A Review of Single-Phase Improved Power Quality AC–DC Converters

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***Abstract*—Solid-state switch-mode rectification converters have reached a matured level for improving power quality in terms of power-factor correction (PFC), reduced total harmonic distortion at input ac mains and precisely regulated dc output in buck, boost, buck–boost and multilevel modes with unidirectional and bidirectional power flow. This paper deals with a comprehensive review of improved power quality converters (IPQCs) configurations, control approaches, design features, selection of components, other related considerations, and their suitability and selection for specific applications. It is targeted to provide a wide spectrum on the status of IPQC technology to researchers, designers and application engineers working on switched-mode ac–dc converters. A classified list of more than 450 research publications on the state of art of IPQC is also given for a quick reference.**

***Index Terms*—AC–DC converters, harmonic reduction, improved power quality, power-factor correction, switch-mode rectifiers (SMRs).**

I. Introduction

SOLID-STATE ac–dc conversion of electric power is widely used in adjustable-speed drives (ASDs), switch-mode power supplies (SMPSs), uninterrupted power supplies (UPSs), and utility interface with nonconventional energy sources such as solar PV, etc., battery energy storage systems (BESSs), in process technology such as electroplating, welding units, etc., battery charging for electric vehicles, and power supplies for telecommunication systems, measurement and test equipments [1]–[25]. Conventionally, ac–dc converters, which are also called rectifiers, are developed using diodes and thyristors to provide controlled and uncontrolled dc power with unidirectional and bidirectional power flow. They have the demerits of poor power quality in terms of injected current harmonics, caused voltage distortion and poor power factor at input ac mains and slow varying rippled dc output at load end, low efficiency and large size of ac and dc filters. In light of their increased applications, a new breed of rectifiers has been developed using new solid state self commutating devices such as MOSFETs, insulated gate bipolar transistors (IGBTs), gate turn-off thyristors (GTO), etc., even some of which have either not been thought or not possible to be developed earlier using diodes and thyristors. Such pieces of equipment are generally known as converters, but specifically named as switch-mode rectifiers (SMRs), power-factor correctors (PFCs), pulsewidth-modulation (PWM) rectifiers, multilevel rectifiers, etc. Because of strict requirement of power quality at input ac mains several standards [1]–[3] have been developed and are being enforced on the consumers. Because of severity of power quality problems some other options such as passive filters, active filters (AFs), and hybrid filters [6]–[8] along with conventional rectifiers, have been extensively developed especially in high power rating and already existing installations. However, these filters are quite costly, heavy, and bulky and have reasonable losses which reduce overall efficiency of the complete system. Even in some cases the rating of converter used in AF is almost close to the rating of the load. Under these observations, it is considered better option to include such converters as an inherent part of the system of ac–dc conversion, which provides reduced size, higher efficiency, and well controlled and regulated dc to provide comfortable and flexible operation of the system. Moreover, these new types of ac–dc converters are being included in the new text books [9]–[22] and several comparative topologies are reported in recent publications [23]–[25]. Therefore, it is considered a timely attempt to present a broad perspective on the status of ac–dc converters technology for the engineers working on them dealing with power quality issues.

This paper deals with a comprehensive survey on the topic of SMR converters. More than 450 publications [1]–[463] are reviewed and classified into four major categories. Some of them are further classified into several subcategories. The first one [1]–[25] is generally on power quality standards, other options, texts, and some survey and comparative topology publications. These converters are subclassified as boost [26]–[250], buck [251]–[306], buck–boost [307]–[427], and multilevel [428]–[463] with unidirectional and bidirectional power flow. The total number of configurations of these converters is divided into eight categories. Some publications belong to more than one category and have been included in the more dominant contribution. The paper is divided into nine sections. Starting with Section I, the others sections cover the state of the art of IPQC technology, configurations, control approaches, components selection, and integration of IPQCs, comparative

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features and others options for power quality improvement, selection considerations for specific applications, latest trends and future developments in IPQC technology, and conclusive observations.

II. State of the Art

The IPQC technology has been developed now at a reasonably matured level for ac–dc conversion with reduced harmonic currents, high power factor, low electromagnetic interference (EMI) and radio frequency interference (RFI) at input ac mains and well-regulated and good quality dc output to feed loads ranging from fraction of Watt to several hundred kilowatts power ratings in large number of applications. It has been revolutionized in the last couple of decade with varying configurations, control approaches, solid-state devices, circuit integration, varying magnetics, etc., for features such as boost, buck, buck–boost, and multilevel with unidirectional and bidirectional power flow. A large number of IPQC configurations have been evolved to suit vastly varying requirements of different applications while maintaining a high level of quality at the input ac source and output dc loads. This section contains the chronological development and the status of the IPQC technology.

With the extensive use of solid-state ac–dc conversion, the power quality has become an important issue [5], [9], [16], [20], [21]. With the increasing use of these converters at vast varying power and voltage levels, these IPQC are classified in four major categories, namely boost, buck, buck–boost, and multilevel converters with a high level of power quality at the input ac source and at dc output.

Since in some applications, a constant regulated output dc voltage is required with unidirectional power flow such as in SMPSs, low-rating ASDs in fans, air conditioners, etc., while in a few applications, a bidirectional power flow is required. Therefore, these IPQCs are categorized into unidirectional boost converter [26]–[202] and bidirectional boost converter [203]–[250]. Moreover, there are a large number of applications which require wide varying dc voltage normally fed from conventional semi-converter and fully controlled thyristor converter with unidirectional and bidirectional power flow. To replace, conventional thyristor based semi-converters and full converters, a breed of improved power quality converters has been developed and classified as unidirectional buck [251]–[300], bidirectional buck [301]–[306] with PWM switching and using self-commutating solid-state devices. Moreover, there are some typical applications, which require buck and boost operations in the same converter, therefore, an additional classification of buck–boost converter [307]–[427] is made with unidirectional and bidirectional power flow. However, for high-voltage and high-power applications, the concept of multilevel converters is developed which may avoid a low-frequency transformer, and reduces the switching frequency of the devices. Next, the category of IPQCs is considered as multilevel converters with unidirectional [428]–[442] and bidirectional power flow [443]–[463].

One of the major reasons for such a remarkable development in ac–dc converters is due to self-commutating devices, namely, for small power rating, MOSFETs have unsurpassed performance because of their high switching rate with negligible losses. In the medium-power rating, an IGBT is considered an ideal device for such converters with PWM technology. In higher a power rating the GTO is normally used with self-commutating and reverse voltage-blocking capabilities at only a few kilohertz switching frequency. Many manufacturers are developing intelligent power modules (IPMs) to give a cost-effective and compact structure to the IPQCs. Another breakthrough has been in IPQCs because of fast-response Hall-effect voltage and current sensors, and isolation amplifiers normally required for the feedback used in the control of these ac–dc converters result in a high level of dynamic and steady-state performance. Many manufacturers such as ABB, LEM, HEME, Analog Devices, and others are offering these sensors at competitive low prices.

