Abstract

This thesis addresses an optimal current operation strategy and harmonic interaction analysis of delta-connected cascaded H-bridge (CHB) multilevel converter based shunt active power filter (APF).

An optimal current operation strategy for a delta-connected CHB based shunt APF under non-ideal grid conditions is presented that minimizes the shunt APF apparent power and satisfies requirements on average power balance, power factor constraint, source current distortion and imbalance characteristics in compliance with grid codes. The optimization problem is formulated using a convex quadratic objective function and non-convex quadratic constraints and solved by sequential convex programming (SCP).

The presented harmonic interaction analysis is based on the derivation of a time-invariant model in dq-frame from a time-varying model in abc-frame. In the derived time-invariant model, the symmetrical components of each frequency order in the shunt APF variables can be decoupled while preserving the interaction with other variables. The harmonic interaction analysis technique is able to predict how harmonics propagate through the system and quantify the shunt APF variables.

The proposed current strategy and harmonic interaction analysis are evaluated by simulations in comparison with related approaches from literature, to demonstrate the effectiveness.

1. Introduction

1.1. Motivation

Nowadays the wide utilisation of power-electronics-based loads causes distortion in voltages and currents as well as reactive power components. These electrical power quality problems have become an important issue in transmission and distribution power systems. Active Power Filters (APFs) are filters that can perform the job of harmonic and reactive power elimination. Depending on the power quality problem to be solved, APFs can be implemented as shunt type, series type, or a combination of shunt and series types. Shunt APF is the use of an electronic power converter to compensate reactive and harmonic currents so that the source currents after compensation can meet grid codes. Shunt APF development/design including several considerations such as follows:

- converter topology
- converter operating current strategy
- modelling and harmonic interaction analysis

A very common shunt APF configuration in three-phase systems is traditional Voltage Source Converters (VSCs) shown in Fig. 2.2. However, limited by voltage ratings of semiconductor switches, this topology is not suitable for medium- or high-power applications. As a result, multilevel converters, including delta- and star-connected Cascaded H-bridge (CHB) multilevel converters [WSDC15, YSL+17], Neutral Point Clamped Converters (NPCs) [MMT+17], Flying Capacitor Converters (FCCs) [AJKM16], Modular Multilevel Converters / Modulare Multilevel Umrichter (MMCs) [SLZ+16] and among others, which can be directly connected to medium voltage systems without transformers are emerged to accommodate this situation. Each converter topology represents advantages and disadvantages. The CHB multilevel converter has the advantage to reduce harmonic distortion level and the rating of power switches. The delta-connected CHB makes the negative-sequence reactive power compensation possible due to a circulating current flowing inside. However, it needs a high number of dc-link capacitors and there is an imbalance control problem, increasing the control complexity. Due to the strong and weak points associated with each topology, the selection depends on particular design criteria. This dissertation is focused on shunt APF based on delta-connected cascaded H-bridge multilevel converter, which has found widespread use in practical projects.

The choice of the converter topology is part of the full shunt APF system. Another issue concerned to shunt APFs is the reference operating current calculation. The reference operating current calculation for delta-connected CHB-based shunt APF includes two parts: a) compensation/terminal current calculation; b) circulating current calculation. The present methods calculate terminal currents and circulating current separately instead of as an integrity. All terminal current calculation methods require that the average power delivered by the source equals to that consumed by the load, in other words, the average value of the total APF active power is zero. The traditional Perfect Harmonic Cancellation (PHC) and Unity Power Factor (UPF) strategies are well-known terminal current calculation methods. The PHC strategy aims at harmonics and unbalance free source currents. The UPF strategy results in source currents in phase with Point of Common Coupling (PCC) voltages. PHC and UPF lead to the same result when the PCC voltages contain solely the positive-sequence fundamental frequency component. However, when the PCC voltages contain harmonics and/or unbalance, the PHC power factor may be low while the UPF source currents may violate grid codes. Optimal algorithms have been proposed in some works to compromise PHC and UPF to maximize power factor while meeting grid codes. One common feature of all the reference terminal current calculation methods is that they do not take the internal structure and characteristics of each converter topology into account, leading to the same results for each converter. Looking into the delta-connected CHB multilevel converter, one key phenomenon that is specific to this converter and provides opportunities for unique design and control optimization is the circulating current, which flows in the delta configuration in such a way that it does not influence the total APF active power but is able to redistribute the active power among the three branches to maintain SubModule (SM) capacitor voltages, when the average active power released and absorbed by per-branch is balanced. Circulating current calculation for objective minimization/maximization such as SM capacitor voltage ripple minimization has been researched, with the foundation that the terminal currents are determined by the conventional PHC or UPF strategy. In fact, the joint calculation of terminal currents and circulating current can be considered to further minimize/maximize objectives, but has not yet been discussed in present literatures. The operational issue concerned to the delta-connected CHB-based shunt APF, a joint reference current calculation, out of the consideration of grid code requirement and APF apparent power minimization, will be tackled in this dissertation.

