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

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***Abstract*—Three-phase ac–dc converters have been developed to a matured level with improved power quality in terms of power-factor correction, reduced total harmonic distortion at input ac mains, and regulated dc output in buck, boost, buck–boost, multilevel, and multipulse modes with unidirectional and bidirectional power flow. This paper presents an exhaustive review of three-phase improved power quality ac–dc converters (IPQCs) configurations, control strategies, selection of components, comparative factors, recent trends, their suitability, and selection for specific applications. It is aimed at presenting a state of the art on the IPQC technology to researchers, designers, and application engineers dealing with three-phase ac–dc converters. A classified list of around 450 research articles on IPQCs is also appended for a quick reference.**

***Index Terms*—Harmonic reduction, improved power quality, power-factor correction, switch-mode rectifiers, three-phase ac–dc converters.**

I. Introduction

THREE-PHASE ac–dc conversion of electric power is widely employed in adjustable-speeds drive (ASDs), uninterruptible power supplies (UPSs), HVdc systems, and utility interfaces with nonconventional energy sources such as solar photovoltaic systems (PVs), 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 [1]–[25]. Traditionally, ac–dc converters, which are also known as rectifiers, are developed using diodes and thyristors to provide controlled and uncontrolled unidirectional and bidirectional dc power. They have the problems of poor power quality in terms of injected current harmonics, resultant voltage distortion and poor power factor at input ac mains and slowly varying rippled dc output at load end, low efficiency, and large size of ac and dc filters. In view 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 (GTOs), etc. Such converters are generally classified as switch-mode rectifiers (SMRs), power-factor correctors (PFCs), pulsewidth-modulation (PWM) rectifiers, multilevel rectifiers, multipulse rectifiers, etc. Because of the strict requirement of power quality at the input ac mains, several standards [1]–[3] have been developed and enforced on the consumers. Because of the severity of power quality problems some other options such as passive filters, active filters (AFs), and hybrid filters [4], [7]–[9] along with conventional rectifiers have been extensively developed, especially in large rating and already existing installations. However, these filters are quite costly, bulky, and have reasonable losses, which reduce overall efficiency of the complete system. Even in some cases the rating of converter used in active filters is almost close to the rating of the load. Under such circumstances, it is considered better option to use such converters as an inherent part of the system of AC-DC conversion, which provides reduced size, high 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 textbooks and several comparative topologies are reported in recent publications [10]–[17]. Therefore, it is considered a timely attempt to present a broad perspective on the status of ac–dc converters technology for the engineers using them and dealing with power quality issues.

This paper presents a comprehensive survey on three-phase ac–dc converters. More than 450 publications [1]–[477] are reviewed and classified into three major categories. Some of them are further classified into several subcategories. The first one [1]–[25] is general on power quality standards, other options, texts, and some surveys and comparative topology publications. The second and third categories are on unidirectional and bidirectional power flow ac–dc converters [26]–[477]. These converters are further subclassified as boost [26]–[245], buck [246]–[347], buck–boost [348]–[383], multilevel [384]–[430], and multipulse ac–dc converters [431]–[477]. The total number of configurations of these converters is divided into ten categories. The paper is divided into nine parts. Starting with the introduction (Section I), other sections cover the state of the art of IPQC technology (Section II), configurations (Section III), control strategies (Section IV), components selection for IPQCs (Section V), comparative factors and others options for power quality improvement (Section VI), selection considerations of IPQCs for specific applications by the designers (Section VII), latest trends and future developments in IPQC technology (Section VIII), and a conclusion (Section IX).

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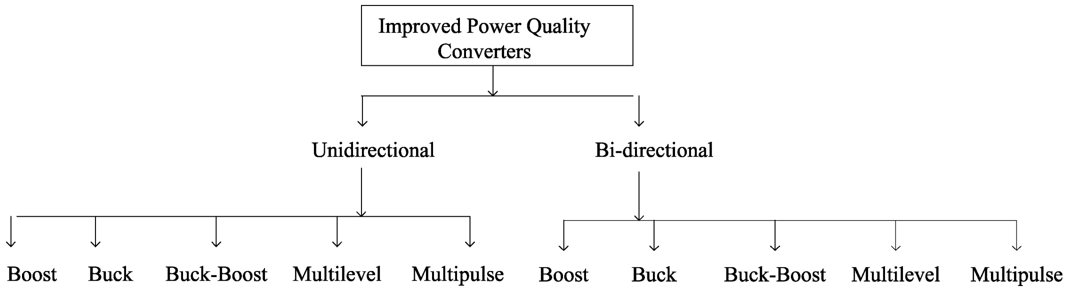

Fig. 1. Converter-based classification of improved power quality converters.

II. State of the Art

IPQC technology is matured at a reasonable 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 kilowatt to megawatt power ratings in a large number of applications. These were developed in the last couple of decades with varying configurations, control strategies, solid-state devices, circuit integration, varying magnetics in topologies such as boost, buck, buck–boost, and multilevel for unidirectional and bidirectional power flow. A large number of IPQC configurations have been evolved to suit vastly varying applications while maintaining a high level of quality at input ac source and output dc loads.

In some applications, a constant-regulated output dc voltage is required with unidirectional power flow such as in UPSs, ASDs in fans, air conditioners, etc., while in some other applications, a bidirectional power flow is required. Therefore, these IPQCs are categorized into unidirectional boost converters [26]–[86] and bidirectional boost converters [87]–[245]. Moreover, there are a number of applications which require widely varying dc voltage, normally fed from a conventional semiconverter or fully controlled thyristor converter with unidirectional or bidirectional power flow. To replace the conventional thyristor-based semi and full converters, a breed of improved power quality converters has been developed and classified as unidirectional buck [246]–[263] and bidirectional buck converters [264]–[347] using PWM switching with 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 converters is made with unidirectional [348]–[373] and bidirectional power flow [374]–[383]. 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 [384]–[430]. Therefore, the next category of IPQC is considered as multilevel converters with unidirectional [384]–[400] and bidirectional power flow [401]–[430].

