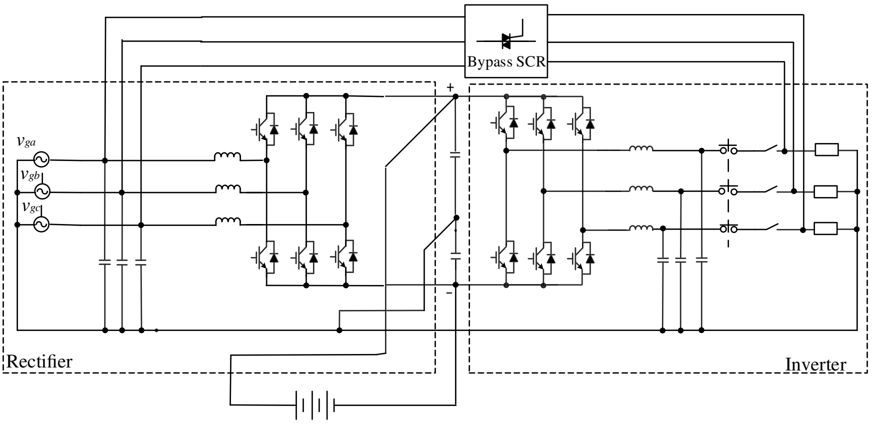


Figure 1.2 Circuit diagram of UPS.

It is assumed that a UPS equipment has rated power 100 kVA at load power factor PF = 0.8. Both the input grid phase voltage and output phase voltage are 220 Vrms. Internal DC bus voltage is 750 Vdc. THD of output voltages is less than 5%. Inductor-capacitor filters are used to improve output voltage waveform. The filter inductors are designed with amorphous core, and their maximum magnetic flux density is Bmax = 1.2 T.

According to the aforementioned assumption, filter inductance of the output converter is designed with different switching frequency as shown in Figure 1.3a. It is observed that the filter inductance decreases with an increase in the switching frequency. Similarly, the size of the filter inductor is also reduced with an increase in the switching frequency as shown in Figure 1.3b. The shaded bar shows the weight of the magnetic core of the filter. The blank bar shows the weight of the copper winding of the filter. The weight of the inductor is reduced about to one of the fifth by increasing switching frequency from 10 to 100 kHz. Figure 1.3c shows total loss of three output filter inductors vs. the switching frequency. The inductor loss also decreases with an increase in the switching frequency. It is because we use a smaller inductance when the switching frequency is higher. A smaller inductance means it has short length of winding so that copper loss is reduced. A smaller inductance needs a smaller core, whose loss depends on its magnetic core volume for a given maximum magnetic flux density. The smaller the core, the smaller the core loss. Thus, a small inductance results in both smaller copper loss and core loss. As a result, with an increase in the switching frequency, both the filter inductor size and loss decrease. Cost of the filter inductor is also cut down. It seems that it is better to design the UPS at higher switching frequency. Unfortunately, there is a switching frequency limit due to the loss of the power semiconductor devices in UPS. It will be discussed later.

Now an inverter used for power trains of electric vehicles is investigated. The main circuit of power train is shown in Figure 1.4. It is composed of battery, film capacitor, three-phase switch bridge and motor. Power density is critical for the power train. The film capacitor C_{dc} occupies a large footprint. To suppress voltage ripple on the battery to a certain value, following capacitance is required [3]:

$$C_{dc} = \frac{3\sqrt{3}I_0 \cos(\varphi)}{16 f_s \Delta V_{dc}} \tag{1.1}$$

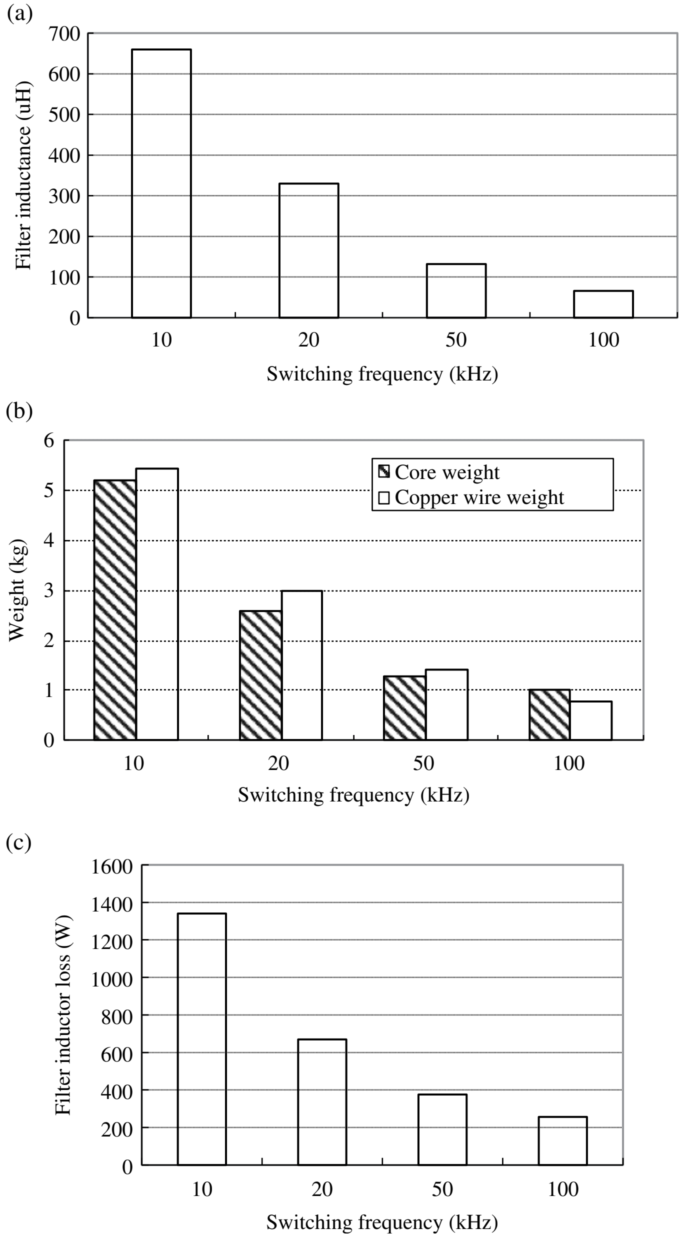


Figure 1.3 Filter inductance, weight and loss vs. switching frequency. (a) Filter inductance vs. fs. (b) Weight of each filter inductor vs. fs. (c) Total loss of three filter inductors vs. fs.

where I_o is output phase current (rms value), $\cos(\varphi)$ is load power factor, f_s is switching frequency, and ΔV_{dc} is maximum DC voltage ripple allowed on the battery. It is observed that the required DC bus capacitance is inversely proportional to switching frequency f_s.

It is assumed that DC bus voltage V_{dc} is 320 V, the inverter power is 120 kW, load current is 400 A, power factor of the motor is 0.93, and maximum DC voltage ripple allowed on the battery $\Delta V_{dc} = 32$ V.