The investment and operational cost of a shunt APF system should also be taken into account. Conventionally shunt APFs employ very large electrolytic capacitors so that the capacitor voltage ripple is negligibly small (typically less than $\pm 5\%$). However, such capacitors are known to be bulky, weighty and costly. The SM dc-link application with small electrolytic capacitors or even film capacitors that have lower capacitance than electrolytic type capacitors with the same volume, leads to higher amplititude low-frequency ($<2\,\mathrm{kHz}$) capacitor voltage ripple, however, can achieve lower cost and size [FHA15, WB14]. In addition, for the same switch and dc-link capacitor in each SM, the higher number of SMs is accompanied with the higher quality of the output voltage, however, the total number of devices, conduction loss which is a function of the SM number inserted in the conduction path, and converter cost are also higher. Therefore, a minimum number of SMs and each SM capacitance with a reduced value, are desired to reduce the converter volume, losses, cost of cascaded multilevel converters [SA15, LQTH16]. The shunt APF modelling and analysis can be split into two subsystems: a) the ac-side dynamics; b) the dc-side dynamics. As for the subsystem a), they are traditionally modelled as linear equations by approximation of SM capacitor voltages as constant, which is reasonable when APFs employ very large electrolytic capacitors. It is useful to use Park's transformation using reference frames rotating at fundamental and harmonic frequencies. This makes it possible to see the d and q components of the converter branch currents/voltages as dc component at each frequency order. However, such linear equations for the ac-side dynamics are inaccurate when SM capacitor voltage harmonics are large, which happens when small electrolytic capacitors or even film capacitors are applied, resulting in that the ac-side dynamics cannot be approximated as a linear system. As for the subsystem b), the harmonics in the instantaneous APF branch power which is the cross coupling of the APF branch voltage and current are finally reflected in the SM dc-link capacitors. There are very few studies discussing the relationship between the harmonics in the APF branch powers and SM capacitor voltages. This dissertation has proposed a harmonic interaction analysis tecnnique that is based a state-space model in dq frame, which is derived from a mathematical abc frame model, in which the ac- and dc-side APF dynamics are integrated. The description of the ac-side dynamics does not ignore the coupling of capacitor voltage ripple and switching functions. The expression of the dc-side dynamics considers the coupling of APF branch voltages and currents. The accurate relationship between the harmonics in the APF branch powers and SM capacitor voltages is given. The proposed harmonic interaction analysis, which is based on the derived dq frame model, is able to predict how harmonics propagate through the system and quantify electrical and nonelectrical quatities (switching functions), providing great reference for APF understanding, designing and controlling.

1.2. Objectives

In this dissertation two main objectives in the operation of the delta-connected CHB-based shunt APF can be summarized as:

Current operation strategy An optimal strategy is presented to determine the combined control reference for the terminal currents and the circulating current of the delta-connected CHB-based shunt APF, hereby minimizing the operational power under ideal and non-ideal PCC voltages conditions, where the ideal PCC voltages contain only the positive-sequence fundamental frequency component and the non-ideal PCC voltages contain unbalance and/or harmonic components. The optimization is carried out to simultaneously meet the desired source current distortion limits, the source current imbalance characteristics and power factor as well as power balance requirements. This strategy cannot be directly used when the power systems contain interharmonics, such as Fig. 2.9. (a) and (c). Reasons will be given in Section 3.8.