In high-power applications, ac–dc converters based on the concept of multipulse, namely, 12, 18, 24, 30, 36, 48... pulses are used to reduce the harmonics in ac supply currents. These are named as multipulse converters [431]–[477]. They use either a diode bridge or thyristor bridge and a special arrangement of magnetics through transformers and tapped inductors. Therefore, the last category is multipulse converters with unidirectional [431]–[455] and bidirectional power flow [456]–[477].

One of the important reasons for such an extensive development in ac–dc converters is due to self-commutating devices. At low power rating, MOSFETs are used with unsurpassed performance because of their high switching rate with negligible losses. At medium power rating, an IGBT is considered an ideal device for such converters with PWM technology. At a higher power rating, a GTO is normally used with self-commutating and reverse voltage-blocking capabilities at only a few kilohertz switching frequency. A number of manufacturers are developing an intelligent power module (IPM) with several devices to give a cost effectiveness and compact size to the IPQCs. Another breakthrough in IPQCs has been 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 the sensors at competitively low prices.

A major boost to the technology of IPQCs has also been due to the revolution in microelectronics. Because of the heavy volume requirement, a number of manufacturers have developed dedicated ICs for cost-effective and compact control of these converters. Moreover, high-speed microcontrollers and digital signal processors (DSPs) are available at reasonable cost. Many processors have been developed to give direct PWM outputs with fast software algorithms such as space-vector control (SVC) [36], [39], [47], [66], [103], [129], [152], [168], [215], [369], [417], normally used in some of these converters, which reduce hardware drastically. With these processors it is now possible to implement new and improved control algorithms to provide fast dynamic performance of IPQCs. Starting with proportional–integral (PI) controllers, sliding-mode, fuzzy logic, and neural-network-based controllers have been employed for the control of these converters. Moreover, a number of instruments are available to measure the performance of these IPQCs, which are named as power analyzers, power scopes, power monitors, and spectrum analyzers. They provide direct harmonic spectrum, total harmonic distortion (THD) even up to 51st order of harmonics, power factor, crest factor, displacement factor, kVA, kVAr, kW and kWh, ripples, surge, swell, notch width, and height.

III. Configurations of IPQCs

IPQCs are classified into ten categories on the basis of converter circuit topologies such as buck, boost, buck–boost, multilevel, and multipulse, with unidirectional and bidirectional dc ouput voltage, current, and power flow. Fig. 1 shows the tree of

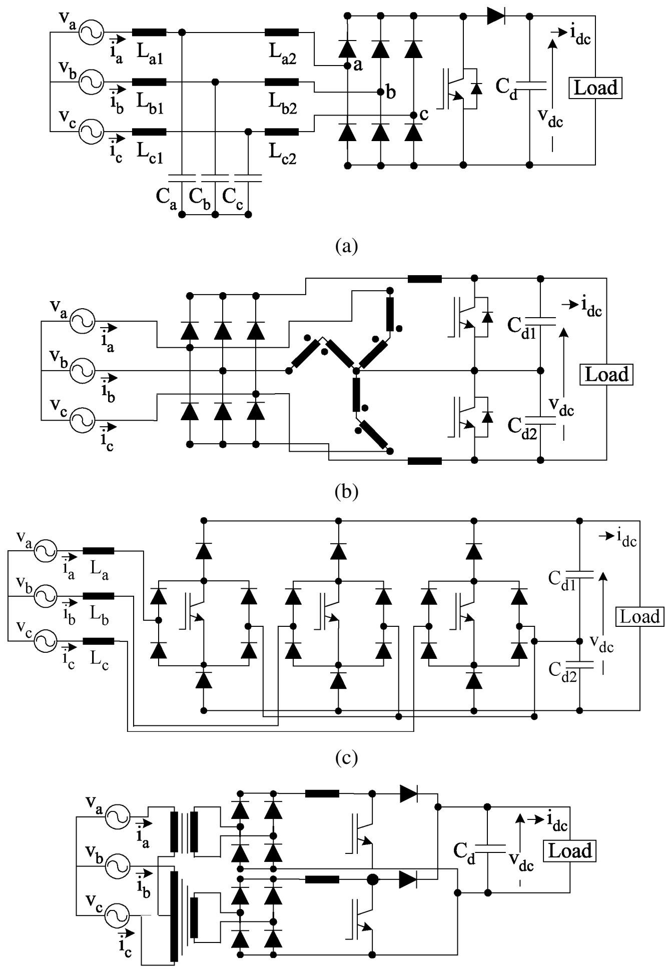

Fig. 2. (a) Single-switch unidirectional boost converter. (b) Two-switch unidirectional boost converter using zigzag injection transformer (Minnesota rectifier). (c) Three-switch unidirectional boost converter (Vienna rectifier). (d) Unidirectional boost converter using isolated Scott connection transformers.

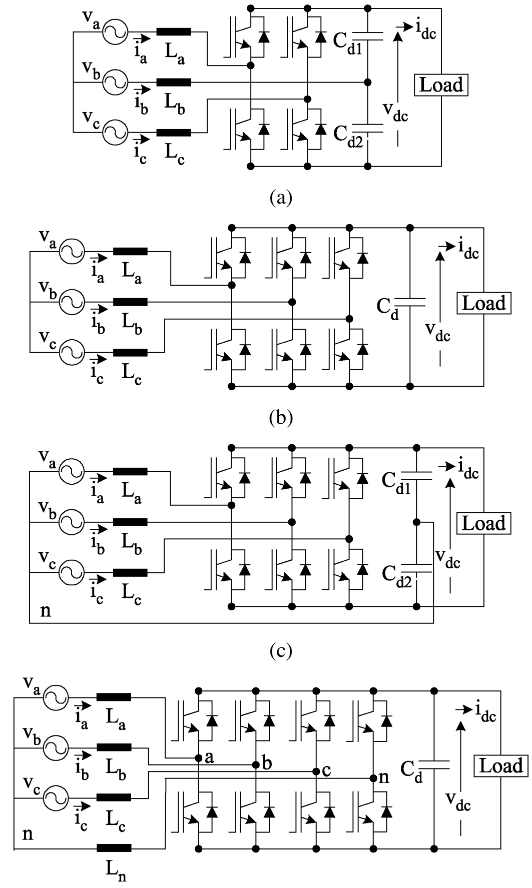

Fig. 3. (a) Four-switch bidirectional boost converter. (b) VSI-bridge-based bidirectional boost converter. (c) Four-wire bidirectional boost converter. (d) Four-legged bidirectional boost converter.