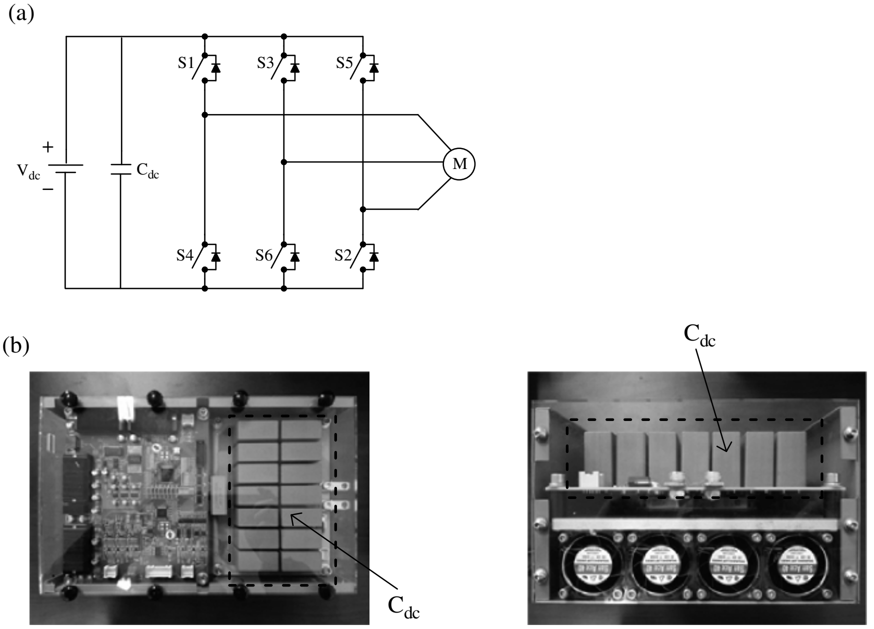


Figure 1.4 Power trains of electric vehicles: (a) circuit of power trains; (b) air-cooled 34 kW inverter for battery EV.

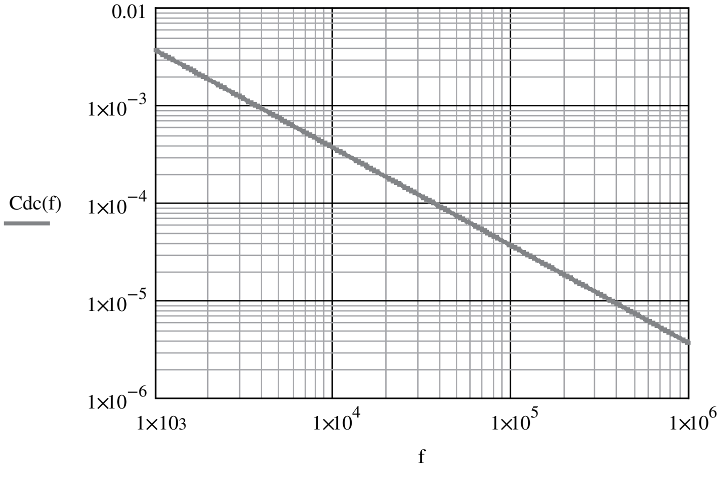


Figure 1.5 DC side capacitance vs. switching frequency.

The relationship between the DC side capacitance and the switching frequency is shown in Figure 1.5. The capacitance is reduced to one of the tenth if the switching is increased by ten times. Therefore, the DC side film can be reduced if we can increase the switching frequency. It is helpful to increase the power density of the power train of the EV. Similar to the discussion earlier, there is an upper limit to the switching frequency due to the loss of the power semiconductor devices in the power train.

1.1.3 Switching Frequency and Impact of Soft-switching Technology

As we mentioned earlier, if the inverter operates at higher switching frequency, the inverter will have smaller filter size and smaller loss on the filter in UPS and smaller DC-side film capacitor in EV power train. In addition, we can get better dynamics. In some applications of ultra-high-speed drives for the industry or aeronautics, inverters are required to operate at very high switching frequency to provide lower ripple fundamental frequency current to the motor/generators. It seems higher switching frequency operating has advantage. What is the maximum switching frequency the inverter can operate at?

Actually, the switching frequency is limited by loss of the power semiconductor devices in the inverter. Figure 1.6 shows loss of the power semiconductor switches of the inverter of 100 kVA UPS exampled in the last section. Typical Insulated Gate Bipolar Transistor (IGBT) devices (Si IGBT FF300R12KT) are used as the switches. The loss of the inverter power semiconductor devices is composed of conduction loss, turn-on loss, turn-off loss, and reverse recovery loss. Conduction loss is static loss, which does not change with the switching frequency shown as the black part of the bar at the bottom of the figure. The other three losses – turn-on loss, turn-off loss, and reverse recovery loss – are dynamic losses, which increase linearly with the switching frequency as shown in the figure. As a result the dynamic loss of the power device depends on the switching frequency. If we want to design the inverter with required efficiency, its maximum switching frequency should be restricted to constrain total power device loss to certain value. Dynamic loss has another commonly used name: switching loss. It means the loss is caused by the device switching actions, either turning on or turning off.

For the same inverter parameters, when SiC MOSFET (CAS300M12BM2) is used, total SiC MOSFET loss of the inverter vs. the switching frequency is shown in Figure 1.7. Since the recovery loss is smaller, it is ignored. The loss of the inverter power semiconductor devices is composed of conduction loss, turn-on loss, and turn-off loss. Similar to the IGBT inverter, the conduction loss is constant while the dynamic loss is proportional to the switching frequency. Although the power device loss of the SiC inverter loss is much smaller than that of the IGBT inverter, the dynamic loss is still the main factor to limit the upper switching frequency.

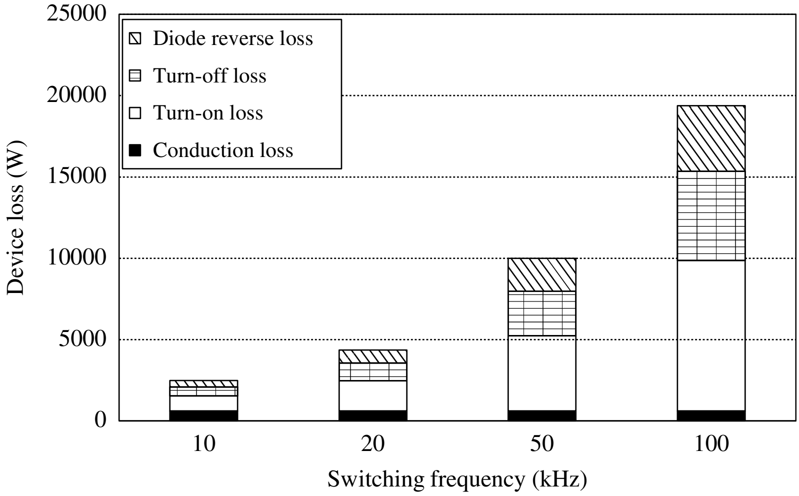


Figure 1.6 Power semiconductor loss of the inverter vs. switching frequency.