Another major push for the technology of IPQC has been due to a revolution in microelectronics. Because of heavy volume requirement, a number of manufacturers such as Unitrode, Analog Devices, Siemens, Fairchild, etc., have developed the dedicated ICs for the cost-effective and compact features to control these converters. Moreover, high-speed and high-accuracy microcontrollers and digital signal processors (DSPs) are available at reasonably low cost. Many processors are developed to give direct PWM outputs with fast software [69], [82], [140] normally used in some of these converters, which reduces hardware drastically. With these processors it is now possible to implement new and improved control algorithms of real-time control to provide fast dynamic performance of IPQCs. Starting with conventional proportional–integral (PI) controllers, sliding-mode-, fuzzy-logic-, and neural-network-based controllers have been employed in the control of these converters. Apart from this, a number of models of instruments are available to measure the performance of these IPQC which are named as power analyzers, power scopes, power monitors, spectrum analyzers, etc., which give direct harmonic bar spectrum, total harmonic distortion even up to 51st order of harmonics, power factor (PF), crest factor (CF), displacement factor (DF), kVA, kVAR, kW, and energy consumed, ripples, surge, swell, notch width, and height, etc.

III. Configurations

IPQCs are classified on the basis of topology and type of converter used. The topology-based classification is categorized on the basis of boost, buck, buck–boost, multilevel, unidirectional and bidirectional voltage, current, and power flow. The converter type can be step-up and step-down choppers, voltage-source and current-source inverters, bridge structure, etc. Figs. 1 and 2 show these two types of classifications of IPQCs.

A. Topology-Based Classification

This classification of IPQC is based on the topology used in the converters. These are classified as boost, buck, buck–boost, and multilevel with unidirectional and bidirectional power flow. Fig. 1 shows the tree of topology-based classification of IPQCs. These converters are developed in such vastly varying configurations to fulfill the very close and exact requirement in variety

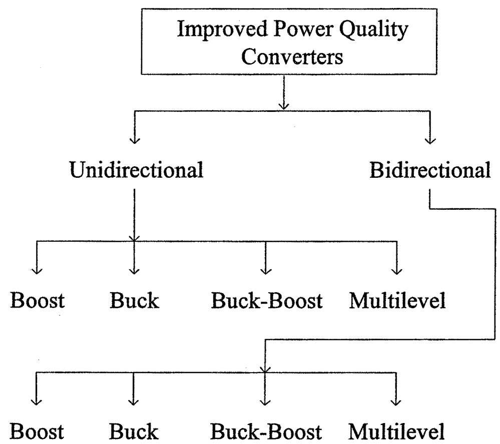

Fig. 1. Topology-system-based classification of improved power quality converters.

of applications. Some of these IPQCs are improved to provide better performance from primitive configurations. Figs. 3–10 show the basic circuit configurations of IPQCs of all eight categories for ac–dc conversion.

- **Unidirectional Boost Converters [26]–[202]**:
  Fig. 3 shows the various configurations of such converter to improve the power quality at ac mains and dc output, reduced losses and noise, enhanced compactness by drastically cutting their weight and volume. In principle, it is a combination of diode bridge rectifier and step-up dc chopper with filtering and energy storage elements. There have been many modifications as shown in Fig. 3(b)–(e) using the concept of interleaved and multicell to improve their performance. High-frequency PWM and hysteresis current control techniques are used in the control of inner current loop and wide-bandwidth closed-loop controllers in outer voltage loop of these converters to provide fast response and high level of power quality at input ac mains and dc output. These IPQCs provide well regulated dc output voltage even under wide varying ac input voltage from 90 to 300 V and frequency ranging from 40 to 70 Hz or dc input resulting in a concept of universal input in number of applications. These converters are extensively used in electronic ballasts, power supplies, variable-speed ac motor drives in compressors, refrigerators, pumps, fans, etc.
- **Bidirectional Boost Converters [203]–[250]**:
  Observing the success of previous converter, these types of converters are developed to meet the requirements of applications of bidirectional power flow in addition to improved power quality at input ac mains in terms of high power factor and low THD with well-regulated output dc voltage. Fig. 4 shows the few circuits of this type of converter. Starting from its basic topology, the other circuits are evolved to enhance its performance. Some of their applications are battery charging and discharging in line interactive UPS, BESS, and transport applications such as metro and traction. This converter is also used for utility interface with nonconventional energy sources such as solar PVs, wind, etc. The basic topology is a PWM-based voltage source inverter with an input ac filter inductor and output energy storage dc capacitor. Concept of dc-link ripple reduction is also investigated using a third active arm as shown in Fig. 4(c) and (d) to improve their performance and reduce the need of an energy storage capacitor at the dc link. These new configurations of these converters also provide fast and wide-bandwidth control of dc output.
- **Unidirectional Buck Converters [251]–[300]**:
  The basic circuits of this topology are shown in Fig. 5. It is a combination of diode rectifier with step-down chopper with input and output filters. Its performance is improved using a ripple filter at dc output for reducing harmonics in ac mains and ripples at dc output voltage. Nowadays, it is also developed using a diode rectifier with filter and various combinations of dc–dc converter with and without high-frequency transformer isolation. Fig. 5(d) shows one of such circuit using full-bridge dc–dc converter with high-frequency isolation. High-frequency transformer isolation reduces the size, cost, weight, and volume of transformer used for isolation and voltage matching. There may be many other combinations of isolated configurations using forward, push–pull, half-bridge dc–dc converters, etc using single, two or four devices. It has been developed to replace conventional thyristor based semiconverter. It has the features of high power factor, low harmonic current in the ac mains, and meets the requirement of varying controllable output dc voltage. These converters also provide very fast response compared to conventional semiconverter resulting in reduced size of ac and dc filters less stress on load and other components. It is used in the small-rating dc motor speed control, battery charging, isolated regulated dc supply, etc. In a high power rating, it can be made with a GTO as shown in Fig. 5(c).
- **Bidirectional Buck Converters [301]–[306]**:
  Fig. 6 shows two typical circuits of these converters. Its basic circuit is a PWM-based current-source inverter with self-commutating devices. Since MOSFETs, BJTs, and IGBTs do not have reverse voltage blocking capability, a series diode is required to provide reverse voltage blocking capability. However, if a GTO is used, it does not require this additional diode but cannot operate at high PWM frequency, which is a prime factor to reduce the size of the filter and energy storage elements. It can be considered as a replacement of a single-phase thyristor bridge rectifier. Similarly to that, it has unidirectional dc current with controllable bidirectional dc-link voltage to provide bidirectional power flow. It provides much faster response compared to a conventional dual converter. Output dc ripple compensation is also made using a third leg as shown in Fig. 6(b) and it needs a reduced size filter with improved performance at input ac mains and output dc load. With the double bridge connection in antiparallel, it provides performance similar to that of a conventional thyristor dual converter. In a large power rating such as in traction, it is used with several series converters with transformers for an isolated single-phase system with GTO to improve power quality at the input ac mains and at dc output. It may also be used in dc motor drives, battery charging, and to provide an ideal dc current source to feed current-source-inverter-based ac motor drives.