such classification of IPQCs. These converters are developed in such vastly varying configurations as to fulfill the very close and exact requirement in a variety of applications. Figs. 2 –11 show basic circuit configurations of three-phase IPQCs of all ten categories for ac–dc conversion.

A. Unidirectional Boost Converters [26]–[86]

These types of converters are widely used nowadays as a replacement of a conventional diode rectifier to provide unity power factor, reduced THD at ac mains, and constant-regulated dc output voltage even under fluctuations of ac voltage and dc load. Fig. 2 shows the few circuits of this category of converters. There is wide variety of configurations with single-switch, two-switch, three-switch, etc., to improve their performance toward ideal power quality conditions at ac input mains and dc output. Single-switch with passive filter [Fig. 2(a)] [26]–[28], Minnesota rectifier [Fig. 2(b)] using harmonic current injection through a zigzag transformer [27], [29], Vienna rectifier [Fig. 2(c)] [41], [72], [78], [84], [86], and isolated Scott-connected transformer with dual-boost PFC [Fig. 2(d)] [25] are a few pioneer configurations of these types of converters. However, large numbers of circuits of these converters are reported using a combination of single-phase boost converters [34] and other modified topologies and extensively used in power supplies and motor speed control.

B. Bidirectional Boost Converters [87]–[245]

For the bidirectional power flow from ac mains to dc output and vice versa, an ideal converter is normally used in hoisst, cranes, lifts, BESSs, line interactive UPSs, etc. [89], [90], [92], [93]. Fig. 3 shows the few circuit diagrams of these bidirectional converters. The closed-loop control of dc-bus voltage decides the amplitude of supply currents, which are in phase with ac mains voltages. PWM current control of the voltage-source-inverter (VSI)-based converter maintains the ac supply current close to sinusoidal and in phase with ac mains voltages.

These converters are developed using four switches to reduce the cost [Fig. 3(a)] for variable-speed induction motor drives [151]. Ideally, a six-device VSI bridge is used in the majority of cases [Fig. 3(b)] [92]. However, four-wire topologies [Fig. 3(c) and (d)] [206], [235] are employed to reduce the dc-link voltage ripple and balancing the supply currents, even in the case of unbalance supply voltages. There have been many pioneer developments in these converters, such as sensorless control to reduce cost and number of components in the hardware [119], [120], [163], [188], [211], [213], [228], [230], [233], [234], [245].

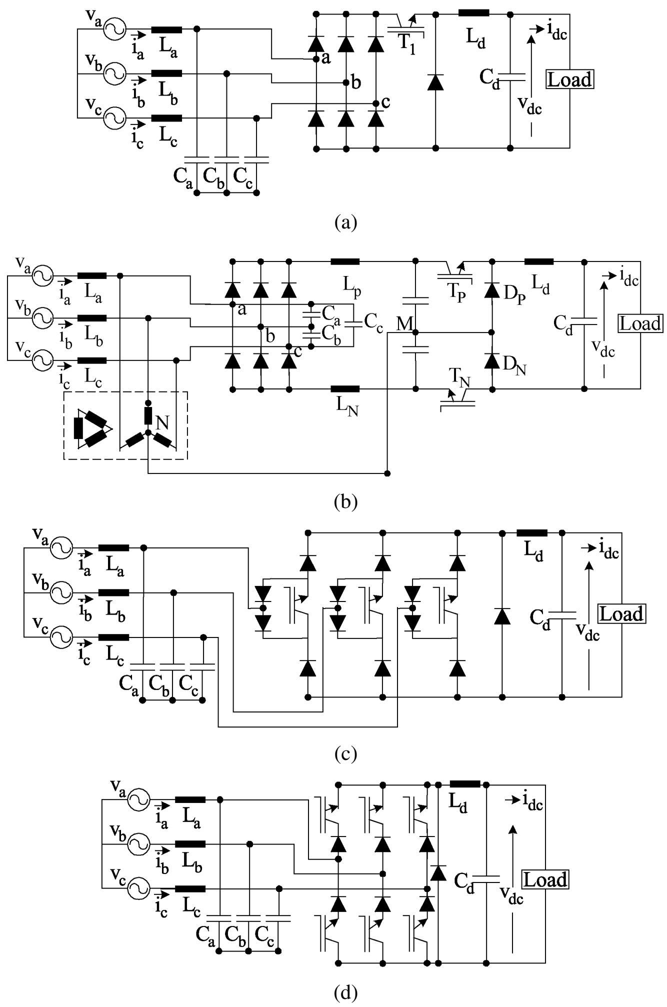

Fig. 4. (a) Single-switch unidirectional buck converter. (b) Two-switch unidirectional buck converter. (c) Three-switch unidirectional buck converter. (d) Three-phase CSI-based unidirectional buck converter.

