CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

One of the trends which have been witnessed in the power electronics field since the early 1980s is the quest for circuit and related control technology which enable efficient power conversion to be achieved with an ever-shrinking circuit size and lighter weight, and with better performance. For example, the migration from uncontrolled single-phase or three-phase rectifier and three-phase six-pulse line-commutated rectifier to the high-frequency switching rectifier helps to reduce the size of the reactive filtering components, sinusoidally shape the input line current waveform or realize power factor correction (PFC), and improve the dynamic response of the circuit. However, a higher switching frequency inevitably increases the associated switching losses. Under this background, various soft-switching techniques have been developed to effectively reduce the switching losses and make the circuit operable at the ever-increasing switching frequency [D13] [G2].

Most of the present soft-switching techniques, especially those for ac-dc and/or dc-ac power conversion, require considerable auxiliary commutation circuitry to achieve the desired soft-switching functions, countering the achievable benefits in many cases. However, there do exist some circuit topologies which can achieve soft-switching at almost no or little extra cost. One well-known example is the full-bridge phase-shift-controlled dc-dc converter where soft-switching for the power components is realized with the otherwise adverse leakage inductance of the isolation transformer [D21]-[D29]. How to take full advantage of this kind of almost effortless soft-switching techniques in the ac-dc and dc-ac power conversion remains largely an open question.

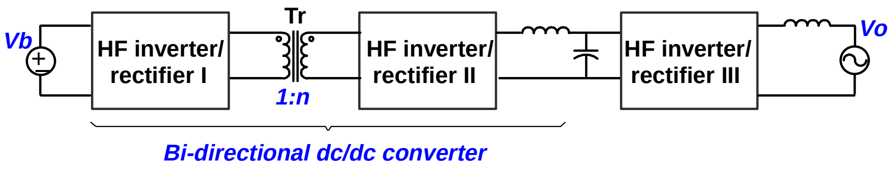
In many ac-dc and/or dc-ac applications, electrical isolation between the input and output is necessary. In these cases, a two-stage power conversion scheme which is composed of a switching rectifier and/or inverter, and a unidirectional or bi-directional dc-dc converter is often adopted [G3]. High circuit performance can be realized with this scheme except that the transferred power is always processed twice along the power flow path, and the circuit efficiency may not be optimized. Under this circumstance, single-stage cycloconverter or matrix converter type of power conversion schemes was proposed [[B1]-[B4] [B11]-[B14] [E1]-[E20]. High conversion efficiency and compact construction stemming from the non-existence of an intermediate low-pass (LP) filter can be attributed to this family of converters. However, almost all of them mandate the use of the four-quadrant switches which are always challenging to securely operate and control [A65]. In addition, their reliability seems constantly under question.

The purpose of the reported research in this dissertation is to develop high-performance, reliable, and efficient circuit, modulation and control techniques to achieve high-power, high-frequency isolated ac-dc and dc-ac power conversion with single-stage power processing. The quasi-single-stage (QSS) power conversion concept and the related soft-switching and control techniques are proposed to achieve that purpose.

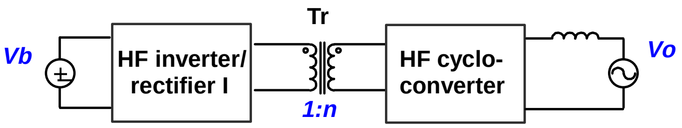
1.2 Previous Researches

1.2.1 Single-Phase Inverter/Charger

Bi-directional inverters/chargers are increasingly used in line-interactive uninterruptible power systems (UPSs), battery-backup stand-alone inverter systems, and alternative energy systems such as wind power and photovoltaic applications. The functions of such a bi-directional inverter/charger can be realized with a bi-directional dc-dc converter in cascade with a four-quadrant full-bridge inverter/rectifier as shown in Fig. 1.1(a). A high-frequency (HF) transformer link T_r is usually required to provide electrical isolation and voltage matching between the input dc and output ac voltages. In this kind of two-stage schemes, three HF inverters/rectifiers of either full-bridge, half-bridge or push-pull topology are needed, and the power flow in either direction is always processed twice. In addition, extra dc-link filtering components are also a necessity.



(a) Two-stage inverter/charger.



(b) Cycloconverter-based single-stage inverter/charger.

Fig. 1.1. Typical bi-directional inverter/charger circuits.