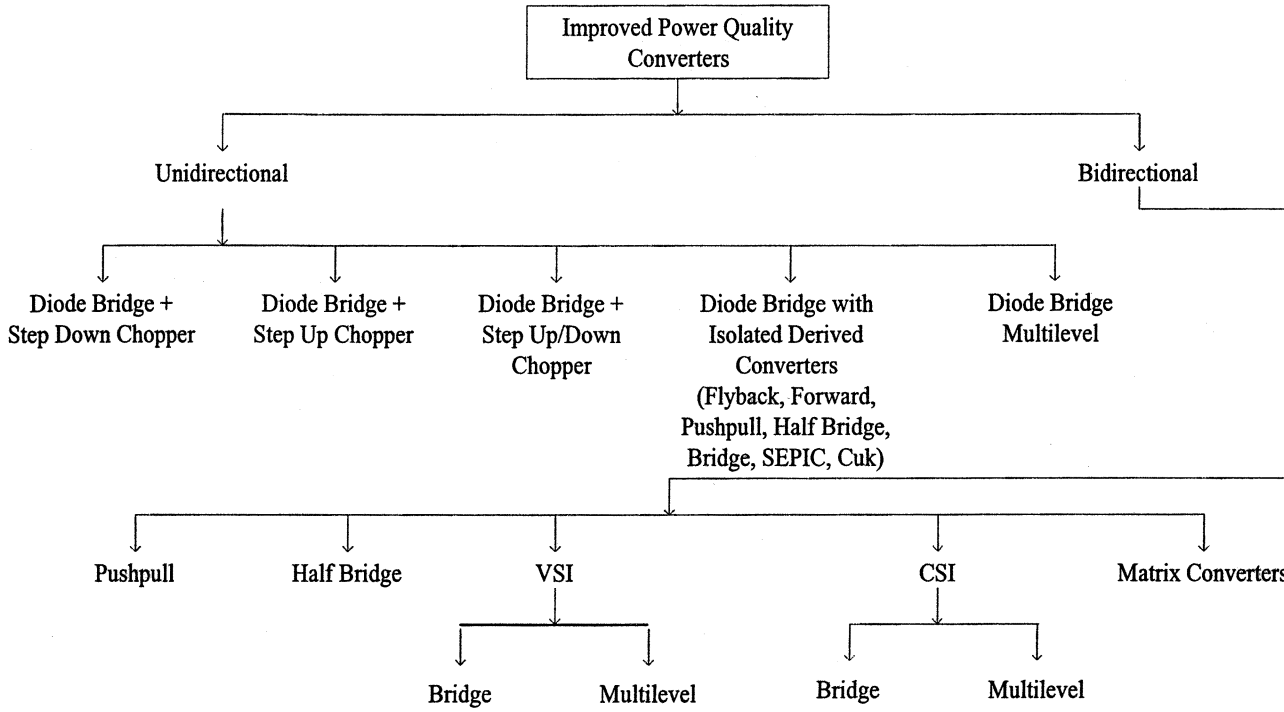

Fig. 2. Converter-based classification of improved power quality converters.

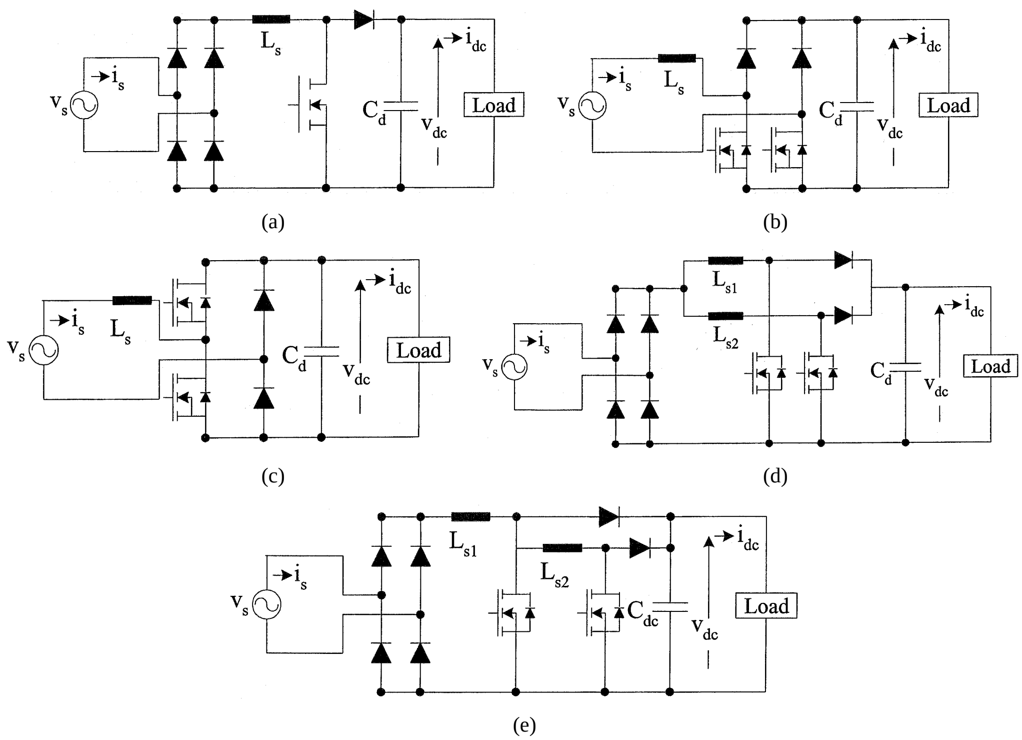

Fig. 3. (a) Unidirectional boost converter. (b) Symmetrical two-device unidirectional boost converter. (c) Asymmetrical two-device unidirectional boost converter. (d) Interleaved two-cell unidirectional boost converter. (e) Unidirectional boost converter with high frequency active EMI filter.