C. Unidirectional Buck Converters [246]–[263]

This is a replacement of the thyristor semiconverter with improved power quality at ac mains and output dc bus. It provides the voltage below the base voltage. Fig. 4 shows the circuits of these converters. The requirement of the filter is normally high in this case. Several topologies, namely, using single device [Fig. 4(a)] [247], two devices [Fig. 4(b)] [251] with harmonic injection transformers, three devices with dual diode [Fig. 4(c)] [249], [259], [263], and six devices with freewheeling diode [Fig. 4(d)] [258] are reported in the literature to improve the power factor and reduce the harmonic currents at input ac mains and well regulated filtered output dc voltage. High-frequency PWM control of switching devices reduces the size of input and output filters, weight, and enhances the efficiency of the overall system. These converters are extensively used in battery charging in automotive applications [252], and dc motor speed control in a number of applications. In these converters, the inrush currents are observed to be of low value. It is because the controlled device (IGBT) is connected in series path of the current flow. These converters are capable of giving the output dc voltage from zero to nominal values at quite a fast rate.

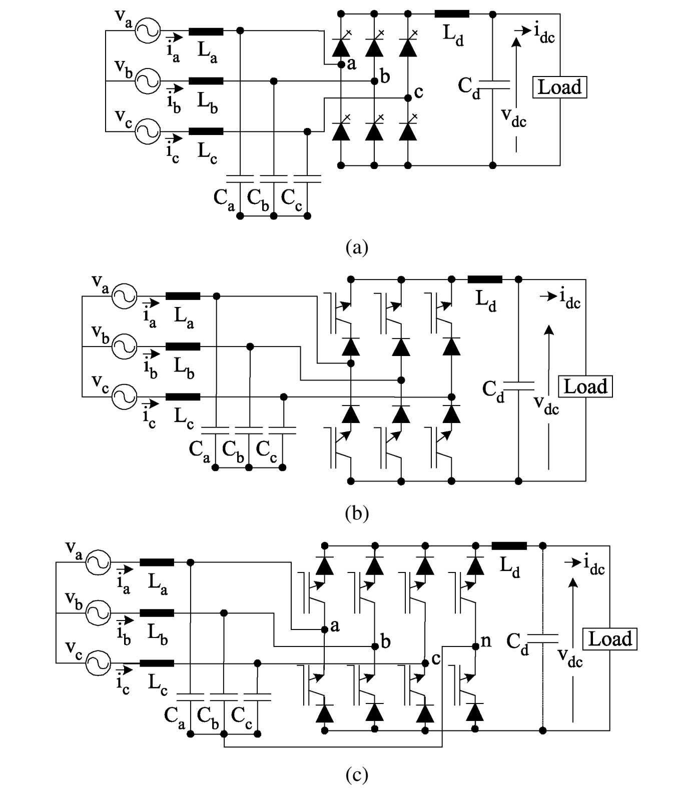

Fig. 5. (a) GTO-based bidirectional buck converter. (b) IGBT-based bidirectional buck converter. (c) Four-pole bidirectional buck converter.

D. Bidirectional Buck Converters [264]–[347]

Fig. 5 shows the circuits of such converters. It provides a similar function as a conventional thyristor bridge converter but with improved power quality in terms of high power factor and reduced harmonic currents at ac mains and fast regulated bidirectional output voltage for reversible power flow. These are developed using GTOs at higher power ratings as shown in Fig. 5(a) [271], [274] and using IGBTs with series diodes [Fig. 5(b)] [310] at low power ratings with high switching frequency, resulting in reduced size of filter components. The four-leg configuration, as shown in Fig. 5(c) [314], is implemented to reduce the output dc ripple and balanced currents under unbalance voltage of the mains. IGBTs, bipolar junction transistors (BJTs), and MOSFETs need series diodes to provide reverse voltage blocking capability required in this converter. These two bridges connected in antiparallel provide behavior similar to a dual converter for four-quadrant operation with improved power quality and fast response [278].

E. Unidirectional Buck–Boost Converters [348]–[373]

Fig. 6 shows some circuits of these converters. These are used in a wide variety of applications. They may have either isolated or nonisolated dc output from input ac mains. It consists of a combination of buck and boost converters as shown in Fig. 6(a) [259]. These converters are also realized as a combination of three-phase diode bridge with filter and buck–boost dc–dc converters such as SEPIC [Fig. 6(b)] [364], flyback [368], [371], Cuk [360], etc. For the isolated dc output with a high-frequency transformer to reduce the size, a diode rectifier in conjunction with flyback [Fig. 6(c)] [366], isolated Cuk [Fig. 6(d)] [360],