In the past decade, single-stage, cycloconverter-based schemes as shown in Fig. 1.2(b) have constantly been sought [E1]-[E15]. The cycloconverter-based bi-directional inverter/charger topology was first introduced in [E1] and [E2], and patented in [E5]. Since then, different pulse-width-modulation (PWM) control methods have been developed to either suppress the transient voltage in the cycloconverter part, achieve reliable four-quadrant operation, or improve the dynamic performance of the converter. The phase modulation method originally proposed in [E2]-[E4] and also adopted in [E13]-[14] achieves output voltage regulation and power flow control by shifting the phase between the inverter and cycloconverter on both sides of the converter. As a result, bipolar voltage is always exerted on the output filter, and it leads to high circulating loss inside the converter and high output ripple. The pre-programmed sinusoidal PWM methods developed in [E1] and E5] normally result in only limited dynamic response. Real-time PWM akin to a dc-dc converter was proposed in [E6]-[E10] [E14]-[E15]. Possible commutation methods, including source commutation, and self-commutation (forced-commutation), were discussed in [E6]-[E7], and the effects of different PWM carriers on the achievable commutation types were also addressed in [E8]. The converter was extended to three-phase ac output case in [E11]-[E13] and the corresponding modulation schemes were also discussed.

The concern about reliable bi-directional operation has been looming large for the cycloconverter-based single-stage inverters/chargers. It stems from two basic topological traits of the converter, i.e. the lack of self-present current freewheeling paths inside the cycloconverter because all of the switches are bi-directional and need control to activate in both directions, and the intrinsic transient voltage appearing on the cycloconverter switches during boost mode operation when power is transferred from the output (ac side) to the input (dc side). The former can be solved by the application of proper PWM sequences which ensure the existence of the output current freewheeling path without shortening the transformer secondary winding. The latter is akin to any isolated boost-type of converters

[D6]-[D9], and has to be solved with extra voltage clamping circuitry. In [E7] and [E12], a bi-directional active clamp circuit was proposed to solve the transient voltage problem for single-phase and three-phase cycloconverters respectively. However, the circuit is rather complicated and costly; four high voltage switches and four extra diodes need to be used. High conduction loss in the clamp circuit is another concern.

1.2.2 Soft-Transition DC-DC Converters

1.2.2.1 Active Clamp Technique

Transient voltage exists in power electronic circuits. To make these circuit operate securely. It has to be effectively clamped. Among the voltage clamp schemes, the active clamp circuit, which was first introduced in [D1]-[D5] for single-ended forward and flyback converters, has the advantages of simple control and soft-switching capability in some cases. As a result of these features, it has been widely used in single-ended lower power switching power supplies. It has recently been successfully extended to solve the transient voltage problem related to the isolated bridge-type boost converters [D6]-[D9].

Although seemingly developed independently, the active-clamp resonant dc-link technique for high power inverter/rectifier first proposed in [C8]-[C9] shares the same basic operation principles as the active clamp technique developed in single-ended converters.

1.2.2.2 Soft-Transition Technique

Historically, it has been known that resonant converters have very low switching losses because the switches can switch under either zero-voltage-switching (ZVS), or zero-current-switch (ZCS). The shortcomings of the resonant converters, mainly the high conduction loss connected with the high energy circulation in these circuits were gradually recognized later on. [D13] recorded the technological evolution along the line. It seems that the developments culminate in the so called soft-transition techniques, which combine the merits of both the low switching loss achievable with conventional resonant converters, and the low conduction loss and device voltage/current rating of the conventional PWM converters.

Generally speaking, the soft-transition technique encompasses zero-voltage-transition (ZVT) and zero-current-switching (ZCT). However, most of the work so far has been concentrated on ZVT [D11]-[D14] [D17]-[D18], mainly because of its capability to successfully alleviate the notorious diode reverse recovery problem and relatively simple implementation. The ZVT technique in dc-dc converter setting was first proposed in [D11]-[D12], and there were also some parallel works in the three-phase power conversion setting [C20]. A modified version was proposed in [D17]-[D18]. It belongs to the more general category of active turn-on snubber [D14], while the ZCT technique [D15]-[D16] belongs to the category of active turn-off snubber, which is closely related to the pulse- or forced-commutation techniques developed for thyristors. Recently, some techniques which can solve both the turn-on and turn-off problems were reported, such as that in [D16]. Comparative study were reported in [D26] and [D20] for active and passive snubbers, and in [D25] for different soft-switching schemes.