- **Unidirectional Buck–Boost Converters [307]–[426]**:
  These converters are developed in both nonisolated and isolated circuit configurations. Fig. 7 shows a few circuits of these converters. It is a combination of diode rectifier with buck–boost dc–dc converters. Since buck–boost converters are developed in nonisolated and isolated topologies, a large number of configurations is also reported, such as a combination of buck and boost or vice versa, buck–boost, flyback, SEPIC, Zeta, Cuk, etc. These are now cascaded with a diode rectifier to improve power quality at the ac mains with required variable controllable output dc voltage to meet the need of specific applications. High-frequency transformer isolation provides voltage adjustment for better control, safety on load equipment, compactness, reduced

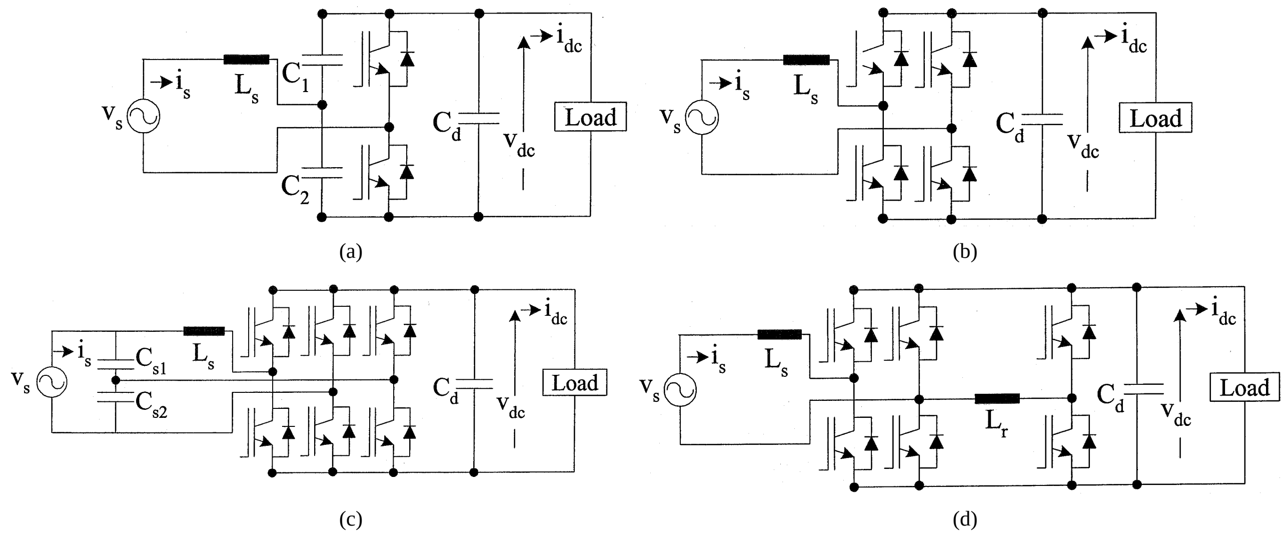

Fig. 4. (a) Half-bridge bidirectional boost converter. (b) VSI full bridge bidirectional boost converter. (c) Bridge bidirectional boost converter with dc ripple compensation using ac midpoint capacitors and third leg. (d) Bridge bidirectional boost converter with dc ripple compensation using an inductor and third leg.

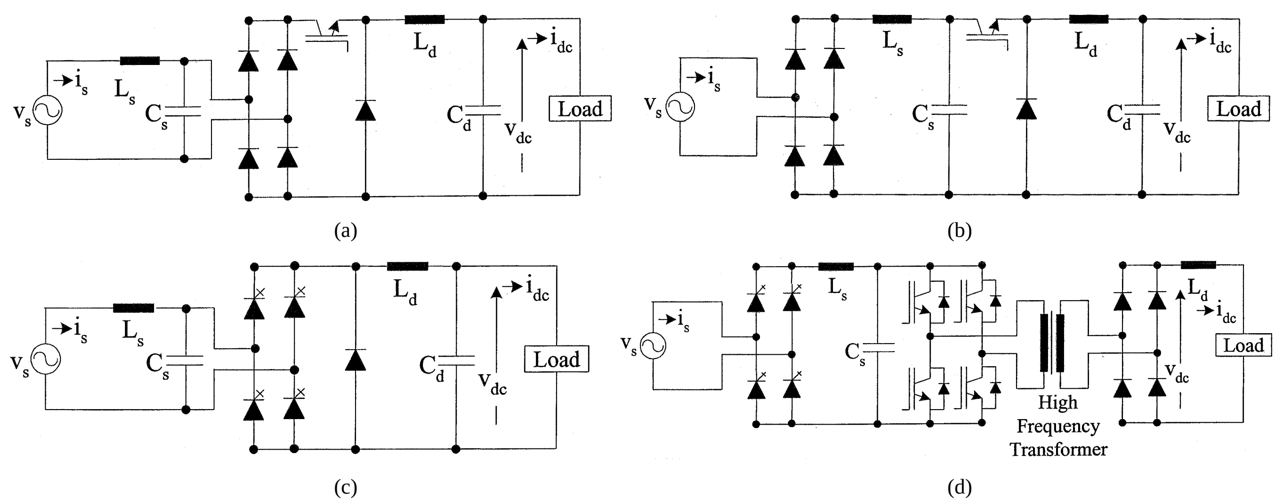

Fig. 5. (a) Unidirectional buck converter with input ac filter. (b) Unidirectional buck converter with input dc filter. (c) GTO bridge-based unidirectional buck converter. (d) Unidirectional buck converter with high frequency isolated dc–dc buck stage.

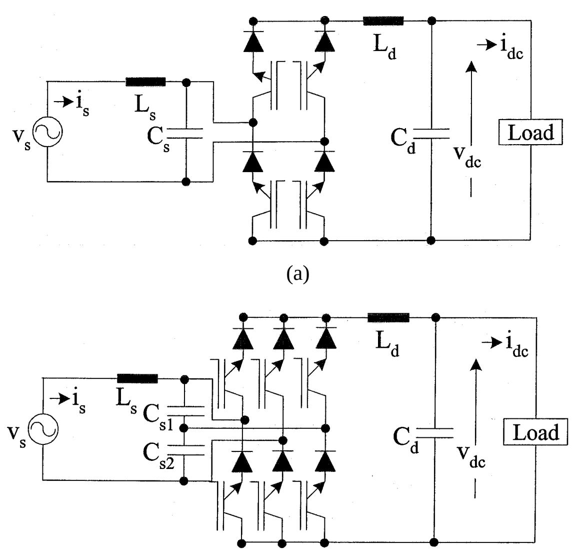

Fig. 6. (a) Bidirectional buck converter. (b) Bidirectional buck converter with a neutral leg.

weight, size, losses, and their suitability to the varying applications. Moreover, it needs only a single switch as shown in Fig. 7(b)–(e) which is inherently capable of giving regulated dc output with reduced ripple and high power factor and low THD at the ac mains through proper control. The concept of soft switching using resonant circuits is also used to reduce switching stresses and losses in the devices to operate at high switching frequency to further reduce the size of magnetics and energy storage elements. Therefore, a large number of circuit topologies is possible and used but here only a few basic circuits are given to provide a basic understanding and exposure to f these converters. These IPQCs are extensively used in SMPSs, railway signaling, battery chargers, UPSs; small-rating brushless ac motor drives, etc.