Harmonic interaction analysis The proposed harmonic interaction analysis is based on the derivation of a time-invariant representation of an integrated model of ac- and dc-side dynamics of the delta-connected CHB - based shunt APF, achieving accurate variable quatification. Retaining the cross coupling between various variables, the time-invariant representation is a multi-input multi-output (MIMO) system, which is characterized by a nonlinear relationship between inputs and state-variables/outputs. Take the ac-side dynamics as an example, the nth frequency order in switching functions can arouse converter currents/voltages with not only the nth but also other frequency orders, while conventionally the relationship between the switching functions and converter currents/voltages is linear by assuming SM capacitor voltages as constant. The analysis technique is proposed when the power systems contain the fundamental frequency and/or harmonic components possibly with unbalance, and even applicable if a couple of interharmonics are of concern.

It should be noticed that although the two objectives implemented in Chapters 3-4 are validated in steady-state (or continuous) power systems, they can be still applied when some types of disturbances (temporarily or permanently) happen, such as Fig. 2.9. (e), as long as the disturbance duration is longer than one fundamental period and the frequencies contained in the power systems are integral multiple times of the fundamental frequency.

1.3. Related Work

After the objectives are specified, the related work is given. Thereby, the open points, which are covered in the thesis, are identified. First, the current operation strategies for three-phase shunt APFs are reviewed. Second, the harmonic interaction analysis methods are discussed.

1.3.1. Current Operation Strategies

The joint design of terminal currents and circulating current simultaneously for delta-connected CHB-based shunt APF for power consumption reduction, to author's best knowledge, has not been studied so far. However, a review of previous work is still given, which focuses on how to calculate either the terminal currents or the circulating current.

Strategies to determine the terminal currents

The current strategies which calculate the terminal currents, have nothing to do with the inner structure of the shunt APF itself, only there is a difference between three-wire and four-wire systems, since three-wire systems cannot compensate the zero-sequence current from the loads while four-wire systems can [VEToMm06]. When the inner converter structure is not considered, possibly additional freedom degrees in some structures are not taken into account that can be actually used to further improve the system performance like the circulating current in delta-connected CHB. The terminal current strategies can be classified into two categories, namely *the traditional current strategies*, such as the generalized p-q, i_d-i_q, the PHC and UPF strategy, and *a joint consideration of traditional strategies*, for instance the joint consideration of the PHC and UPF strategy.

Traditional Current Strategies Some current strategies have been presented in [MCG07, RMG08] for the desirable terminal currents calculation: the generalized p - q strategy, the i_d - i_q method, PHC and UPF strategy respectively. In all of the current strategies, the constant active power provided by the source is equal to that consumed by the load. Under the p - q strategy, the load current compensation is achieved by cancellation of the instantaneous zero-sequence power at the source side. The i_d - i_q method is based on the assumption that the source provides the mean value of the direct-axis component of the load current. In the PHC strategy, the source currents are in phase with the fundamental positive-sequence PCC voltages. In this strategy, the imbalance and all the harmonics are compensated. Under the UPF strategy, the waveform of the source currents resembles that of the PCC voltages, which means, the three-phase load current is compensated for the purpose that the nonlinear load together with the compensator are viewed as a symmetrical and constant resistive load from the point of view of the PCC voltages. If the PCC voltages are ideal, containing the fundamental positive-sequence phase component, PHC and UPF can be achieved simultaneously. These two goals cannot be carried on when the PCC voltages are distorted and/or unbalanced. For instance, if the PCC voltages are severely distorted, the Total Harmonic Distortion (THD) of the UPF source currents may exceed the limitation of the standard requirement although the power factor is unity (in three-wire systems). The PHC source currents contain neither harmonics nor unbalance, however, the PHC efficiency can be low under distorted and/or unbalanced PCC voltages.

A joint consideration of traditional strategies: Under non-ideal grid conditions, a joint design of PHC and UPF to maximize the power factor by meeting some current harmonic distortion constraints has been reported based on a rather simple combination [RTGG01, UMG09, KKZ13]. References [RTGG01, UMG09] formulate the optimization problem as nonlinear and solve the formulated problem with the MATLAB optimization toolbox. In reference [KKZ13] a single-step noniterative optimized control algorithm has been proposed for a three-phase four-wire shunt APF to achieve a compromization between efficiency and total harmonic distortion. In this paper [KKZ13] the comparison of the noniterative optimized control algorithm and the iterative Newton-Raphson (NR) method shows that the proposed single-step noniterative algorithm has smaller computation time. The convergence analysis has not been done in literatures [RTGG01, UMG09, KKZ13].