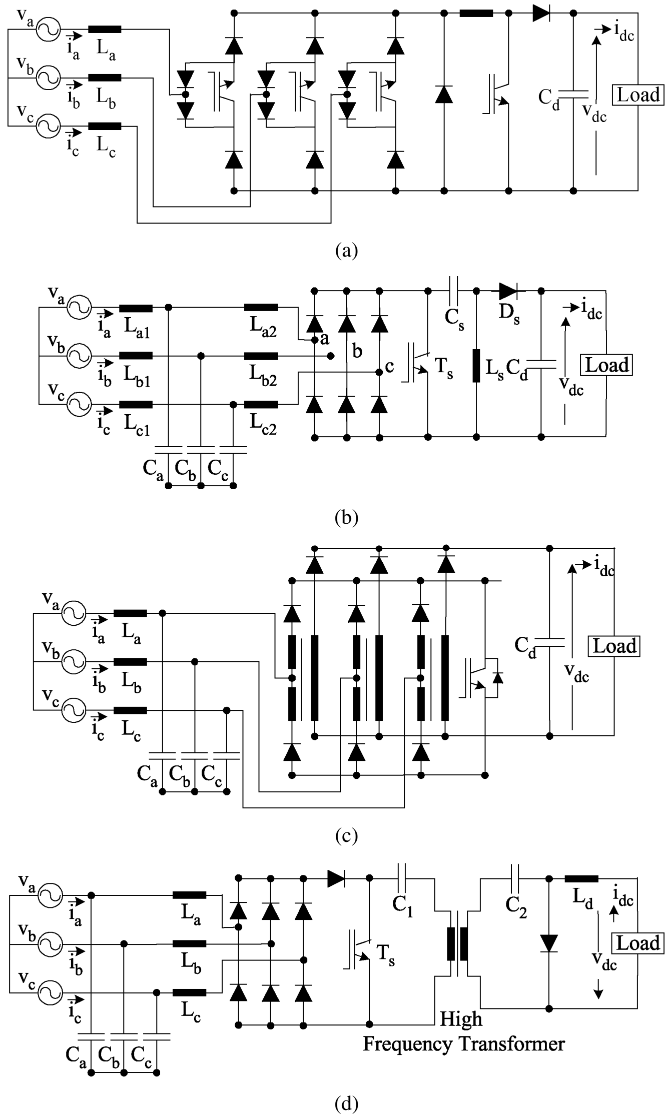

Fig. 6. (a) Four-switch unidirectional buck–boost converter. (b) SEPIC-derived unidirectional buck–boost converter. (c) Flyback-derived unidirectional buck–boost converter. (d) Isolated Cuk-derived unidirectional buck–boost converter.

and many others, such as Zeta [373], SEPIC [364], bridge, half-bridge, and push–pull are used with a first stage PFC. Nowadays, two-stage conversion is integrated together and even in single stage it is possible to achieve the same level of performance, as shown in Fig. 6(c) and (d) [366], [368] using single switch. There are such novel configurations to provide compact, integrated, high-power-density, high-efficiency power supplies for use in a number of applications such as telecommunication power supplies, battery charger units, etc.

F. Bidirectional Buck–Boost Converters [374]–[383]

There are some applications which require output dc voltage widely varying from low voltage to high voltage with bidirectional dc current as four-quadrant operation and bidirectional power flow. These converters can be implemented in many ways, such as cascading the buck and boost converters, but the simplest way of realizing them is by using a matrix converter as shown in Fig. 7 [382]. With the high-frequency switching,

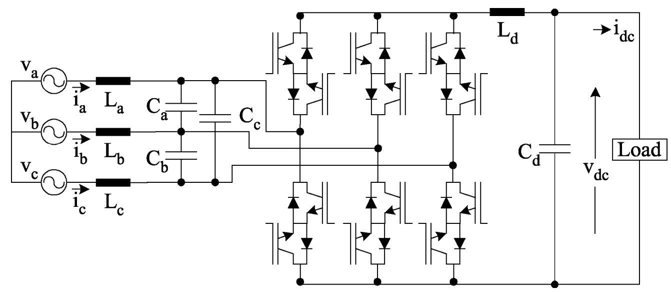

Fig. 7. Matrix-converter-based bidirectional buck–boost converter.

the size of the input ac filter and output dc filter is reduced which allows the fast response of this converter. It is capable of working as bidirectional buck and bidirectional boost converters and is an ideal solution for ac–dc conversion. It is derived from matrix converters normally used for ac–ac conversion for a wide frequency range at input as well at output. It can also be realized using GTOs for high power rating but with restricted switching frequency. Since it (GTO) does not need an additional series diode, its offers high efficiency.

G. Unidirectional Multilevel Converters [384]–[400]

Fig. 8 shows some of the basic circuits of these converters. The concept of multilevel is used to reduce the harmonics and switching losses in the converter through operating the switching devices at low switching frequency. Three-level three-phase converters can be implemented using either three devices [Fig. 8(a)] [398] or six devices [Fig. 8(b)] [400]. However, higher level converters such as a five level shown in Fig. 8(c) [400] require a higher number of devices but can avoid PWM switching losses while maintaining the same level of performance in terms of power quality at input ac mains and regulated dc output. These converters also offer boost operation for the output voltage with unidirectional power flow. It has lower voltage stresses on the devices and avoids PWM switching of them and, therefore, it is an ideal converter for high-voltage and high-power applications. These converters can be developed for a high number of levels to offer reduced THD and improved power factor of supply current at input ac mains and reduced ripple and regulated dc output voltage under varying load conditions.

H. Bidirectional Multilevel Converters [401]–[430]

Fig. 9 shows some circuit diagrams of bidirectional multilevel converters. These are used at high power ratings at high voltages with boost voltage for bidirectional power flow. These are further classified as clamped diode type [Fig. 9(a)] [400] and (b) [401] for three and five level), flying capacitor type [Fig. 9(c)] [404], and cascaded type multilevel converters. These converters are recommended for high-power and bidirectional power flow applications such as battery energy storage systems [401], four-quadrant variable-speed ac motor drives [411], [414], HVdc transmissions, flexible alternating current transmission systems (FACTs) [428], and static var compensation, to offer high efficiency and low THD of voltage and currents in the absence of PWM switching. For low- and medium-power applications, the IGBT is an ideal device,