- **Bidirectional Buck–Boost Converters [427]**:

  Fig. 8 shows the circuit of this type of converter. This circuit is similar to a matrix converter, which outputs variable bidirectional dc voltage and reversible current. It is quite a versatile converter with bidirectional power flow. It can work

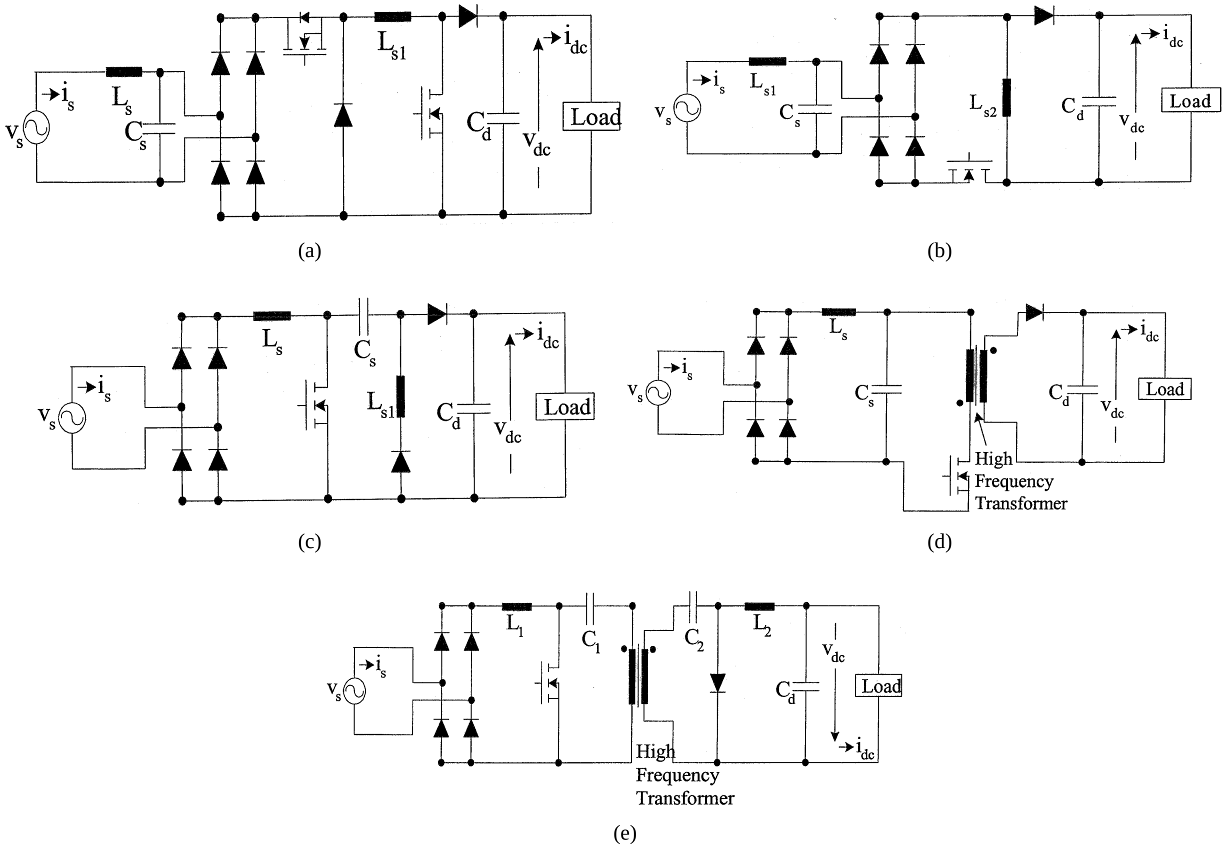

Fig. 7. (a) Cascaded unidirectional buck–boost converter. (b) Single-device unidirectional buck–boost converter. (c) SEPIC-derived unidirectional buck–boost converter. (d) Flyback-based unidirectional buck–boost converter. (e) Isolated Cuk-derived unidirectional buck–boost converter.

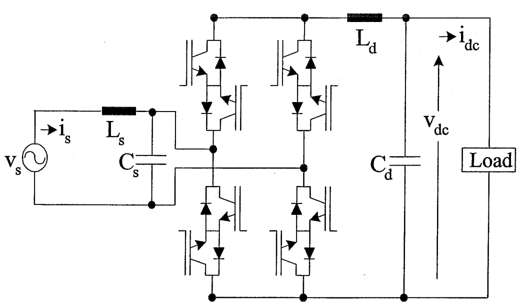

Fig. 8. Bidirectional buck–boost converter.

as a current-source or a voltage-source rectifier and inverter with reduced energy storage elements for fast response. It is a most interesting converter, which operates as a four-quadrant converter and has the capability of operating in buck as well as boost mode. Here, increasing its switching frequency can further reduce the size of input and output filters. However, for a high power rating, it can be implemented using a GTO which also avoids the series diode normally used with IGBTs to provide reverse voltage blocking capability.

- **Unidirectional Multilevel Converters [428]–[442]**:

Fig. 9 shows the five circuits of these types of converters. It is implemented using diode rectifier with PWM controller and active bidirectional switch to reduce the harmonics. Many circuit configurations are reported in the literature [430], [433], [440], [441] and few are shown in Fig. 9(a)–(e) using unidirectional and bidirectional switches with single, dual, and three capacitors at the dc link. It can be half bridge as shown in Fig. 9(a) and full bridge as given in Fig. 9(b)–(e) with varying features. These converters provide high power factor and reduced THD of current at the input ac mains and ripple-free regulated dc output voltage. It reduces the stresses on the components and their rating and provides same level of performance at reduced switching frequency, thus resulting in low switching losses and high efficiency. These are extensively used for feeding the variable-speed drive employing brushless motors with an inverter having unidirectional power flow in applications such as air conditioning, variable speed fans, pumps, compressors, etc.

- **Bidirectional Multilevel Converters [443]–[463]**:

Other types of bidirectional boost converters are multilevel converters as shown in Fig. 10. These converters offer the advantages of low voltage stresses on switches, reduced losses at reduced switching frequency for the same level of performance in terms of reduced harmonics and high power factor at the input ac mains and regulated ripple-free dc output voltage at varying loads. These are further classified as diode clamped (Fig. 10(b)), flying capacitor (Fig. 10(c)), and cascaded (Fig. 10(d)) multilevel converters. These converters have bidirectional power flow and are used for even high-power applications such as BESS, metros, traction, etc. These can be developed for a higher number of levels for high-voltage and high-power applications. It has been reported that the ac supply current THD can be reduced below 1% without using PWM control [446].