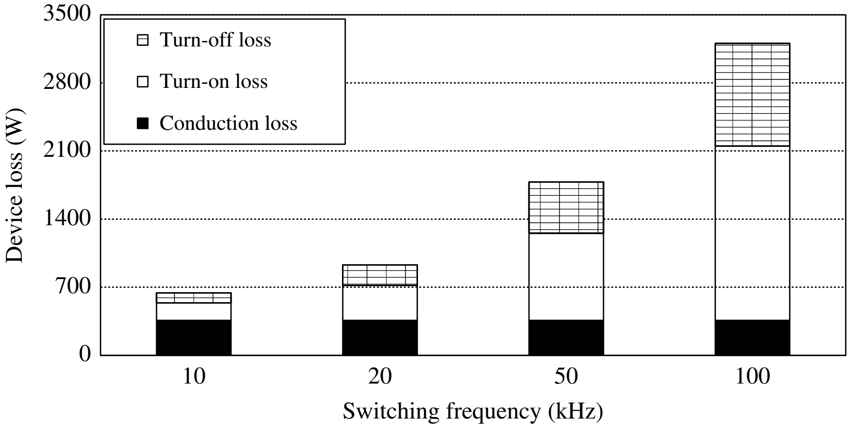


Figure 1.7 Total SiC MOSFET loss of the inverter vs. switching frequency.

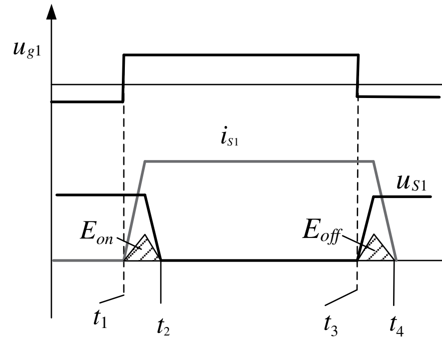
As a result, conducting loss is almost constant while switching loss increases with switching frequency. Actually, the voltage and the current of the power device have an overlap time during the switching transient process, which causes switching losses. The average switching loss is proportional to the switching frequency. To get an expected conversion efficiency, the switching frequency of inverters needs to be restricted. This type of converter is called hard-switching converter. Hard-switching converters can operate only at lower switching frequency. Lower switching frequency operation in turn results in bulkier passive components and higher audible noise. The wall to prevent the switching frequency from increasing is due to the switching loss. Can we reduce the switch loss of the inverter so that it can operate at higher switching frequency? To realize this goal, a technology to shape voltage and current of the power device during switching transient process, known as soft-switching, occurs. Before a power device in a converter changes its status, either from on-state to off-state or from off-sate to on-state, the voltage across it or the current through it is set to zero with the help of the resonance between inductance and capacitance in the circuit. Soft-switching is able to reduce the switching loss of the power semiconductor devices so that the converter can operate at higher switching frequency.

1.2 Concept of Soft-switching Technique

A power device undergoes a switching transient process during its turn-on as shown in Figure 1.8. From time t_1 to t_2, both voltage u_{S1} across the device S_1 and current i_{S1} through it have high values during turn-on transient process. The voltage and current overlap on the device occurs during switch turn-on process, which results in turn-on loss. The turn-on loss E_{on} is equal to integral of multiplication of the voltage u_{S1} across the device S_1 and the current i_{S1} through it in the turn-on transient duration. Similarly, when the device turns off, it also undergoes a turn-off transient process. The voltage and current overlap on the device occurs in the switch turn-off process, which results in turn-off loss E_{off}.

To reduce the turn-on and turn-off loss of the power device, soft-switching techniques occur. The soft-switching technique is a way to shape voltage and current of the power device during switching transient process by changing converter topology and/or introducing a unique control. Thus the

Figure 1.8 Typical switching waveforms of a power device.



overlapping of voltage and current on the power device during switching commutations is reduced. It not only reduces switching loss but also suppresses voltage stress on the power devices and electromagnetic interference (EMI) noise.

1.2.1 Soft-switching Types

Soft-switching techniques are realized with innovated converter topologies and/or by introducing a unique control. There are many soft-switching converter topologies and their control methods. Soft-switching techniques can be summarized as four types as follows.

Zero-Voltage-Switching Turn-on (ZVS-on): During a power semiconductor device turn-on process, voltage applied on the power device decreases almost to zero before the gate drive signal jumps to the high level for turning on the device. Thus the voltage and current overlapping of the device during turn-on transient process is eliminated. As shown in Figure 1.9, voltage u_{S1} on the device S_1 is set to zero before its gate drive signal u_{g1} goes to the high level. Typically, a diode is antiparalleled with device S_1. Once voltage u_{S1} on the device S_1 decreases to zero, the antiparalleled diode D_1 will conduct. It creates zero voltage turn-on condition for the device S_1. Thus the overlapping of voltage and current of the power device during turn-on process is got rid of. The integral of multiplication of u_{S1} and i_{S1} during turn-on process becomes zero. Thus turn-on loss of the device is avoided. ZVS-on is ideal turn-on process since it has no turn-on loss.

Zero-Current-Switching Turn-on (ZCS-on): During a power device turn-on process, its current gradually increases from zero value while its voltage quickly goes down. Thus the voltage and current overlapping of the device during turn-on transient process is reduced. As shown in Figure 1.10, when gate drive signal steps up, the current i_{S1} of the device gradually increases from zero value while the voltage quickly goes down. Typically, there is external inductor serially connected with the power device, which creates zero current turn-on condition for the device S_1. Thus the

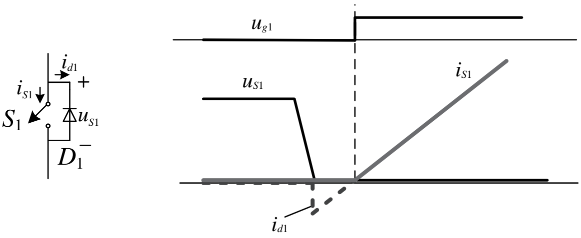


Figure 1.9 Zero-voltage-switching turn-on.

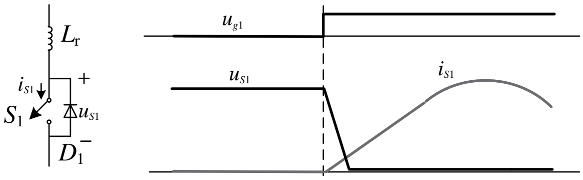


Figure 1.10 Zero-current-switching turn-on.

overlapping of voltage and current of the power device during turn-on process is reduced. The integral of multiplication of u_{S1} and i_{S1} during turn-on duration becomes smaller than that of the hard switch. Thus turn-on loss of the device is reduced. However, ZCS-on is not ideal turn-on process because turn-on loss still exists. It still has the overlapping of the voltage and current in turn-on transient process.

Zero-Voltage-Switching Turn-off (ZVS-off): During a power device turn-off process, its voltage gradually increases from zero value while its current quickly goes down. Thus the voltage and current overlapping of the device during turn-off transient process is reduced. As shown in Figure 1.11, when gate drive signal steps down for turning off the device, the voltage u_{S1} of the device gradually increases from zero while the current i_{S1} quickly goes down. Typically, there is capacitance paralleled with the power device, which suppresses the voltage increasing rate when the device turns off. Thus the overlapping of voltage and current of the power device during turn-off process is reduced. The integral of multiplication of u_{S1} and i_{S1} during turn-off process becomes smaller. Thus turn-off loss of the device is reduced. However, ZVS-off is also not ideal. There still exists turn-off loss.