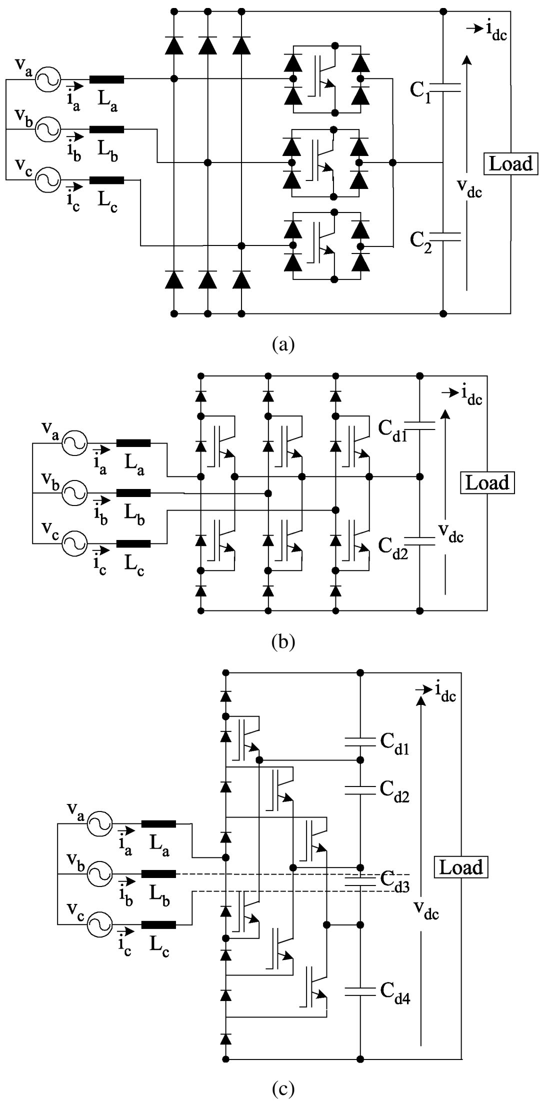

Fig. 8. (a) Three-switch unidirectional three-level converter. (b) Six-switch three-level unidirectional converter. (c) Unidirectional five-level converter.

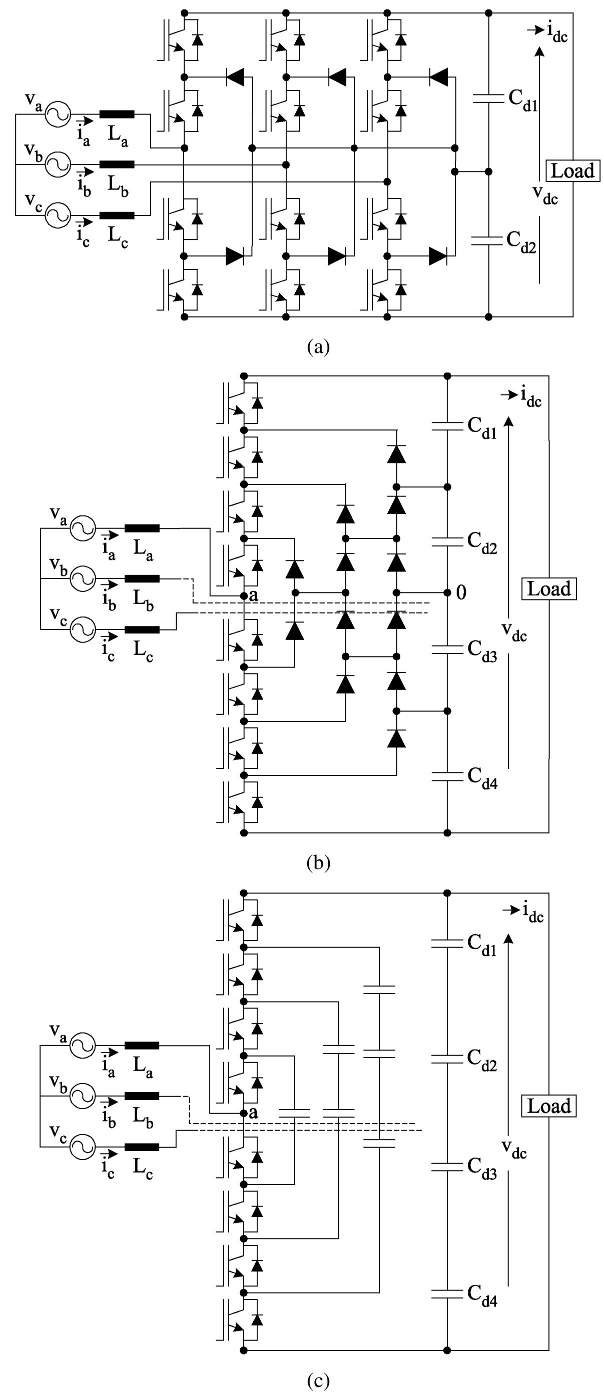

Fig. 9. (a) Three-level diode-clamped bidirectional converter. (b) Five-level diode-clamped bidirectional converter. (c) Five-level flying capacitor bidirectional converter.

however, for high-power applications, the GTO is invariably used. These converters provide a high level of power quality at input mains with reduced THD, high power factor and reduced EMI noise and boost, and ripple free, regulated dc output voltage insensitive to load and supply disturbances. They also avoid the use of transformers in some applications, which further enhances the efficiency of these converters.

I. Unidirectional Multipulse Converters [431]–[455]

Fig. 10 shows some of the circuits of these converters. Normally, diode bridges are used with a higher number of pulses for reducing harmonics in ac mains and reduced value of ripple voltage in the dc output. These are developed in 12-, 18-, 24-, 30-, 36-, 48-pulse, etc., converters, through input multipulse auto/isolation transformers and ripple current injection employing interphase reactors. It has been reported by many investigators that it is possible to reduce the THD of supply current below 2% even in 18-pulse converters [13], [433]. The rating, size, cost, and weight of different components of these converters are reduced using novel concepts in autotransformer configurations to achieve a higher number of phases from input three-phase AC mains through phase splitting at different angles, some of which are shown in Fig. 10(a) [13], (b) [13], and (c) [445] for 12-, 18-, and 24-pulse converters. The concepts of phase shift through input transformers and pulse multiplication through input tapped reactors and injection transformers at the dc link are at the heart of these converters. Normally, these converters employ only slow converter grade diodes, thus resulting in negligible switching losses and high efficiency, high power factor, low THD at input ac mains, and ripple-free dc output of high quality.