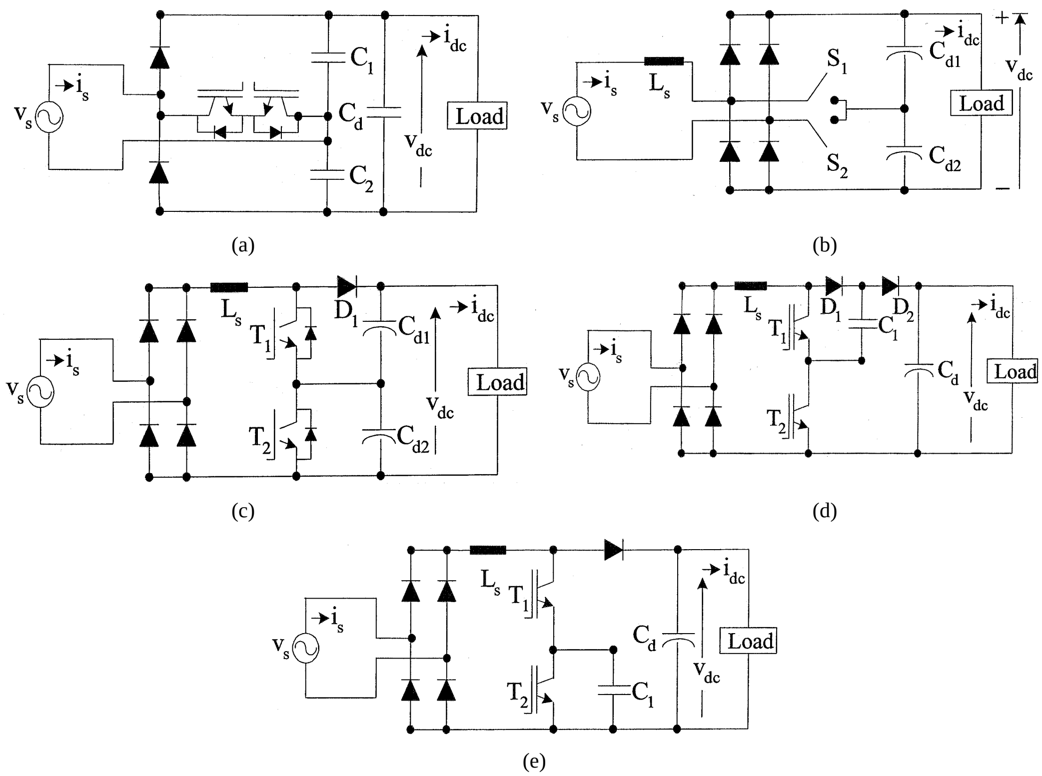

Fig. 9. (a) Half-bridge unidirectional multilevel converter. (b) Two-bidirectional-switch unidirectional multilevel converter. (c) Two-switch midpoint unidirectional multilevel converter. (d) Adapted unidirectional multilevel converter. (e) Modified adapted unidirectional multilevel converter.

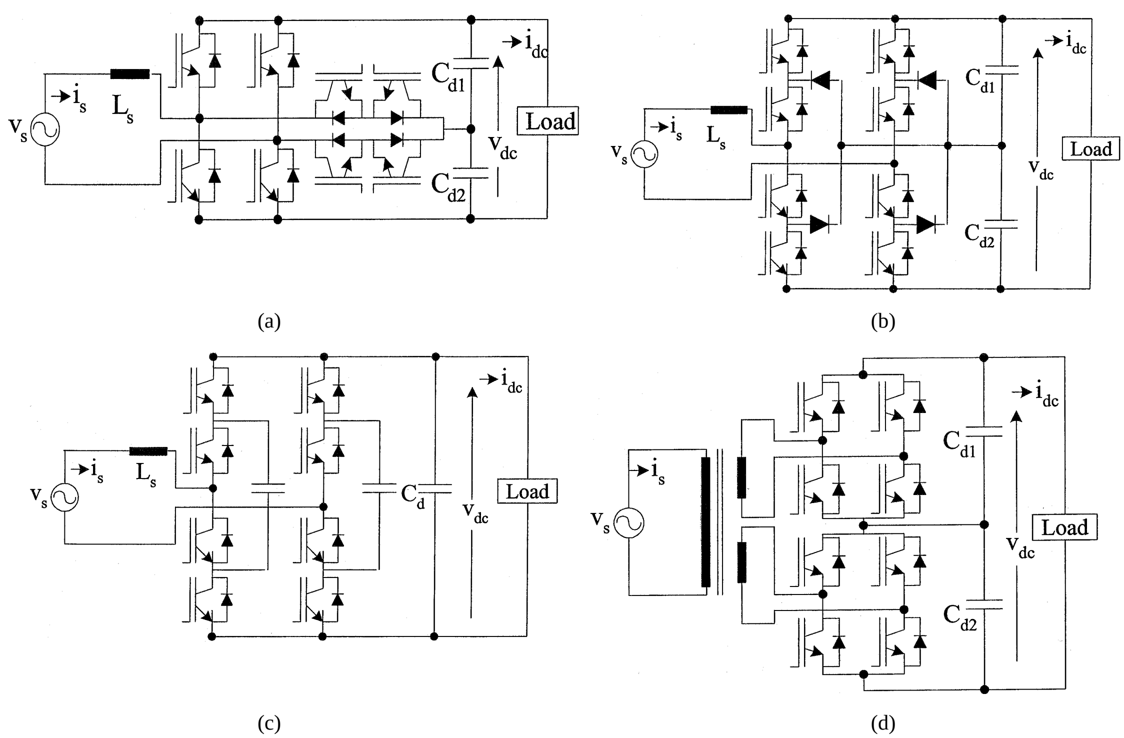

Fig. 10. (a) Bidirectional three-level converter using two bidirectional switches. (b) Bidirectional diode clamped three-level converter. (c) Bidirectional flying capacitor clamped three-level converter. (d) Bidirectional cascaded five-level converter.

The stepped voltage waveform generated by multilevel converters avoids high-order harmonics, reduces switch losses and stress on switching devices, and these are most suitable for high-power and high-voltage applications.

B. Converter-Based Classification

This type of classification is based on the converter used as shown in Fig. 2. These are broadly classified into two types, namely, unidirectional and bidirectional converters.

Unidirectional converters are realized using a diode bridge in conjunction with other basic power electronic converters, namely, step-down chopper, step-up chopper, step-up/down chopper, isolated, forward, flyback, push pull, half bridge, bridge, SEPIC, Cuk, Zeta, etc., and multilevel converters. The concept of multicell, interleaved, and soft switching are pioneer developments to improve their performance. Nowadays, these converters are implemented in a single stage to reduce the size, cost, weight, volume, and losses. A high-frequency isolation transformer offers reduced size, cost, weight, appropriate voltage matching, and isolation to optimum voltage. Multilevel converters have the advantages of low stresses on the devices, low losses and, thus, high efficiency, and are suitable for high-power applications. It has a stepped voltage waveform instead of PWM and has reduced high-frequency currents. Unidirectional converters are quite popular in a large number of applications such as power supplies, variable-speed drives for fans, compressors, air conditioning, etc.

Bidirectional ac–dc converters consist of basic converters normally used in inverters such as push–pull, half-bridge, voltage-source inverters, current-source inverters employing MOSFETs for low-power, IGBTs for medium-power, and GTOs for high-power converters. These ac–dc converters are extensively employed for adjustable-speed drives used to drive active loads such as a hoist, a crane, traction, etc., line interactive UPS, and BESS. Four-quadrant ac–dc converters are normally implemented using matrix converters. These converters have the additional features of boosting output dc voltage in comparison to classical thyristor-based dual converters. Multilevel converters with a higher number of levels have the advantages of avoiding low-frequency transformer magnetics and PWM switching, resulting in reduced size, high efficiency, and reduced high-frequency noise. These are considered a new breed of converters for high-voltage and high-power applications.