Zero-Current-Switching Turn-off (ZCS-off): Current through a power device already decreases to zero before the gate drive signal steps down to the lower level for turning off the device. Thus the voltage and current overlapping of the device during turn-off transient process is eliminated. As shown in Figure 1.12, current i_{S1} through the power device S_1 is set to zero before its gate drive signal u_{g1} goes to the low level for turning off the device. Typically, there is an external inductor or L-C resonance branch serially connected with the power device S_1, which causes the current of the device S_1 decrease to zero automatically before the turn-off signal is applied to the gate drive.

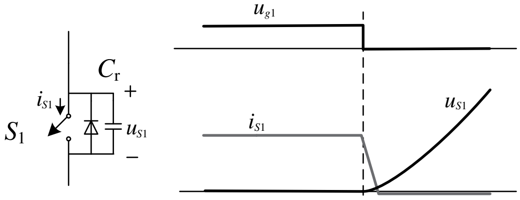


Figure 1.11 Zero-voltage-switching turn-off.

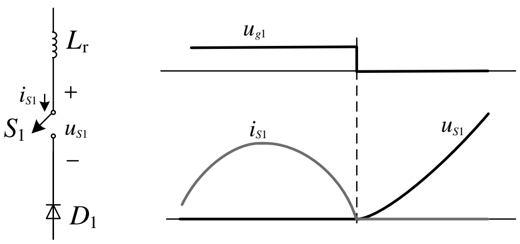


Figure 1.12 Zero-current-switching turn-off.

Thus the overlapping of voltage and current of the power device during turn-off process is eliminated. The integral of multiplication of u_{S1} and i_{S1} in turn-off duration becomes zero. Thus turn-off loss of the device is avoided. ZCS-off is ideal turn-off. There is no turn-off loss.

Among the four soft-switching techniques mentioned earlier, two methods, ZVS-on and ZCS-on, are used for turn-on loss reduction while other two, ZVS-off and ZCS-off, are used for turn-off loss reduction. ZVS-on and ZCS-off are ideal and can totally eliminate the switching loss. However, ZCS-on and ZVS-off are not ideal. They reduce switching loss, but the switching loss still exists.

1.2.2 Soft-switching Technique for Three-phase Converters

Soft-switching techniques for three-phase converters have been investigated by many predecessors. For three-phase applications, soft-switching converters can be divided into three classes: DC resonance converter, AC resonance converter, and soft-switching converters with triangular current mode (TCM) control [4].

In the DC-side resonance converters, an auxiliary resonant circuit is installed between DC input source and DC side of three-phase switch bridge of the converter. The fundamental philosophy of the DC-side resonance is to use an auxiliary resonant circuit to create zero-voltage duration at the DC side of the three-phase switch bridge at the desired switching instant. Thus all devices of the switch bridge are turned on or turned off when the voltage on them is equal to zero so that both turn-on loss and turn-off loss are significantly reduced. Besides, the DC-side resonance converter only needs one auxiliary resonant circuit regardless of the number of AC phases of the converter. This simple structure makes DC-side resonance attractive in multiphase converter applications. The resonant DC link (RDCL) converter [5] is milestone topology in evolution of soft-switching history. To reduce voltage stress on the devices, a revised version known as active clamped RDCL (ACRDCL) converter occurred [6, 7]. Both RDCL and ACRDCL converters are controlled with discrete pulse modulation (DPM). It is found that the soft-switching converters with DPM require higher switching frequency than that of the PWM converter for comparable current spectral performance. Many other topologies have been developed such as the quasi-resonant DC link (QRDCL) PWM inverter with PWM control [8–11]. They often use more complex auxiliary circuit. Zero-voltage-switching SVM (ZVS-SVM) for three-phase active clamping converters was proposed by Dehong Xu [13, 14]. The auxiliary power device only switches once in each switching cycle to realize ZVS for all the switches. It features fixed switching frequency and lower voltage stress of the power switch devices. The converter basically operates like PWM converter [15, 16]. Afterward it is generalized to edge-aligned PWM (EA-PWM) [17–19]. EA-PWM is suitable to three-phase converter, three-phase four-wire converter, three-phase four-wire BTB converter, etc.

The second class of the soft-switching converter is AC resonance converters. Auxiliary resonant circuits are installed in AC side of the switch bridge. Distinctive advantage of the AC-side resonance is that the auxiliary circuits are in shunt with the switch bridge and does not carry the load current. Thus the conduction loss in the auxiliary circuits is smaller. In addition, SPWM and SVM control can be applied because the converters basically operate as conventional PWM converters. Auxiliary resonant commutated pole (ARCP) converter is one of the earliest AC resonance converters [12, 20]. It achieves ZVS-on for main switches and ZCS-off for auxiliary switches. The inductor coupled zero-voltage transition (ZVT) inverter achieves ZVS-on for main switches and near-zero current turn off for auxiliary switches [21]. DC-side split capacitor voltage control needed for ARCP converter is avoided. The zero-current transition (ZCT) inverter achieves zero current switching for all of the main and auxiliary switches and their antiparallel diodes [22, 23]. It is suitable to converters with IGBT devices, which can reduce turn-off loss of IGBT due to its tail current. Other AC resonance circuits are developed [24–27]. The AC resonance converter has complex circuit because it generally needs three auxiliary resonant circuits. The number of power devices to be controlled are almost doubled in comparison to the original converter.

The third class of the soft-switching converter is known as the soft-switching converters with TCM. The concept comes from critical conduction mode (CRM) in DC-DC converter to achieve ZVS-on [28, 29]. With TCM control, AC-side filter inductor currents of three-phase converters are controlled as the triangle waveform in a switching period [30, 31]. TCM is originally introduced to single-phase totem-pole power factor correction (PFC) converters and then extended to three-phase converters. The distinct advantage of the soft-switching converter with TCM is that no auxiliary resonant circuit is needed. However, there are some drawbacks such as wider range of variable switching frequency, higher rms current, and turn-off current. Recently, there are many studies about TCM control. For readers interested in this research can read the related references on IEEE Xplore.

As mentioned earlier, the DC-side resonance converter only needs one auxiliary resonant circuit shared by three-phase legs of the converter. It has issues such as variable switching frequency, higher voltage stress on devices, etc. To overcome these drawbacks, the ZVS-SVM and EA-PWM for three-phase active clamping converters were proposed. The auxiliary power device only switches once in each switching cycle to realize ZVS for all the switches. It features fixed switching frequency and lower voltage stress of the power switch devices. The converter basically operates like the conventional PWM converter.

As an example of the soft-switching technique, the concept of three-phase active clamping converters with EA-PWM is briefly explained. With EA-PWM, the converter operates at the fixed switching frequency. An auxiliary circuit with auxiliary switch S_7 is installed in the DC side of the converter in Figure 1.13a. Once a high loss switch commutations in the switch bridge happens, the auxiliary switch S_7 will turn off, which starts a resonant process to create a slot with duration $\lambda_7 T_S$ on the DC bus voltage waveform v_{bus} where λ_7 is the turn-off duty ratio of the auxiliary switch S_7 and T_S is the switching period in Figure 1.13b. During $v_{bus} = 0$, the switches in the three-phase switch bridge make the commutation under zero voltage on their terminals, which is known as zero voltage switching. Thus the switching loss is reduced. With EA-PWM, all high loss commutations of the switch bridge in each switch cycle are synchronized. The auxiliary power device only switches once in a switching cycle to realize ZVS for all the switches. More detailed introduction will be given in Chapter 3.