Strategies to determine the circulating current

The strategies which calculate the circulating current, which flows within converters and does not affect the terminal currents injected at the grids, have been proposed depending on different objectives, for instance circulating current suppression, selective harmonic current suppression [WHO14, YWT+18], capacitor voltage ripple suppression [WLZX13, KWS10], converter current rating reduction [BMLB15a, LZX+16, KKGB15], power semiconductor temperature fluctuation minimization [BMLB15b], among others. References [WHO14, YWT+18] claim that the MMC circulating current can increase semiconductor current stress, converter power losses, submodule capacitor voltage ripples and even instability during transient state, they made effort to perfectly suppress even-order harmonics in the differential/circulating current. However, for some special applications such as capacitor voltage ripple shaping, converter branch current Root Mean Square (RMS) reduction, and so on, the circulating current harmonics are not necessarily undesirable. Circulating current injection methods have been proposed for capacitor voltage ripple suppression [WLZX13, KWS10]. These methods result in the usage of smaller capacitors and reduced costs. Current RMS reduction via circulating current injection has also been investigated for MMCs in High Voltage Direct Current (HVDC) applications/driver systems [BMLB15a, LZX+16, KKGB15] so that the device losses can be reduced. Also the effect of the circulating current on minimizing the temperature fluctuations of power semiconductors in an MMC has been studied in [BMLB15b], resulting in the improvement the devices life time.

The basic idea to inject the fundamental frequency circulating current for delta-connected CHB-based Static Synchronous Compensators (STATCOMs) under unbalanced and undistorted grid conditions has been reported in [BB17, HMA12, YKT+17, WCCC17] for power balancing among the converter branches. In these literatures, the circulating current is hardly adjusted since there is only fundamental-frequency component in the power supplies and load currents. [WSDC15, BJH+15] discuss circulating current injection for branch current RMS reduction of the delta-connected CHB. The approaches unfortunately can only work under ideal power supplies.

1.3.2. Harmonic Interaction Analysis

So far the harmonic interaction analysis of delta-connected CHB-based shunt APFs has not been reported, however, references [IANN12, JJ15, SP04] have proposed the analysis with frequency domain models for MMCs [IANN12, JJ15] and CHB-based STATCOMs [SP04], where the desired/nominal low-frequency switching function is assumed as the ratio between the desired SM output voltage and the dc component of the SM capacitor voltage, leading to that the frequency orders in the switching function are the same with those in the desired SM output voltages, thus the analysis results are relatively simple and incomplete. The similar assumption has been adopted in references [WCC17, CWL+15, LWY+17, KV17, DXM16], which have studied CHB multilevel converters. Actually, due to the existing harmonics in the SM capacitor voltages, the switching functions contain other low-frequency orders besides those in the desired SM output voltages.

References [SL14, MH09, KWB+17, KWB+16] have proposed harmonic interaction analysis based on that the modulation signals contain only the fundamental frequency which is calculated from the conventional method as in [SP04], and the switching function harmonics are brought during the modulation stage. Therefore different modulation strategies lead to different analysis results. In such methods, when the fundamental frequency modulation signal and the modulation strategy are settled, the mathematical expression of the switching function which includes baseband harmonics (i.e., simple harmonics of the fundamental line-frequency), harmonics of the carrier frequency and carrier sidebands which cluster around the carrier harmonics can be immediately obtained. Based on the expression of the switching function, they start the analysis step by step in the time-domain [SL14] or the frequency domain with the help of the Fourier transform and the convolution theorem [MH09, KWB+17, KWB+16].

There are two common features of [IANN12, JJ15, SP04, SL14, KWB+17, KWB+16]. One is that they have not considered the low-frequency harmonic orders in switching functions which are caused by the interaction with SM capacitor voltage harmonics. Another feature is that they deal with each phase separately, therefore there is no limitation for the system as it can be either single- or poly-phase. However, the decoupling of the sequence quantities, which is essential to analyse the three-phase systems with unbalance, has not been directly achieved.

References [BDSD18, JJ16] successfully achieve decoupling the sequence quantities of each frequency order when dealing with the harmonic coupling for MMCs in multiple *dq* rotating coordinate frames, including dc, the 1st to 3rd harmonics in the positive-, negative- and zero-sequence. However, it has not been extended to a high number of harmonics and a systematic approach has not been developed so that it cannot be applied to a network which contains higher frequency orders.

1.4. Outline and Contribution

This dissertation is consisted of two parts. The first part focuses on an operation strategy to calculate optimal terminal currents and circulating current (Chapter 3) and the second part (Chapter 4) is devoted to harmonic interaction analysis.