1.2.2.3 Phase-Shift-Controlled ZVS and ZVZCS Full-Bridge Converter

Phase-shift-controlled ZVS full-bridge converter was first proposed independently in [D21], [D22]-[D23], and [D24] in the early 1980s. Since then, it has become the most widely used circuit topology for isolated high-power dc-dc power conversion. ZVS for the power switches is achieved almost free, i.e. without any additional commutation component compared its hard-switching full-bridge counterpart, although sometimes, the leakage inductance of the transformer is intentionally enlarged to expand the ZVS range for one of the two converter legs, usually called the lagging leg. With this scheme, the otherwise harmful leakage energy is stored in a freewheeling path on the primary side during the off duty-cycle, and is used to realize ZVS for the lagging leg switches at the beginning of the next active duty-cycle. ZVS for the leading leg switches is achieved with the load current. With all the active switches working under ZVS, even the slow internal diode of the high-voltage MOSFET can be adequately used. Many variations of the original scheme have since been proposed to improve the performance of the circuit. Only some of them are referred in [D25]-[D29].

The main disadvantages of the original circuit includes: high freewheeling loss of the primary leakage current, limited ZVS range for the lagging leg switches, duty-cycle loss seen on the secondary side, and energy feedback to the source. Besides, the ZVS range for the leading leg switches is usually not a concern, so capacitive snubber can be used to reduce their turn-off loss. However, the lagging leg switches have to turn off the load current under hard switching. This becomes a particular concern in high-power applications where IGBTs which have relatively high turn-off loss are frequently used.

The class of the so-called zero-voltage-/zero-current-switching (ZVZCS) full-bridge converters was proposed to alleviate the above problems related to the ZVS full-bridge converters. Realizing that ZVS for the lagging leg is anyway difficult to achieve, the ZVZCS scheme tries to reset the primary leakage current during the off or freewheeling duty-cycle. With the leakage current reset to zero, the lagging leg switches can be turned off under ZCS, while ZVS for the leading leg switches is kept intact.

The first such ZVZCS scheme uses the reverse avalanche characteristics of the IGBTs to reset the leakage current at the expense of dissipating the leakage energy in the active devices [D30]. A simple and effective ZVZCS scheme was introduced in [D31], where only a small saturable inductor and a shrunken blocking capacitor is used in series with the transformer primary to reset the leakage current. The scheme has recently been adopted in several typical applications [D31]-[D33] [B5]-[B6]. Some other ZVZCS schemes use a temporary voltage reflected from the secondary side of the transformer to reset the primary freewheeling current [D34]-[D36] [D38]-[D39] [D41]-[D43]. These schemes will further be discussed in Chapter 4 for potential applications in isolated buck rectifiers.

1.2.3 Three-Phase PFC Rectifier

1.2.3.1 Non-isolated Buck Rectifier

Non-isolated three-phase buck PWM rectifier, or voltage source rectifier (VSR), referred to as buck rectifier hereafter, evolved directly from the phase-controlled rectifier to obtain better power factor, reduce harmonic distortion, reduce the size and cost of the filtering components, and improve the dynamic response. Compared with the dual three-phase boost rectifier, it has more benign control characteristics, inherent shoot-through capability, and easy soft-start capability. Initial efforts were made to use it in high-power, medium-voltage type of applications, such as static VAR compensator [A35], and rectifier/inverter system with a current link [A3]. The related current-source-inverter (CSI) now becomes almost obsolete because of its performance limitation [A9].

The PWM controlled buck rectifier as shown in Fig. 1.3 was first introduced separately in [A1]-[A4] and [H4]. A three-switch version was first proposed in [A6] and [A13] to reduce implementation cost. Its current bi-directional version was introduced in

[A5] and was later studied in [A28]-[A30]. Another circuit topology variation with neutral point switched was presented in [A8]. Another variation with only two active switches was proposed in [A34]. Input filter design considerations were given in [A24].

Different carrier-based and algorithm-based PWM schemes have been developed to better control the buck rectifier [A2] [A4] [A6]-[A7] [A11]-[A13] [A32]-[A33]. The current space vector modulation (SVM) based modulation scheme together with the multiloop control was proposed in its infant days [A2]. Carrier-based six-step PWM were also proposed later [A4] [A6]. In [A31] two saw-tooth carriers were used to replace the triangular carriers to synchronize the switching of the rectifier legs to reduce the switching loss.