1.3 Applications of Soft-switching to Three-phase Converters

1.3.1 Renewable Energy and Power Generation

The increasing applications of renewable energy and distributed power generation have become a new driving force for application of power electronics. Three-phase converters are playing more and more important role in the grid. More efficient and more reliable power converters are required. Soft-switching technique can be applied to converters for renewable energy integration, energy storage systems, and Flexible AC power transmission (FACTS) devices to increase power density and dynamics and reduce size of the equipment [32].

A single-phase PV inverter is widely used for residential PV applications as shown in Figure 1.14. The front boost converter is used to extend solar energy harvesting duration each day so that the inverter can feed power to grid with a wider PV panel output voltage. By introducing an auxiliary

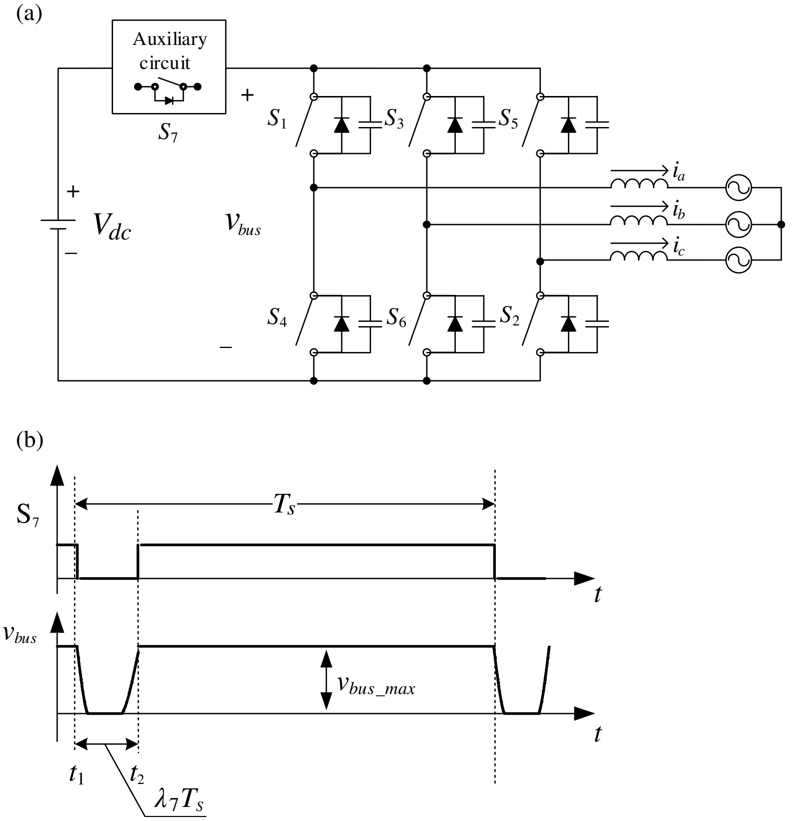


Figure 1.13 Active clamping converters: (a) circuit; (b) auxiliary switch state and DC bus voltage.

resonant circuit and EA-PWM control, both the boost stage and the H-bridge inverter stage can realize soft-switching operation. Due to the soft-switching, the switching frequency is increased so that passives such as inductors and capacitors may be reduced. The PV inverter becomes more compact.

Three-phase PV inverters are widely used in medium power or large power PV power generation systems. Six switch inverter circuits are commonly used due to their circuit simplicity. To reduce its switch loss, an auxiliary resonant circuit is introduced in the DC side of the converter as shown in Figure 1.15. The soft-switching SiC MOSFET grid inverter achieves a high efficiency of 98.6% at 300 kHz switching frequency, which is about three times of the original hard-switching counterpart with the same conversion efficiency [33]. Thus the inverter becomes more compact due to small passives. Besides, EMI noise caused by high dv/dt of SiC MOSFET is relieved due to the soft-switching.

Another circuit used in distributed PV generation systems is the string inverter [17]. The string inverter is basically composed of two conversion stages: the DC-DC and DC-AC stages. The DC-DC stage is adopted to extend the PV voltage operation region and harvest more solar energy as mentioned before. It usually has multiple DC-DC boost converters, as shown in Figure 1.16, which are connected in parallel to increase the maximum power point tracking (MPPT) efficiency and power capacity as well. By introducing the soft-switching technique, higher power conversion and higher power density can be obtained.

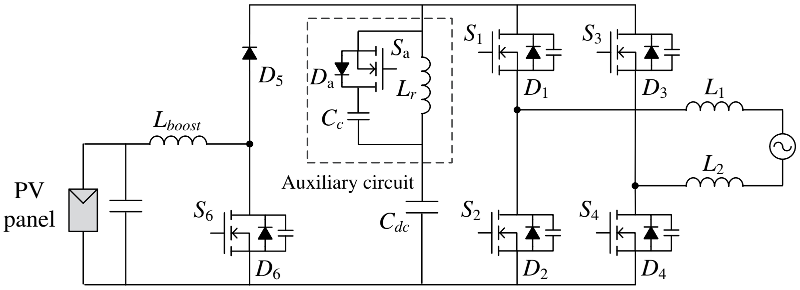


Figure 1.14 Single-phase PV inverter for residential applications.

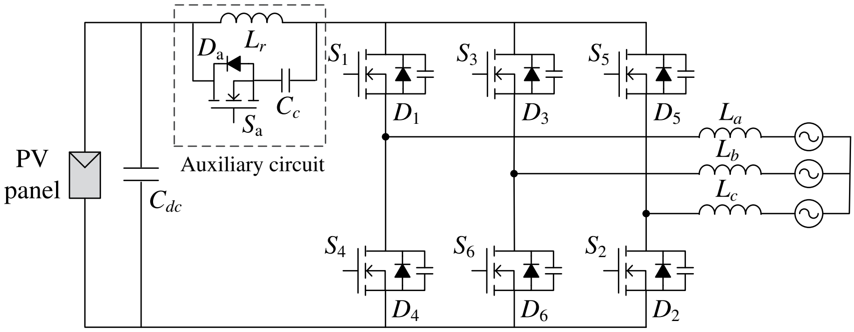


Figure 1.15 Three-phase ZVS PV inverter.

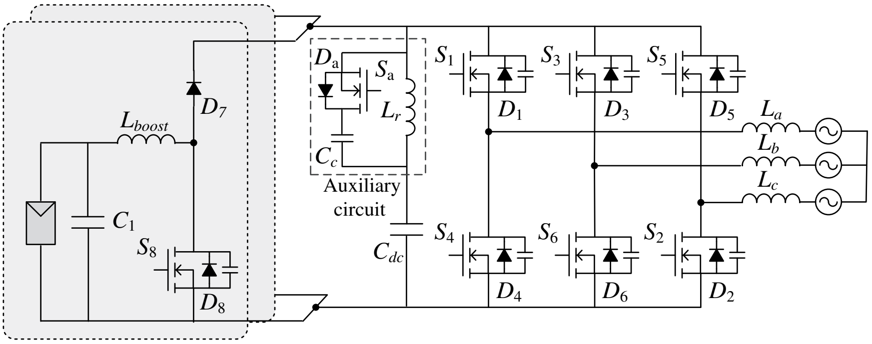


Figure 1.16 Two-stage three-phase ZVS inverter for PV system.