IV. Control Strategies

The control strategy is the heart of IPQCs and normally implemented in three parts. In the first part of control, the essential variables used in control are sensed and scaled to feed to the processors for the use in control algorithm as the feedbacks. These signals are input ac mains voltage, supply current, output dc voltage, and, in some cases, additional voltages such as capacitor voltage and inductor current, which are used in the intermediate stage of the converters. The ac voltage signal is sensed using potential transformers (PTs). Hall-effect voltage sensors, isolation amplifiers, and low-cost optocouplers are used to sense dc voltages, especially in small power supplies. These voltage signals are scaled and conditioned to the proper magnitude to feed to the processors via ADC channels or as the synchronizing signals for zero-crossing detection. The current signals are sensed using current transformers (CTs), Hall-effect current sensors, and low-cost shunt resistors or tapped isolated winding in the inductors to reduce the cost. These current signals are also conditioned and used as the feedbacks at different stages of control either in control algorithm or in current control stage such as in PWM controllers or in both stages of control. These signals are sometimes filtered either through analog hardware circuits or through software in the processor to avoid noise problems in the control. These sensed voltage and current signals are also used sometimes to monitor, measure, protect, record and display the various performance indices such as THD, displacement factor, distortion factor, power factor, crest factor, individual harmonics, ripple factor, percentage ripples, sag and swell, surges and spikes, components stresses, etc. The cost of these sensing devices such as Hall-effect sensors and other components used in sensing are drastically reducing day by day because of mass manufacturing and competition among the manufacturers. Moreover, some indirect sensing of these signals is also used through additional feedback nodes (terminal) in the IPM of MOSFETs and IGBTs to reduce the cost and to enhance the reliability of the converter.

The second stage of control, which is the heart of the control strategy, is the control algorithm responsible for the high-level transient and steady-state performance of the IPQCs. The control algorithms are implemented through analog controllers, low-cost microcontrollers, fast high number of bits DSPs, application- specific integrated circuits (ASICs) depending upon the rating, customer requirements, cost, and types of converters. Normally, dc output voltage of the converters is the system output used as feedback as in outer closed loop control and various control approaches such as PI controller, proportional–integral–derivative (PID) controller, sliding-mode control (SMC) [196], [230], [342], [385] also known as variable-structure control (VSC), fuzzy logic controllers (FLCs) [77], [147], adaptive controllers, neural-network (NN)-based controllers [54] are employed to provide fast dynamic response while maintaining the stability of the converter system over the wide operating range. The output of this voltage controller is normally considered the amplitude of the ac mains input current or indirect derived current such as inductor current and multiplied with unit template derived in phase of ac voltage to generate the desired reference unity power factor, sinusoidal supply current.

The third stage of the control strategy of the IPQCs is to derive the gating signals for the solid-state devices of the converters. The reference supply current along with sensed supply current is used in the current controller, which directly generates the switching signals. A number of current controllers namely hysteresis, PWM current or PWM voltage control through proportional, PI, PID, SMC, FLC, and NN-based controllers, are implemented either through hardware (analog and digital ICs) or through software in the same processors (DSPs or microcontrollers, which are used in the second stage) to derive the gating signals. Nowadays, processors are available which are developed only for power electronics applications and have dedicated PWM controllers as an inbuilt feature to implement concurrently all three stages of the control strategy for improving the transient and steady-state performance of the IPQCs.

Moreover, in some control approaches, the second and third parts of the control strategy of IPQCs are implemented in the integrated manner over the sensed voltage and current signal. The voltage and/or current or derived power signals are used in the closed loop controllers to derive reference current or voltage signals for generating directly gating signals. The concurrent and integrated implementation of three stages of control algorithm provides cost-effective, compact, and fast response of the IPQCs.

The derived gating signals, obtained either through digital output from the processors or dedicated hardware, are normally fed to the optocoupler for isolation, and then amplified to the required level before giving them to the power devices of IPQCs. There are some dedicated driver ICs for this purpose, which result in compact and clean interfacing between control and power stages of the hardware. Moreover, nowadays, IPMs are developed which provide inherent inbuilt derivers along with protection in the power modules. However, the complete integration of control, interfacing and power module of the IPQCs are on the race of development to provide compact, cost-effective, reliable, reduced-weight, and high-efficiency ac–dc converters. Because of heavy application potential of some of the IPQCs, many semiconductor manufacturers have developed dedicated ICs, namely, Unitrode (UC3854), Motorola (MC34261), Analog Devices (ADMC 401), Siemens (TDA 16 888), Texas (TMS320F240), etc., for the control of these converters.

V. Components Selection and Integration of IPQCs for Specific Applications

The selection of components of the IPQCs is very important to achieve a high level performance of ac–dc converters. The main and costly component of the IPQCs is the solid-state power device. In small power rating converters, normally MOSFETs are used resulting in reasonably high efficiency even at high switching frequency responsible to reduce the size of magnetics. In medium power rating IPQCs, IGBTs are invariably used because of their good gating characteristics and capability to operate in wide switching frequency range to make optimum balance between magnetics, size of filter components and switching losses. In a high power rating, GTOs are normally used with advantages of self-commutating and reverse voltage-blocking capability.

The concepts of power module, IPM, smart devices, etc., have given a real boost to IPQCs technology because of circuit integration, compactness, cost reduction, reduced noise, and high efficiency. With the several power devices in one module along with their gating and protection integration, it has become possible to develop small-sized and lightweight IPQCs. In many cases, the complete control of IPQCs is also integrated in the same module along with the required modifications to suit for specific applications.

Another set of components of IPQCs is the energy storage elements such as inductors, capacitors and other devices used in filters, protection circuits and resonating circuits. For example, a series inductor at the input of a PFC or VSI bridge working as bidirectional boost converter is normally employed as the buffer element between ac mains voltage and PWM voltage generated by the converter to shape the input current into desired manner. The value of this inductor is quite crucial in the performance of IPQCs. With the small value of this inductor the large switching ripples are injected in to supply current, and large value of it does not allow shaping the ac mains current in the desired fashion. Therefore, the optimum selection of this inductor is essential to achieve satisfactory performance of the IPQCs. Similarly, the value of capacitor and inductor as an input filter in buck converter is also quite important for proper response, stability and optimum design of the IPQCs. Moreover, the design of the inductors is also very important to avoid saturation and reducing losses under ac, dc, and mixed excitation. The value of dc-bus capacitor in boost converters and *LC* filters in buck converters is quite crucial as it affects the response, cost, stability, size and efficiency. A small value of the capacitor results in large ripple in steady state and big dip and rise in dc-link voltage under transient conditions. A high value of it reduces the dc voltage ripple but increases cost, size, and weight.