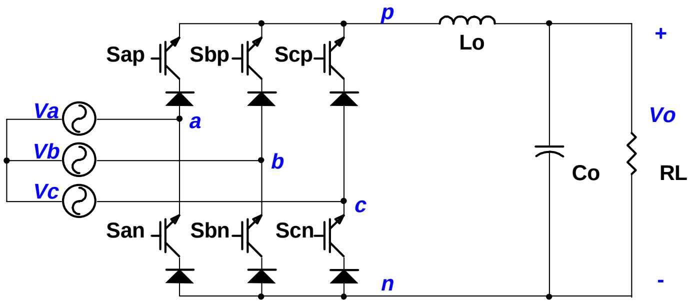


Fig. 1.2. Three-phase buck rectifier.

The compensation of the input displacement factor separate control of output voltage were first achieved in [A14] and were also the topic later in [A22]-[A23], [A25] and [A27]. The small-signal model of the buck rectifier were derived in d-q co-ordinate system in [A22]-[A23]. The behavior of the converter under unbalanced input line conditions and the compensation algorithm were extensively studied [A10] [A17]-[A21].

State feedback control was employed to achieve better input filter damping [A15]-[A16] [A26]. An input-output linearlization control was proposed to remove the non-linearity of the rectifier system when used in regenerative applications [A36].

1.2.3.2 Non-Isolated Boost Rectifier

Non-isolated three-phase boost rectifier, referred to as boost rectifier hereafter, as shown in Fig. 1.3, is the circuit dual of the buck rectifier [G1]. It is also called current-source rectifier (CSR), and its basic circuit topology and modulation technique are exactly the same as the widely used voltage source inverter (VSI). Therefore, it is even difficult to identify the early work to use VSIs and boost rectifiers to achieve PFC function. In today's lower-voltage (<2000 V) dc-ac conversion, VSIs are preferred to CSIs in most applications because of the following reasons [A58]: the capacitive dc storage has a lower weight, lower cost, and higher efficiency than the inductive one; VSI matches the inductive characteristics of most ac loads without using output filter capacitors; anti-parallel diodes exist in some active switches due to their physical structures or are included in the package; there are no series diodes with the active switches for VSIs, leading to lower conduction loss.

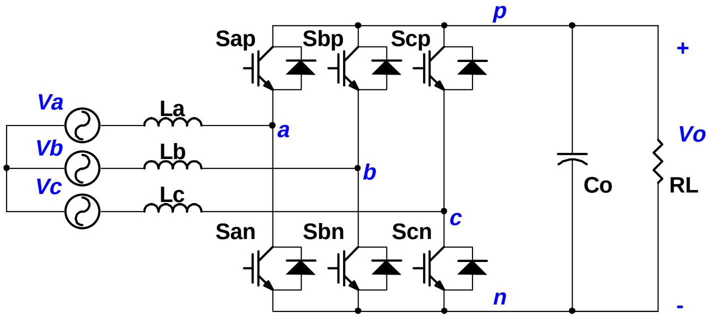


Fig. 1.3. Three-phase boost rectifier.

Early works seem to appear in the middle to later 1980s, when different current control schemes for the boost rectifier, including hysteresis control and average current mode control or proportional-integral (PI) control, were proposed to shape the input current sinusoidally and achieve unity or controllable power factor [A37]-[A38] [A40]-[A44] [A50]. Numerous PWM algorithms have been developed to control both the VSI and boost rectifier [G4]. it was realized that the space vector modulation (SVM) or its equivalent six-step PWM schemes are generally advantageous than the carrier-based modulation schemes without over-modulation.

Unlike VSIs that normally require bi-directional energy flow capability and have witnessed no change for at least half of a century in circuit topology, boost rectifiers usually need to work only in unidirectional power flow with near unity power factor. In this circumstance, the circuit topology can be simplified. Some of these circuit variations were found in [A53]-[A56] and [A57]. Further simplification of the circuit leads to the group of the so-called single-switch three-phase boost rectifier operating in discontinuous mode (DCM) [A45]-[A49] [A51], which theoretically absorbs non-sinusoidal current from the ac mains.