Similar to PV inverters, the soft-switching technique can also be applied to wind power systems. Two most popular wind power conversion systems (PCSs) are doubly fed induction generator (DFIG) and permanent magnet synchronous generator (PMSG). Both of them utilize a BTB converter to interface the grid side. The BTB converter for the PMSG system with the soft-switching technique is shown in Figure 1.17. In a typical wind power system, the entire power converter is packed in a cabinet and placed in a nacelle with limited space. The soft-switching BTB converter operates with higher switching frequency so that the volume and weight of the passive components can be significantly reduced. The reduced size and weight of the power converter can spare more

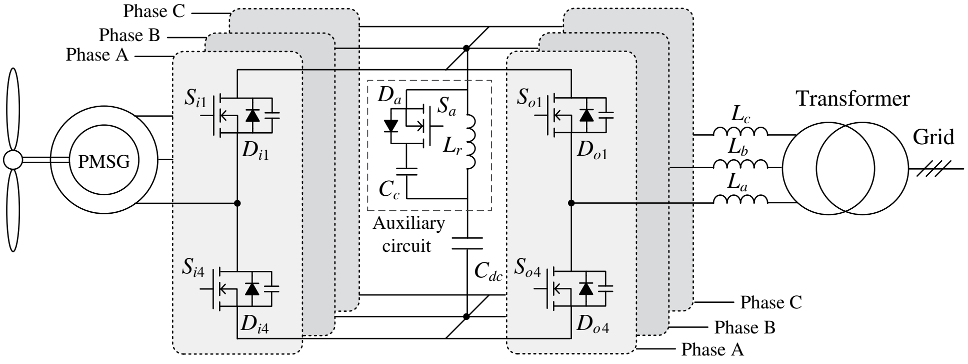


Figure 1.17 ZVS back-to-back converter for PMSG system.

room in the nacelle. Thus a step-up transformer can be accommodated in the nacelle to reduce the cable cost and energy losses.

1.3.2 Energy Storage Systems

Energy storage systems have become a key enabling technology for a robust, high efficiency, and cost-effective power grid. Grid level energy storage systems are used in frequency regulation, spinning reserve, peak load shaving, load leveling, and so on. Besides, energy storage systems are also introduced in distributed systems to stabilize the power output of renewable energy. The converter is the interface to connect the energy storage component with the grid. Energy storage systems require a bidirectional power flow control such as the battery energy storage system (BESS). The energy loss is also doubled during the whole energy utilization cycle by charging and discharging the energy storage component. Therefore the efficiency of the converter becomes more critical than that of the unidirectional converters. The soft-switching technique has a potential in the energy storage applications.

The PCS for the BESS can be divided into single-stage and double-stage structures. For the single-stage PCS, the battery voltage should not fluctuate widely during the discharging or charging process, which is typically related to the characteristics of the battery technology. The soft-switching technique can be applied as PV inverters, as shown in Figure 1.18. To extend the system power capacity and improve fault tolerance, a PCS structure with paralleled three-phase converters is adopted as shown in Figure 1.18. An auxiliary resonant circuit is installed in the common DC bus. Both converters can realize the ZVS operation with EA-PWM.

The double-stage PCS consists of a bidirectional DC/DC conversion stage and a DC/AC stage as shown in Figure 1.19. The DC/DC stage boosts the battery voltage to the suitable level so that the inverter stage can be directly interfaced to the grid. This type of PCS is suitable for maximum utilization of the battery stored energy, whose voltage has a wider variation during the entire SOC. With the ZVS auxiliary circuit, it can realize soft-switching for both DC/DC stage and DC/AC stage.

The double-stage interface has the advantage of a common DC bus line. Different energy storage units can be integrated into the system, which makes the system more expandable and fault tolerant. Figure 1.20 shows the diagram of the double-stage interface with two boost converters interfacing to the fuel cell and super-capacitor, respectively. All power devices can realize ZVS operation with only one auxiliary circuit in the middle DC link. Further extension to multiple energy sources system is shown in Figure 1.21 where various types of energy storage components are integrated by

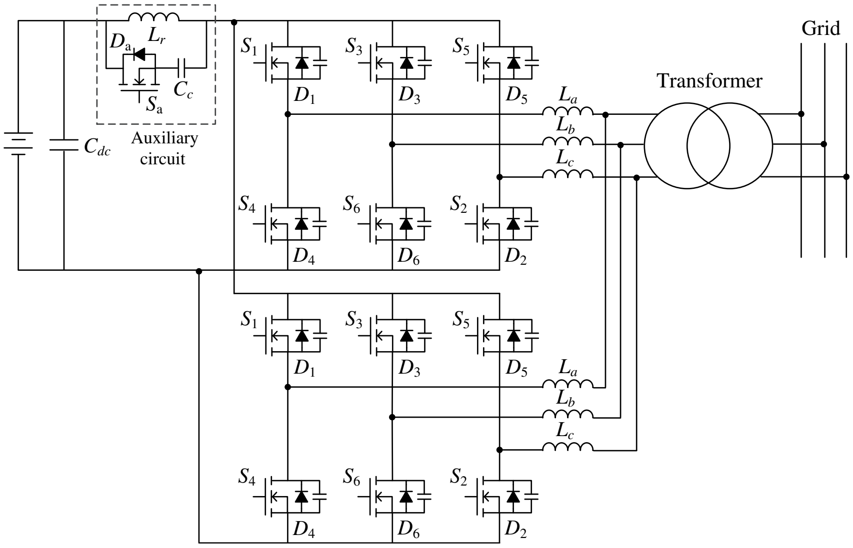


Figure 1.18 Paralleled three-phase ZVS inverter for BESS.

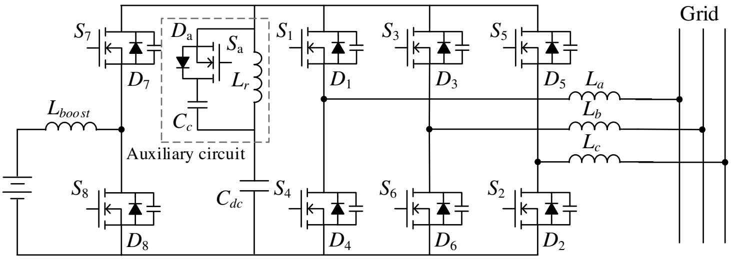


Figure 1.19 ZVS inverter with front boost stage for BESS.

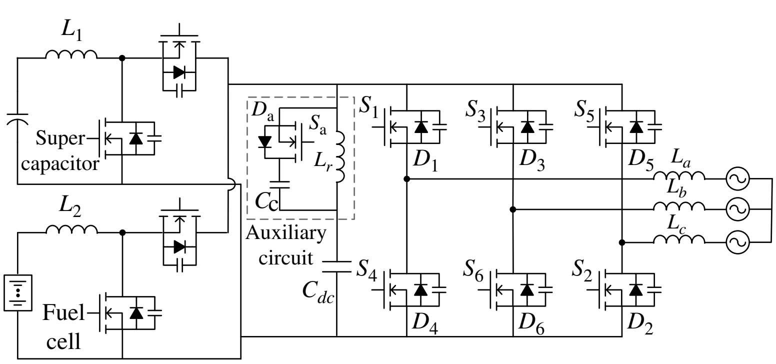


Figure 1.20 ZVS inverter with paralleled DC/DC converters for BESS.