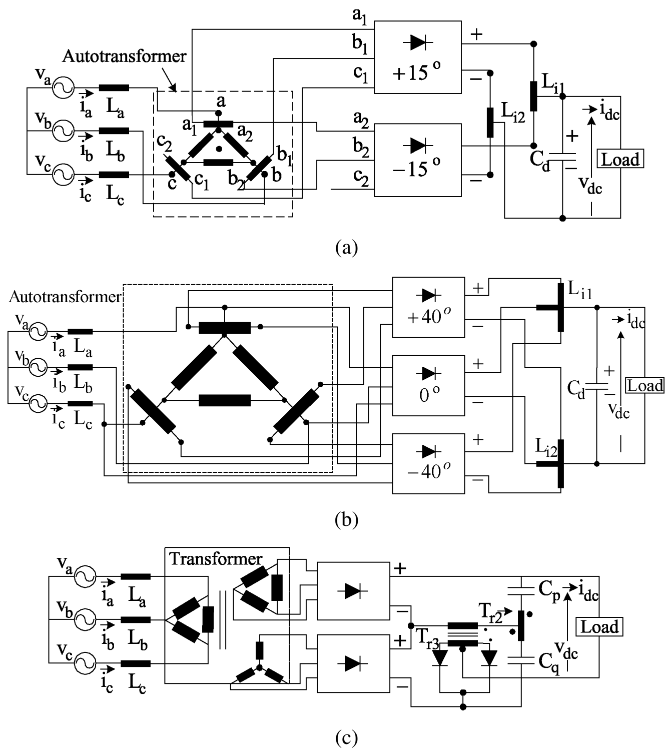

Fig. 10. (a) Unidirectional 12-pulse converter. (b) Unidirectional 18-pulse converter. (c) Unidirectional 24-pulse converter.

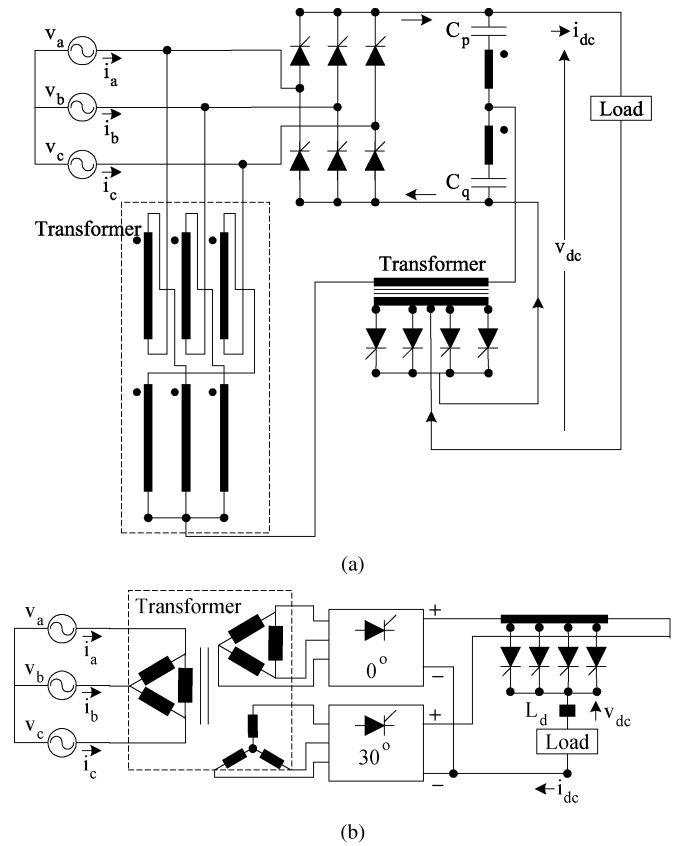

Fig. 11. (a) 24-pulse bidirectional midpoint reactor converter. (b) 48-pulse bidirectional converter.

J. Bidirectional Multipulse Converters [456]–[477]

These converters normally use thyristors and harmonics reduction is made effective with pulse multiplication using magnetics [463]. Fig. 11 shows the two typical circuits of such converters [477]. The use of fully controlled thyristor bridge converters offers bidirectional power flow and adjustable output dc voltage. The use of a higher number of phases through an input multiple winding transformer and pulse multiplication using tapped reactor [463], and an injection transformer [456], reduces THD to input ac currents and ripples in the output dc voltage. These converters are used in high rating dc motor drives, HVdc transmission systems, and in some typical power supplies. Fig. 11(a) [477] shows a typical multipulse converter, which can be operated as a 6-, 12-, and 24-pulse converter. Similarly, the converter shown in Fig. 11(b) [458], [463] can be operated in 12-, 24-, and 48-pulse modes of operation. The cost and weight of input transformers can be reduced by using autotransformers in low- and medium-voltage applications.

IV. Control of IPQCs

The control strategy is the heart of IPQCs and is implemented in three parts. In the first part of the control algorithm, the essential variables used in control are sensed and scaled to feed to the processors for use in the control algorithm as the feedbacks. These signals are normally input ac mains voltages, supply currents, output dc voltage and, in some cases, additional voltages such as capacitor voltages and inductor currents are used in the intermediate stage of the converters. The ac voltage signals are sensed using potential transformers (PTs). Hall-effect voltage sensors, isolation amplifiers, and low-cost optocouplers are used to sense dc voltages. 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 feedbacks at different stages of control either in the control algorithm or in the 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 indexes 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 Half-effect sensors and other components used in sensing are being drastically reduced day by day because of mass manufacturing and competition among 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 is the control algorithm responsible for the transient and steady-state performance of the IPQCs. The control algorithm is implemented through analog controllers or low-cost microcontrollers in low-power-rating converters. However, the DSPs and application-specific integrated circuits (ASICs) are used to control converters of high power ratings in sophisticated systems, depending upon the customer requirements. Normally, the dc output voltage of converters is the system output used as feedback in outer closed loop control. Various control approaches such as the PI control, proportional–integral–derivative (PID) control, sliding-mode control (SMC) [104], [138], [150], [175], [196], [218], [224], [318] also known as variable-structure control (VSC), fuzzy logic controllers (FLCs) [139], [161], [192], [202], [226], adaptive controllers, neural-network (NN)-based controllers [140], [149], [300], [302] are employed to provide fast dynamic response while maintaining the stability of the converter system over the wide operating range. The output of voltage controller is normally considered the amplitude of input ac mains current or indirect derived current such as inductor current and multiplied with units template in phase with ac voltages to derive the reference desired unity power factor and sinusoidal supply currents.