1.2.3.3 Matrix Converter

Matrix converter, or force-commutated cycloconverter, is capable of converting a three-phase ac voltage to another three-phase ac-voltage of any frequency directly. Although it is still far from wide-spread applications, unabated academic interests on it remains. Early fundamental works on matrix converter dated back to the later 1970s [A59]-[A60]. Some equivalent alternative topologies with varied performance were proposed in [A61]. Different modulation and implementation aspects were reported in [A62]-[A66]. The space vector modulation was introduced to control the matrix converter in [A67]-[A68]. Rigorous derivation of the modulation algorithm to achieve both power factor correction and input displacement compensation was also given. The matrix theory was extended to the general case with arbitrary phase numbers in [A69]. In [A70], a small-signal model of the matrix converter was presented, while an analysis based on the Dyadic matrix theory was proposed in [71].

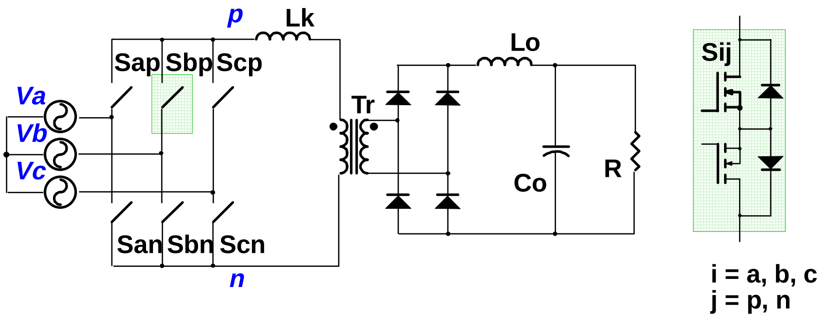
1.2.3.4 Isolated (Matrix) Three-Phase Rectifier

Efforts have been made to realize input PFC, output regulation, and electrical isolation in a single-stage. For high-power applications, symmetrical excitation of the isolation transformer is normally preferred. In this case, the output of the rectifier needs to be a high-frequency ac voltage or current. That is, the primary circuit of the rectifier needs to realize the function of a three-phase-to-single-phase cycloconverter or matrix converter.

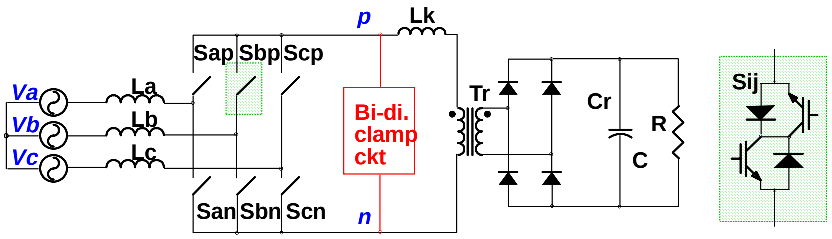
The buck-derived matrix rectifier, as shown in Fig. 1.4(a), together with the associated modulation schemes was proposed along the line in [B1]-[B2]. Its ZVS version, i.e. the ZVS isolated buck rectifier, was proposed in [B3]-[B4] [H6]. The circuit is exactly the same as shown in Fig. 1.4(a). However, it realizes ZVS turn-on for all the power devices in the same way as in the familiar phase-shift controlled ZVS full-bridge dc-dc converter [D21]-[D29]. For lower voltage and lower power applications where MOSFETs are used as the switching devices predominantly, the implementation is very rugged because with ZVS turn-on, the slow internal diodes of the MOSFETs can be utilized safely. But for high power applications where devices such as IGBTs and GTOs are of practical choices, the turn-off losses of the power switches are still a concern.

It should be mentioned that in [B1] a quasi-single-stage version of the isolated matrix rectifier was shown as the functionally equivalent circuit configuration of the latter. However, the advantages of that version, such as lower switching loss and soft-switching capability, were not recognized.

An interesting isolated buck rectifier, which incorporates only a six-switch current-unidirectional buck bridge, was presented in [B9]. The circuit is radically simple, and its operation is based on the two-switch forward converter. Therefore, the achievable maximum duty-cycle is limited. This, coupled with its asymmetrical transformer excitation, may limit its usefulness in high power applications. An isolated buck/boost or flyback rectifier also with limited power handling capability was proposed in [A52].



(a) Isolated buck rectifier.



(b) Isolated boost rectifier.

Fig. 1.4. Three-phase isolated buck (matrix) PWM rectifier.

Early this year, a single-stage isolated buck rectifier called Vienna Rectifier III was proposed in [B10]. It was derived from a three-switch buck bridge in cascading with a full-bridge dc-dc converter, and only five active switches are used in the final integrated topology. With the full-bridge type of sub-circuit topology eliminated, the circuit is difficult to realize soft-switching, and the leakage energy trapped in the transformer primary side during the active duty-cycles will create high transient voltage across the primary switches. Both factors may limit its power handling capability. Besides, the PWM scheme seems unnecessarily complicated.