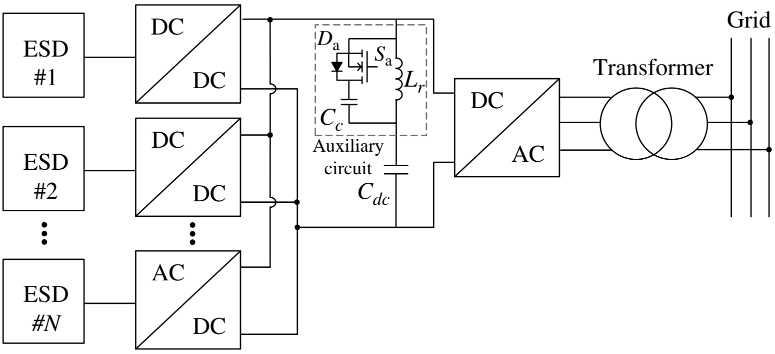


Figure 1.21 Multiple energy storage system with ZVS converters.

bidirectional DC/DC converter to the DC bus with only one auxiliary resonant circuit. All the converters connected to the DC bus can realize the soft-switching operation with only one auxiliary resonant circuit.

1.3.3 Distributed FACTS Devices

Distributed FACTS devices are used to improve reliability, power quality, and efficiency of the distributed systems. It includes static var compensators (STATCOMs), active power filter (APF), unified power flow controller (UPFC), unified power quality controller (UPQC), dynamic voltage restorer (DVR), etc.

A shunt APF is usually installed near the nonlinear load for the compensation of the harmonic current generated by the nonlinear load. The power converter can operate with higher switching frequency with soft-switching technique. Higher switching frequency means the APF has better dynamics and precisely cancel harmonic of the nonlinear load. Figure 1.22 shows soft-switching APF. The same topology can also be utilized in STATCOM.

DVR can stabilize voltage of the utility to loads. It also benefits from the application of the soft-switching technique with regard to fast control response and reduced system size. Figure 1.23 shows a DVR using the soft-switching technique.

The UPQC combines the functions of the shunt var compensation and series var compensation. It consists of two BTB connected converters shown in Figure 1.24. The one converter is connected in series with the grid while the other is connected in parallel with the grid. Each converter can generate reactive power at its own AC output terminal. By inserting the auxiliary circuit in the middle DC link, both converters can realize ZVS operation. The dynamics or power density of the UPQC are enhanced since the switching frequency is increased due to the soft-switching.

1.3.4 Uninterruptible Power Supply

Uninterruptible power supply (UPS) is widely used in data centers and manufacturing processes to provide continuous and higher quality power. UPS is composed of the rectifier, inverter, and neutral line control half-bridge. Totally there are seven switch legs. By installing an auxiliary resonant circuit in the DC side as shown in Figure 1.25, all switches in these seven switching legs can realize soft-switching. Thus the power density of the UPS can be enhanced [19].

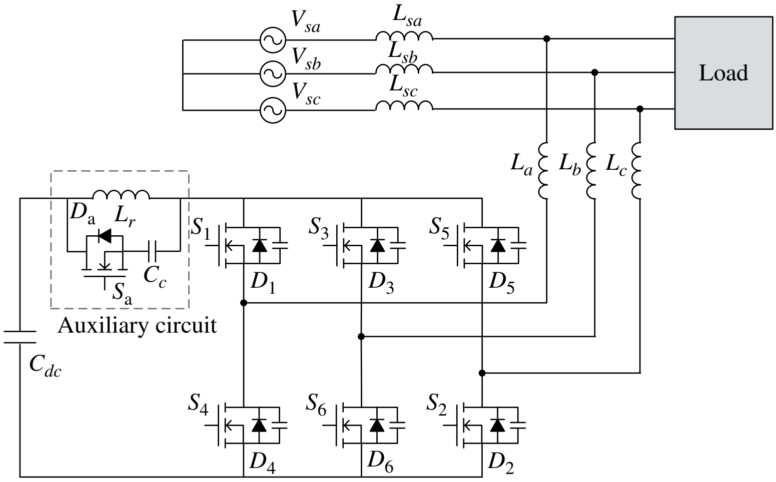


Figure 1.22 ZVS inverter for APF/STATCOM.

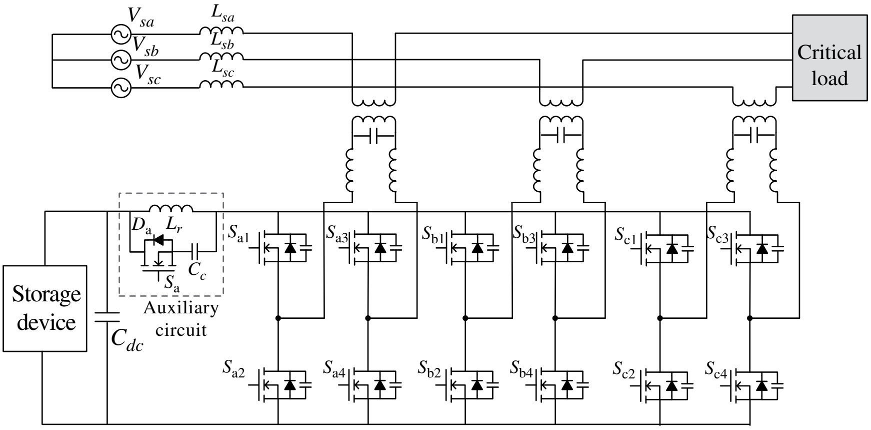


Figure 1.23 ZVS converter for DVR.

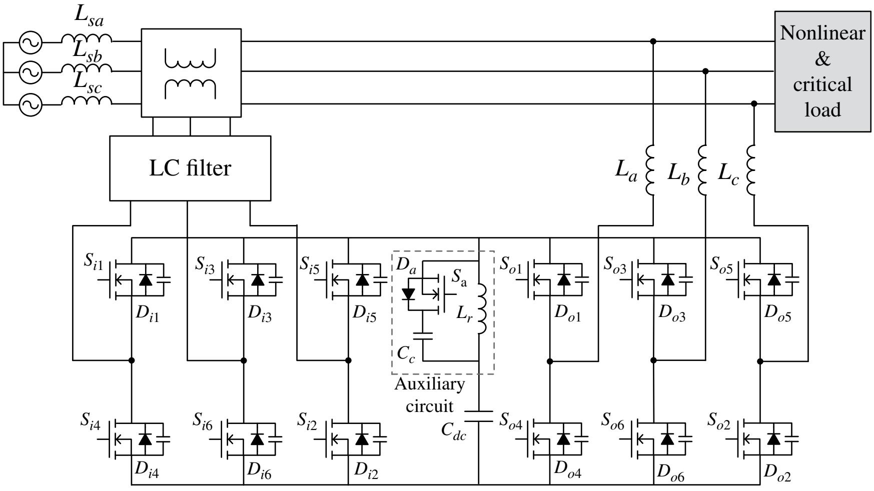


Figure 1.24 ZVS converter for UPQC. *Source:* Based on Shi et al. [19].