Chapter 2 The application of various voltage source converters is reviewed. The reasons to choose delta-connected CHB multilevel converter as shunt active power filter are given. In addition, the operation of delta-connected CHB as shunt APF operated under non-ideal PCC voltages, for a generic consideration, will be discussed in Chapters 3-4, thereby various faults in power supplies are reviewed and the mathematical expression of non-ideal PCC voltages is given.

Chapter 3 An optimal current operation strategy for a delta-connected CHB-based shunt APF under non-ideal grid conditions is presented that minimizes the APF apparent power and satisfies requirements on average power balance, power factor constraint, the source current distortion constraint as per IEEE STD-519 and imbalance characteristics as per IEEE STD-1159. This optimal strategy consists of two parts: the optimization problem formulation and the optimal solution searching for the formulated problem. The design approach is explained step by step including the appropriate analysis to formulate an optimization problem, which has a quadratic convex objective function and quadratic non-convex constraints, called non-convex Quadratic Constraints Quadratic Programming (QCQP) problem. In order to solve the non-convex QCQP problem, a proper treatment of the non-convex optimization based on local linearisation and iterative sequential programming have been made, resulting in the convergence to a local optimal solution. The operational power comparison of the presented optimal strategy, the traditional UPF and PHC strategy combined with the fundamental frequency circulating current, and the current strategies with feasible solutions, which are slightly shifted from the optimal solution of the non-convex QCQP problem validates the minimum shunt APF apparent power in the presented optimal strategy.

The presented strategy makes a contribution in the context of a joint reference current calculation, including the terminal currents and the circulating current in the delta-connected CHB-based shunt APF. Optimal strategies in the present research, typically propose the calculation of either the optimal terminal currents [RTGG01, UMG09, KKZ13] or the optimal circulating current [WSDC15, BJH+15]. Additionally, this chapter makes a contribution to the problem formulation. This chapter uses some concepts in [RTGG01, UMG09, KKZ13], where the concepts without transformation are directly formulated into optimization problems, resulting in nonlinear problems in a manner reflecting the situation being modelled but cannot be classified into one specific category of optimization programming. For such formulated problems without appropriate transformations, stochastic methods that cannot guarantee the convergence to an optimal solution in finite time are often used to solve these optimization problems. In the dissertation some proper transformation of the concepts is made targeting for a good problem formulation that the existence of a unique and optimal solution is assured.

Chapter 4 The harmonic interaction analysis is presented to predict the harmonics propagated through the system and quantify the electrical and non-electrical variables (switching functions/modulation signals) for the delta-connected CHB based shunt APF, based on the assumption that the switching functions are unknown beforehand. The main difficulty of this part is to derive the time-invariant dq representation from a time-varying expression, denoted by $x^{abc} = y^{abc} \circ z^{abc}$, in which $\boldsymbol{x}^{abc} = [x_{ab} \quad x_{bc} \quad x_{ca}]^\top$, $\boldsymbol{y}^{abc} = [y_{ab} \quad y_{bc} \quad y_{ca}]^\top$ and $\boldsymbol{z}^{abc} = [z_{ab} \quad z_{bc} \quad z_{ca}]^\top$ are three-phase time-varying signals containing multiple frequencies with the positive-, negative- and zero-sequence components. In addition, $\circ$ denotes element multiplication, i.e., $\begin{bmatrix} a \\ b \end{bmatrix} \circ \begin{bmatrix} c \\ d \end{bmatrix} = \begin{bmatrix} ac \\ bd \end{bmatrix}$. The electrical quantities (currents, powers, SM capacitor voltages) and switching functions can be quantified based on the harmonic interaction analysis and the derived time-invariant representation. Comparisons of variable quantification between with and without the harmonic interaction consideration have been made, validating the accuracy of the presented harmonic coupling analysis results.

The presented analysis makes a contribution in the context of the time-invariant derivation in which the symmetrical components at each frequency order can be decoupled while preserving the interaction with other variables. Therefore this work is specified for three-phase systems, unlike the harmonic interaction analysis which tackles each phase separately and have not decoupled sequence quantities [IANN12, JJ15, SP04, SL14, KWB+17, KWB+16]. In addition, the presented harmonic interaction and time-invariant model make a contribution of the steady-state quantification at the low-frequency range for the delta-connected CHB-based shunt APF.