The isolated boost rectifier as shown in Fig. 1.4(b), the circuit dual of the three-phase isolated buck rectifier, was proposed in [B13]-[B14]. A ZCS scheme for it was given in [H6]. Its simplified single-phase version was proposed in [B1]-[B2] and [D7]. A three-phase DCM version was presented in [D6]. A new integrated version called Vienna Rectifier II was recently introduced in [B15]. The isolated boost rectifier is, generally speaking, not worthwhile to pursue, especially for higher ac voltage applications, because it suffers from high device voltage rating when the line side and output voltage ranges are relatively large, as is the case for typical telecommunication and UPS applications where the output is usually connected to a battery bank with large voltage fluctuations. The inevitable transient voltage makes the situation even worse. In the case of the isolated matrix rectifier version, a complicated bi-directional voltage clamp circuit across the primary winding is necessary to secure the circuit operation.

1.2.4 Soft-Switched Three-Phase PFC Rectifiers

1.2.4.1 Soft-Switched Buck Rectifier

So far only very limited soft-switching techniques are available for non-isolated buck rectifiers [C26] [H9]. The main reason for that is thought to be attributed mainly to the specific series connection of the diode and the active switch in their implementation, which, generally speaking, prevent the exercise of analogy of the soft-switching techniques developed for dc-dc converters.

A few successful examples are the soft-switching techniques for isolated matrix or quasi-single-stage (QSS) buck rectifiers developed recently [B3] [B5]-[B8] [H6], thanks to the incorporation of the soft-switching techniques developed for phase-shift-controlled full-bridge dc-dc converters.

Among the few soft-switching schemes for non-isolated buck PWM rectifiers, a controlled resonant tank is placed on the dc side in the scheme proposed in [C1]. With the resonant inductor in the main power path, the *di/dt* of the main switch currents during both turn-on and turn-off is controlled, and the reverse recovery problem of the freewheeling diodes and switches is also solved. However, they are achieved with the heavy penalty that all the devices in the circuit need to sustain at least twice the voltage seen in the regular hard-switched buck rectifiers.

Similar schemes presented in [H6] and [C2] utilize an auxiliary branch composed of an resonant inductor in series with a unidirectional switch also across the dc side. Zero-voltage-switching (ZVS) turn-on is achieved by reversing the normally positive output voltage of the buck rectifier bridge. Therefore, it prevents the use of the extra freewheeling diode to reduce the conduction loss. Also, the regular PWM sequence needs to be modified to create the negative output voltage and extra turn-off losses happen in the rectifier switches. Efforts were made in [C3] to improve the performance. But the drawbacks mentioned above remain. A so-called ZCT commutation circuit for buck rectifiers was recently introduced, but the complexity of the circuit and its operation is even difficult to justify [C4].

A relatively promising ZVT buck rectifier was proposed in [H9]. In that scheme, one ZVT cell plus some guiding diodes connected to the middle point of the switch and diode connection is used for each of the upper and lower half of the buck rectifier bridge. By doing so, ZVS turn-on can be achieved for the bridge switches, however, a temporary over-voltage resulting from the discharging of the commutation inductor energy still builds up on the dc side simply because the buck rectifier is current-unidirectional.

It can be concluded that all the few soft-switching schemes for non-isolated buck rectifiers present severe drawbacks, and their practical usefulness is limited.

1.2.4.2 Soft-Switched Boost Rectifier

In the past decade, numerous efforts have been directed to the soft-switching techniques for the three-phase boost rectifier. There are two major reasons behind that, that is, its close relationship with the widely used voltage-source inverter and the high switching frequency requirement to achieve better PFC. Almost all the soft-switching techniques developed for VSIs can be directly used for boost rectifiers.

The soft-switching, mostly ZVS, techniques for boost rectifiers and VSIs can be divided into two categories: dc-side soft-switching and ac-side soft-switching according to the position of the auxiliary commutation network. DC-side soft-switching circuit can be viewed as a common commutation circuit for all the bridge switches.

For boost rectifiers and VSIs, the dc-side is a stiff voltage source. To achieve ZVS for the main bridge switches, the bridge terminal voltage has to collapse to zero at least at the commutation or switching instants. Therefore, a series impedance has to be inserted to temporarily disengage the bridge terminals from the voltage source. This impedance is realized with a resonant inductor in resonant dc-link converters [C7]-[C11] [C19[-[C22]and with a diode or a switch in many other dc-side soft-transition converters [C12]-[C18] C23]-[C25].