Transformers operating at high frequency are used in power supplies in which transformer weight, size, and rating are quite important. There are continuous attempts to reduce their size and cost through new configurations. The high-frequency transformers are also used in isolated topologies of IPQCs and their design is very important to reduce size, cost and losses. The use of newer magnetic materials and operating frequency plays an important role to revolutionize the technology of IPQCs especially in some power supplies.

Some of the IPQCs are developed as an integral part of total converter system for few typical applications. In case of high-frequency electronic ballasts for lighting systems, PFC-based IPQCs are the integral part of high frequency converter system because of compactness for reducing total number of solid-state devices and their control. Similarly, a PFC-based IPQC is also an integral part of switch-mode power supplies, battery chargers, inverter-fed variable-speed drives, etc. Since IPQCs are used as an input front-end converter to feed number of converter and inverter systems for many applications, it is now a very common feature to integrate IPQCs with the second stage converter, resulting ina single-stage and/or compact, high-power-density, lightweight, reduced-cost, efficient complete converter system. Moreover, dedicated controllers are also available for an integrated unit to reduce the cost and to enhance the reliability of total system.

VI. Comparative Features of IPQCs and Other Options of Power Quality Improvement

The classified IPQCs of eight categories mentioned in the previous section do not clash with each other in the way of ac–dc conversion and have all together different features to suit a number of applications. Therefore, according to the requirement of application and/or second stage conversion, a particular choice of IPQCs may be considered to provide the most suitable option. However, within the same category of IPQCs, there are many circuits which have relative merits and demerits toward ideal characteristics. Typically, for example, in a single-phase unidirectional boost converter, there is a basic circuit with one device and other circuits with two devices, interleaved and multicell configurations. These additional configurations have improved performance but at higher cost. Therefore, the designer has to decide a configuration of a particular IPQCs on the basis of a tradeoff between performance and cost. A similar comparison exists for other IPQCs within their different configurations. In a few cases, a choice can also be made among different IPQCs for specific applications. However, in such cases, there are not many options for the selection to the designer and one can have straightforward decision to opt right IPQC, which offers better performance at comparable cost. There are many publications which can be looked at for such comparisons among different circuit configurations [23], [24], [45], [60], [144], [187], [188], [250], [296], [333], [402], [405]. There are also some other options for power quality improvement in ac–dc conversion. For example, one can choose a series active filter or shunt active filter or hybrid filter in the input of diode rectifier with capacitive filter at dc output to feed a number of dc loads [6]–[8]. It means one can have a number of options to select one of the best converter for a particular application. For example, if a diode bridge rectifier is already working at sites then the filter may be right choice in such cases. Moreover, one has to decide the best filter configuration among all possible options. However, if a designer is at the decision design stage then IPQCs may be a better option, which may provide improved performance in terms of output dc voltage regulation and high power factor and low THD of the mains current. Similar situations may occur in a number of cases and the design engineer must be aware of all possible options and their relative features to select the best converter from the overall point of view.

VII. Selection Considerations of IPQCs for Specific Applications

Selection of IPQCs for a particular application is an important decision for application engineers. The following are a few factors responsible for selection of right converter configuration for specific applications:

- required level of power quality in input (permitted PF, CF, THD);
- type of output dc voltage (constant, variable, etc.);
- power flow (unidirectional and bidirectional);
- number of quadrants (one, two, or four);
- nature of dc output (isolated, nonisolated);
- requirement of dc output (buck, boost, and buck–boost);
- required level of power quality in dc output (voltage ripple, voltage regulation, sag and swell);
- type of dc loads (linear, nonlinear, etc.);
- cost;
- size;
- weight;
- efficiency;
- noise level (EMI, RFI, etc.);
- rating (W, kW, MW, etc.);
- reliability;
- number of dc outputs;
- environment (ambient temperature, altitude, pollution level, humidity, types of cooling, etc.).

Moreover, these are only a few factors. There are some other considerations such as comparative features of other options of power quality improvement, types of device, magnetic components, protection, etc., in the selection of best IPQCs for a specific application.

VIII. Latest Trends and Future Developments in IPQCs Technology

IPQCs technology has been developed to a mature level and is finding widespread applications in fraction of watt power supplies to megawatt converter systems in ac–dc–ac link, BESSs, ASDs, etc. However, there are consistent new developments in IPQCs for further improvements in their performance. Some of the new trends are soft-switching techniques to reduce switching losses in IPQCs even at high switching frequency to enhance the dynamic response and to reduce the size of energy storage elements (filters at input and output, high-frequency transformers). The concept of interleaved and multicell is used in the development of PFC-based IPQCs to improve performance and to eliminate EMI passive filters. The new developments toward single-stage conversion have resulted in increased efficiency, reduced size, high reliability, and compactness of IPQCs.

Sensor reduction has also revolutionized the IPQC technology to reduce the cost and enhance the reliability. Dedicated ASICs for the control of IPQCs are finding wide spread use in the new applications. The new approaches in multilevel converters are offering high efficiency, reduced stress on devices, and reduced high-frequency noise.

The further improvement in solid-state device technology in terms of low conduction losses, higher permissible switching frequency, ease in gating process, and new devices especially with low voltage drop and reduced switching losses will give a real boost for IPQCs in low-voltage dc power applications required for high-frequency products. The multiple device integration into a single power module as a cell for direct use as a configuration of IPQCs will result in size reduction, increased efficiency, and a low-cost option. The sensors, control, gating, and protection integration in the IPM will provide a new direction in the development of IPQCs. Dedicated processors and ASICs development for IPQCs are also expected in the near future to reduce their cost, ease in control, and compact and efficient ac–dc conversion. Soft-switching technology is also to be a big hope to relieve thermal design, size reduction, and improving the efficiency of ac–dc converters. The invention of new configurations and conversion stage reduction in IPQCs will explore a number of newer applications.

IX. Conclusion

An exhaustive review of IPQCs has been presented to explore a wide perspective of various configurations of IPQCs to researchers, designers, application engineers, and end users of ac–dc converters. A broad classification of IPQCs into eight categories with further subclassification of various circuits is expected to provide easy selection of an appropriate converter for a particular application. These IPQCs can be considered to be a better alternative for power quality improvement because of reduced size of overall converter, higher efficiency, lower cost, and enhanced reliability compared to other means of power quality improvement. These converters provide improved power quality not only at the input ac mains but also at dc output for the better overall design of equipment. These converters have given the feature of universal input to the number of products which can have input power either from ac mains of a varying voltage of 90 to 300 V with a varying frequency from 40 to 70 Hz or dc input.

Moreover, the use of these IPQCs results in equipment behaving as a linear resistive load at the ac mains. The new developments in device technology, processors, magnetics, and control algorithms will give a real boost to these IPQCs in the near future. It is hoped that this survey on IPQCs will be a useful reference to the designers, users, manufacturers, and researchers working on ac–dc converters.

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