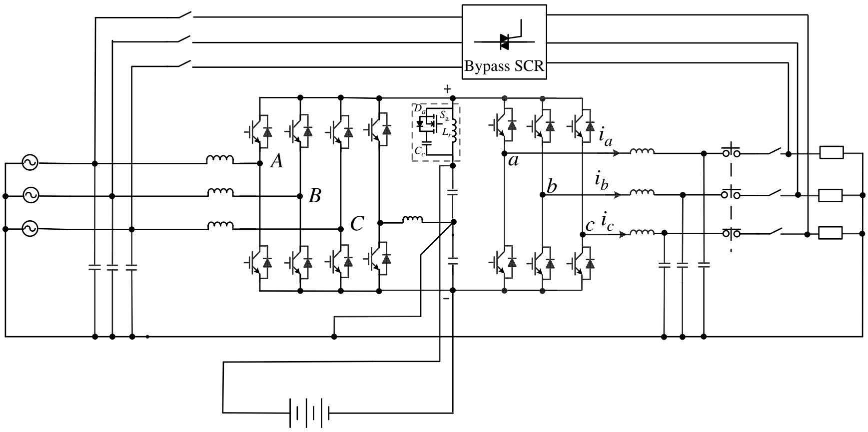


Figure 1.25 UPS with the auxiliary resonance circuit for soft-switching.

1.3.5 Motor Drives

High speed drives such as pumps or compressors are applied in the industry. The inverter of high speed drives needs to operate at very high switching frequency up to tens of kHz. Since switching loss is proportional to switching frequency, switching loss of the power semiconductor in a high speed drive is so high that the power devices have to operate at its derating state for the safety. Thus the power rating of power device is unable to be fully utilized. An auxiliary resonance circuit is introduced to the DC side of the inverter as shown in Figure 1.26. The switch loss of the inverter is significantly reduced due to soft-switching of the power devices in the inverter.

1.3.6 Fast EV Chargers

To reduce charging time of EV, power rating of EV chargers is becoming large and large. The EV charger shown in Figure 1.27 is composed of two power conversion stages. To increase power density of the charger, soft-switching technique is used. The first stage is three-phase rectifier where an auxiliary resonant circuit is introduced to realize soft-switching for the rectifier. For the second stage, double inductors and one capacitor (LLC) resonant DC/DC converter is used. It can realize soft-switching for all switches in the DC/DC converter. All switches in EV charger can realize soft-switching so that its power density is enhanced.

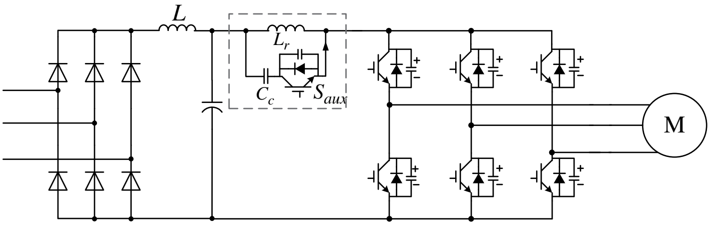


Figure 1.26 High speed drives with auxiliary resonance circuit.

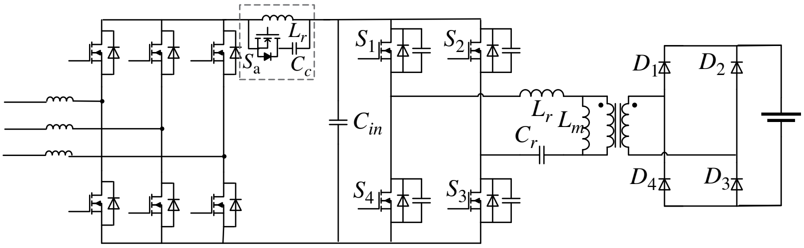


Figure 1.27 Soft-switching EV charger.

1.3.7 Power Supply

With development of big data, cloud computing, etc., it is more stringent than ever to require the data centers to have higher computing speed and density with less energy consumption. Compared with super junction Metal-oxide-semiconductor field effect transistors (MOSFETS), Gallium nitride high Electron mobility Transistor (GaN HEMT) shows significant improvement on the switching performance, but its switching frequency is still limited when hard switching is used. A ZVS totem-pole PFC circuit with fixed switching frequency is investigated for server power supply [34]. In Figure 1.28, the right leg with switch S_{2H} and S_{2L} operates at utility frequency and silicon MOSFET is used. The left leg with S_{1H} and S_{1L} operates at 500 kHz and GaN HEMT is chosen. With the auxiliary circuit, the GaN device can operate at ZVS condition. The turn-on loss of the GaN is eliminated and its turn-off loss is reduced.

1.4 The Topics of This Book

This book will focus on the soft-switching technology for three-phase converters or inverters and their applications. Aiming to reduce or even eliminate the voltage and current overlapping during the switching transient process, soft-switching techniques provide a solution for power converters to achieve high conversion efficiency with dramatic reduction of the switching losses. This book is divided into four parts:

Part 1(Chapters 1–3) will provide an introduction to fundamentals of soft-switching technology for three-phase conversion. Impacts of the soft-switching technique on three-phase converter performance such as conversion efficiency, power density, and EMI noise is explained. Applications of

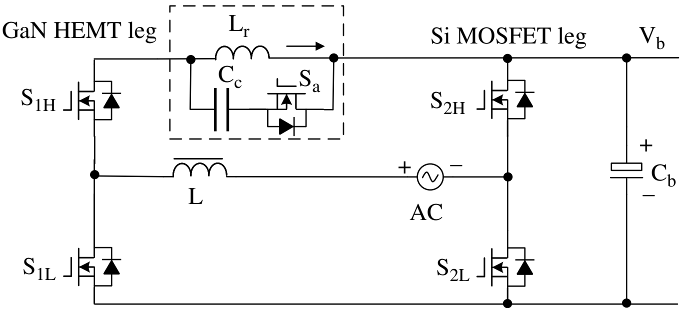


Figure 1.28 ZVS totem power-factor-correction circuit.

three-phase power converters in renewable energy, industry drives, power supplies, etc. are introduced. Development of soft-switching technology for three-phase converters is reviewed. A general soft-switching PWM method for three-phase converters, edge-aligned PWM (EA-PWM), is introduced.

Part 2(Chapters 4 and 5) will investigate applying soft-switching technology to three-phase rectifiers. Two types of soft-switching circuits are investigated. It includes circuit analysis, soft-switching condition derivation, and circuit parameters design. Then experimental result of the soft-switching rectifier prototypes are provided.

Part 3(Chapters 6–9) will aim at applying soft-switching technology to three-phase grid inverters. Two types of soft-switching circuits are investigated. It includes circuit analysis, soft-switching condition derivation, and circuit parameters design. Then experimental result of the soft-switching grid inverter prototypes are provided. Since the resonant inductor is a critical component with respect to its loss, size, and thermal design, design of the resonant inductor is introduced. In addition, optimization method for the grid inverter based on the loss model is provided.

Part 4(Chapters 10–12) will introduce the impact of SiC devices on soft-switching converters. Improvement of efficiency and power density by introducing SiC to soft-switching three-phase converter will be investigated. Converter circuit layout design and its effect are explained. Designs of single-phase grid inverter, a three-phase grid inverter, and a BTB converter with soft-switching technique are provided.

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