Among the dc-side soft-switching schemes, the resonant dc-link (RDCL) and the subsequent active-clamp resonant dc-link (ACRDCL) converters were first proposed [C7]-[C11]. The ACRDCL technique reduces the dc-link or device voltage stress down to 1.2-1.4 times from 2-3 times the dc-side voltage with the RDCL technique. However, several serious problems undermine its practical values. First, the effective switching frequency of the RDCL or ACRDCL converter or its equivalent PWM frequency is low, usually less than 1/5, compared with the actual resonant or switching frequency. As a result, to achieve the same quality of the ac-side waveform and system bandwidth as its hard-switched counterpart, its switching frequency needs to be at least 5 times higher. Even with the benefit of lower switching loss in each switching action, this usually leads to even poorer converter efficiency than the hard-switched converter with the same effective switching frequency. Second, pulse density modulation is usually used to control these converters, and this induces subharmonics on the ac-side waveforms. Third, the inevitably higher device voltage rating is a limitation in certain applications.

To overcome the aforementioned problems associated with the RDCL and ACRDCL techniques, hybrid pulse density and pulse width modulation was tried in [C19] and [C21]. The real PWM scheme for the ACRDCL converter with slight manipulated topology was first proposed in [C20], where the effective switching frequency and the resonant frequency is made the same. Basically, it changes the converter into a resonant transition, or ZVT type of converter, similar to active-clamp dc-dc converters. It was also realized in [C20] that as a general rule, specific PWM control schemes have to be used for specific converter topologies, especially for the soft-switched converters.

To further reduce the device voltage rating, the parallel resonant dc-link (PRDCL) technique, also named the quasi resonant dc-link (QRDCL) technique, was proposed thereafter [C12]-[C18] [C23]-[C25] [C29]. Recognizing that the resonant components should not be involved in the major power transfer processes and should only function during the switching transients, the resonant components were shifted to a path in parallel with the dc-link, and auxiliary switches were used to control the resonance so that it would only occur during the short switching transients. In this way, the bridge device voltage stress is reduced to the lowest possible value, which is the dc source voltage. Lots of topology variations have been proposed under different names so far. However, all of them use a series switch, or diode in the rectifier case, to block the dc-side voltage source from the bridge. This incurs higher conduction loss in the circuit which has to be compensated by the reduction in switching losses.

AC-side soft-switching techniques are recently under intensive research for the reason that soft-transition can be easily achieved without adding series element in the main power path, i.e. without increasing the voltage rating of the main switches and without extra conduction loss [C26]-[C34]. This category includes the auxiliary resonant commutation pole (ARCP) converter first proposed in [C27]-[C29], and various ZVT [C30]-[C34] and ZCT [D16] schemes. Most of these schemes are analogous to the corresponding soft-switching schemes developed first in dc-dc converters. However, in three-phase converter case, the situation is complicated by the fact that the instantaneous ac voltages, which correspond to the duty-cycle of the switches, and currents are constantly changing and alternative. So the auxiliary commutation circuitry is usually non-trivial in both circuit and control complexity and cost, while the effect may not be as conspicuous as in dc-dc converters.

1.2.5 Charge Control

Charge control for dc-dc converters was first proposed in the late 1970s [F4], about the same time when peak current mode control was introduced [F1]-[F2] and is one form of average current mode control [F3] [H5]. It features a resettable integrator to control the average value of a pulsating circuit variable, in this case the charge flowing through the switch or diode, on a cycle by cycle basis, so it can also be called *instantaneous average current control*. The original motivation to use charge control was to improve the dynamic performance and increase the noise immunity in high power applications [F4] resulting from the averaging effect of the integrator. The concept is also found in [F5]. Due to its capability to control the charge or average current, it has been successfully applied to the cases where other current-mode controls fail to function or have severe performance limitations, such as single-phase buck/boost or flyback PFC converters running in continuous-current mode (CCM) [F6] [F8], and multi-resonant dc-dc converters [H5]. The complete small-signal model and design guidelines of charge control for dc-dc converters were derived in [F7] and [H5], and an alternative model with the concept of charge controlled switch was given in [F10].

So far no effort has been reported toward the extension of the basic charge control concept to the control of three-phase PFC rectifiers.