1.5. Publications

A modelling and control method of the delta-connected CHB as STATCOM is introduced in [WTWL14]. [WL15] proposes an adaptive Kalman filter for harmonic detection. The separate calculation of an optimal reference terminal current and the circulating current can be seen in [WL16] and [WL17] respectively. A joint design of terminal currents and circulating current for APF apparent power minimization is introduced in [WL19b]. The harmonic interaction analysis has been published in [WL19a].

2. Foundation of Delta-connected CHB Multilevel Converter

The chapter reviews the classification and application of various voltage source converters, including multilevel converters. The reasons to choose delta-connected CHB as shunt APF are presented. Various power system disturbances are introduced, as the preliminary knowledge for the future chapters. In addition, the challenges of the two tasks of this dissertation are discussed.

2.1. Voltage Source Converters

2.1.1. Classification

The classification of voltage source converters (VSCs) is various dependent on different criterion, such as the number of phases, types of semiconductor devices, topologies and etc. Based on the number of phases to classify VSCs it can be such as two-wire (single-phase) and three- or four-wire three-phase systems. With the development of power systems, in order to meet the demand of high power, cost reduction and efficiency, at one side, the researchers have reacted to develop semiconductor technology to reach higher nominal voltages and currents, at the other side, new converter topologies have been developed, known as multilevel converters [RFK+09]. The advantages of multilevel converters lie in less harmonic generation, low switching losses, higher voltage operating capability compared with traditional two-level VSCs. Thus for high-power applications, such as transmission and distribution voltage levels, the multilevel-based VSCs become a more attractive solution. Some multilevel configurations have been studied and documented in technical literature, such as NPC, FCC and other modular multilevel VSCs based on cascaded H-bridge or cascaded half-bridge with isolated dc-link supply.

Fig.2.1 based on the structures shows the classification of VSCs for overview.

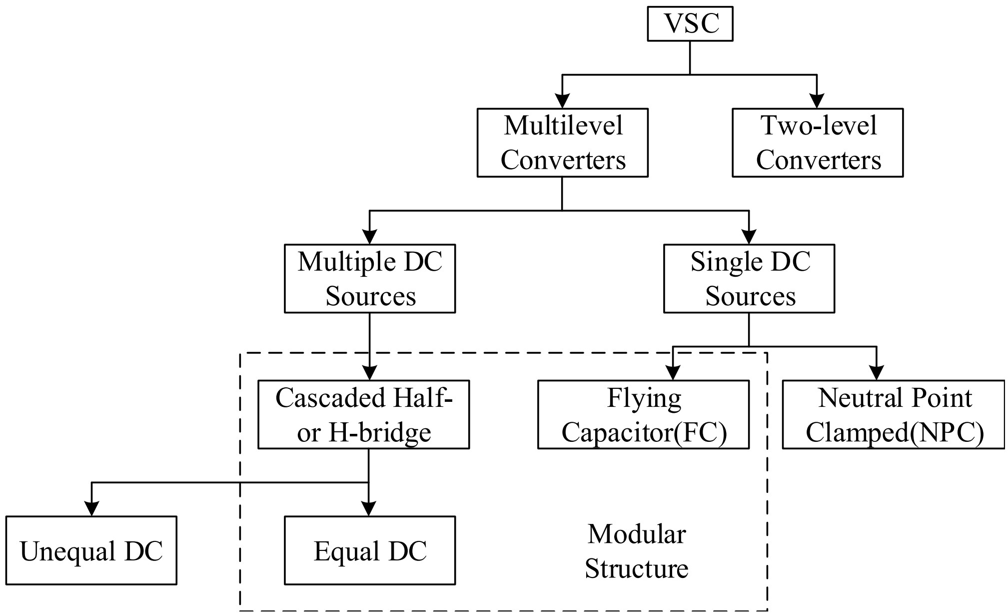

Figure 2.1.: Voltage source converter classification

Traditional Voltage Source Converters

Fig. 2.2 shows a traditional two-level converter. Because of the well-known circuit structure and control methods, two-level VSCs are competitive for low-voltage applications, up to few kV. In the case of the conventional two-level converter configurations, by going to higher power application, higher rated semiconductors are needed, which are more expensive. The harmonic reduction of this converter output is achieved by raising the switching frequency, leading to higher power losses. If other power quality requirements have to be fulfilled, then the need of power filters is introduced.