1.3 Outline of the Dissertation

The main results and contributions of the dissertation are outlined as follows:

Chapter 2: The general topological concept of quasi-single-stage (QSS) isolated power conversion is introduced and defined following an illustrative example of a cascaded three-phase buck rectifier. The preliminaries and soft-switching issues of the buck rectifier are also adequately exposed to facilitate the discussions in the later chapters. The family of QSS power converters feature single-stage power processing without a dc-link low-pass filter, a unidirectional pulsating dc-link voltage, soft-switching capability with minimal extra commutation circuitry, simple PWM control, and high efficiency and reliability. Some other non-isolated QSS power conversion examples including VSI/CSR, and matrix converter are given.

Chapter 3: A new soft-switched single-phase quasi-single-stage (QSS) bi-directional inverter/rectifier (charger) topology is derived based on the QSS power conversion concept elaborated in Chapter 2. It is functionally equivalent to the single-stage, cycloconverter-based topology, yet performance-wise, superior to the latter. A simple active voltage clamp branch is used to clamp the otherwise high transient voltage on the current-fed ac side, which is caused by the unavoidable leakage inductance of the transformer, and at the same time, to achieve ZVS for the switches in the output side bridge. Seamless four-quadrant operation in the inverter mode, and rectifier operation with unity power factor in the charger (rectifier) mode is realized with the proposed uni-polar center-aligned PWM scheme. Single-stage power conversion, standard half-bridge connection of devices, soft-switching for all the power devices, low conduction loss, simple center-aligned PWM control, and high reliability and efficiency are among its salient features. Experimental results on a 3 kVA bi-directional inverter/rectifier prototype validate the reliable operation of the circuit.

The proposed basic QSS inverter/rectifier topology can also be extended to include other single-phase topologies, such as the inverter/rectifier with a full-bridge primary circuit, and the three-phase bi-directional inverter/rectifier. In the three phase case, a QSS isolated three-phase ZVS boost rectifier can be easily obtained by replacing the dc-side switches with diode rectifiers in the bi-directional topology.

The circuits in this family all involve the isolated boost operation when the power is enforced to flow from the current-fed side to the voltage-fed side. Although with a simple active voltage clamp branch, the transient voltage can be effectively suppressed theoretically, the voltage overhead necessary on the clamp capacitor, and the transient voltage induced by the parasitic inductance in the layout may limit their applications in high-voltage off-line applications, e.g. in the case of a 480 V three-phase ac supply.

Chapter 4: A new QSS isolated three-phase ZVZCS buck PWM rectifier for high-power off-line applications is proposed. It consists of a three-phase buck bridge switching under zero current and a phase-shift-controlled full-bridge with ZVZCS, while no intermediate dc-link is involved. Input power and displacement factor control, input current shaping, tight output voltage regulation, high-frequency transformer isolation, and soft-switching for all the power devices are realized in a unified single stage. Because of ZVZCS operation, it can work at high switching frequency while maintaining reliable operation and achieving higher efficiency than that with standard two-stage approaches.

The general topological concept of ZVZCS full-bridge dc-dc converters is also introduced, and possible implementations summarized. The concept is then extended to the case of QSS isolated three-phase buck PWM rectifier to obtain a family of isolated ZVZCS buck rectifiers. The circuits in the family all feature a pulsating dc-link, hybrid ZVZCS operation, global soft-switching capability, and relatively simple implementation. Simulation results validate the principles of operation of these circuit topologies.

Chapter 5: The concept of charge control (or instantaneous average current control) of three-phase buck PWM rectifiers is introduced. It controls precisely the average input phase currents to track the input phase voltages by sensing and integrating only the dc rail current, realizes six-step PWM, and features simple implementation, fast dynamic response, excellent noise immunity, and is easy to realize with analog circuitry or to integrate. One particular merit of the scheme is its capability to correct any duty-cycle distortion incurred on only one of the two duty-cycles which often happens in the soft-switched buck rectifier topologies because of the intervention of the soft-switching action. Another merit with this scheme which is practically important is the smooth transition of the input currents in the 60^o sector boundaries because the charge controller is always reset in every switching cycle. The concept, implementation, and design guidelines are addressed. Simulation and preliminary experimental results show that smooth operations and high quality sinusoidal input currents in the full line cycle can be achieved. The proposed control scheme can be easily extended to realize different PWM patterns, and to control various three-phase buck rectifier-based systems.