The third stage of the control strategy of the IPQCs is to derive the gating signals for the solid-state devices of the converters. Reference supply currents along with sensed supply currents are used in the current controllers, which directly generate switching signals. A number of current controllers, namely, hysteresis, PWM current or PWM voltage control employing 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 gating signals. Nowadays, processors are available which are developed only for power electronics applications and have dedicated PWM controllers as a built-in feature to implement concurrently all three stages of control strategy for improving transient and steady-state performance of the IPQCs.

Moreover, in some control approaches, the second and third stage of control strategy of IPQCs are implemented in the integrated manner using some transformations such as "$\alpha - \beta$," "d-q" over the sensed voltage and current signals. The transformed voltage and/or current or derived power signals are used in the closed loop controllers to derive reference current or voltage signals for generating gating signals. The concurrent and integrated implementation of three stages of control algorithm provides cost effective, compact, fast response of the IPQCs.

V. Components Selection for IPQCs

Selection of components of IPQCs is very important to achieve a high level of performance of ac–dc converters. The main and costly component of the IPQCs is the solid-state power devices. In low-power-rating converters, MOSFETs are normally used, resulting in reasonably high efficiency even at high switching frequency, which is responsible for reducing the size of magnetics. In the medium power rating of IPQCs, IGBTs are invariably used because of their good gating characteristics and capability of operating in a wide switching frequency range to make an optimum balance between magnetics, size of filter components, and switching losses. At high power ratings, GTOs are normally used, with the advantages of self-commutating and reverse voltage-blocking capability. In multipulse converters, thyristors and diodes are still employed with the expected level of performance of IPQCs.

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

Other components of IPQCs are 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 VSI bridge working as a 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 in a 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 into the supply current, and large value does not allow shaping the ac mains current in a desired fashion. Therefore, the optimum selection of this inductor is essential to achieve satisfactory performance of the IPQCs. Similarly, the value of the capacitor and inductor as the input filter in a buck converter is also quite important for proper response, stability, and optimum design of the IPQCs. Moreover, designs of inductors are also very important to avoid saturation and reducing losses under ac, dc, and mixed excitation. The value of the dc-bus capacitor in boost converters is quite crucial as it affects the response, cost, stability, size, and efficiency. A small value of dc-link capacitor results in a large ripple in steady state and a 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 low frequency are used in multipulse converters in which transformer connection, weight, size, and rating are quite important. There are continuous attempts to reduce their size and cost through new configurations and with the use of tapped reactors at the dc link. However, high-frequency transformers are 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.

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

The IPQCs classified in ten 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 best suitable option. However, within the same category of IPQCs, there are many circuits which have relative merits and demerits toward ideal characteristics. These additional configurations have improved performance but at higher cost. Therefore, the designer has to decide on a configuration of particular IPQCs on the basis of a tradeoff between performance and cost. Similar comparison exists for other IPQCs within these different configurations. In some cases, a choice can also be made among different IPQCs for specific applications. However, in such case, there are not many options for the designer to select and one can have a straightforward decision to opt for the right IPQC, which offers better performance at comparable cost. 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 the diode rectifier with a capacitive filter at the dc output to feed a number of dc loads [7]–[9]. Moreover, in IPQCs, also, one can choose a multipulse converter or three-phase unidirectional boost converter with one device, two devices, or multilevel configuration. It means one can have a number of options to select one of the best configurations of the converter for a particular application. For example, if a diode bridge rectifier is already working on site, then filters may be the right option in such a case. Moreover, one has to choose the best filter configuration among all possible options. However, if a designer is at the deciding design stage, then IPQCs may be the better option, which may provide improved performance in terms of output dc voltage regulation and high power factor and low THD of mains current. Similar situations may occur in the number of cases and the design engineer must be aware of all possible options and their relative features to select the best converter from an overall point of view.

VII. Selection of IPQCs for Specific Applications

Selection of IPQCs for a specific application is an important decision. The following are some of the factors responsible for selection of right converter 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 output DC (isolated, nonisolated);
- requirement of output dc (buck, boost, and buck–boost);
- required level of power quality in output (voltage ripple, sag, and swell);
- type of dc load (linear, nonlinear, etc.);
- cost, size, and weight;
- efficiency;
- noise level (EMI, RFI, etc.);
- rating (kilowatt, megawatt, etc.);
- reliability;
- environment (ambient temperature, altitude, pollution level, humidity, types of cooling, etc.)

These are only some factors. There are some more 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 Further Developments in IPQCs

IPQC technology has developed to a mature level and is employed in widespread applications in fraction of kilowatt to megawatt converter systems such as UPSs, ac–dc–ac links, BESSs, ASDs, etc. However, there are new developments in IPQCs for further improvements in their performance. The new trends are improved control algorithms and 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 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 their cost and enhance their reliability. Novel configurations in autotransformers for multipulse converters have resulted in their reduced size, cost, rating, weight, and losses. The new approaches in multilevel converters are offering high efficiency, reduced stress on devices, and a low level of 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 low voltage drop and reduced switching losses, will give a real boost for IPQCs in low-voltage dc power applications. 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 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, provide ease in control, and result in compact and efficient ac–dc conversion. The invention of new configurations and reduction in conversion stages in IPQCs will help explore a number of newer applications.

IX. Conclusion

A comprehensive review of three-phase IPQCs has been carried out to explore a broad perspective on their different configurations to researchers, design and application engineers, and end users of ac–dc converters. The proposed classification of IPQCs in ten categories with further subclassification of various circuits is expected to provide an easy selection of an appropriate converter for a specific application. These IPQCs may be considered to be better alternatives for power quality improvement because of reduced size of the 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 input ac mains but also at dc output for better design of the overall equipment. Moreover, the use of these IPQCs results in any equipment behaving as a linear resistive load at the ac mains. The new developments in device technology, processors, magnetics, and control algorithms, will result in a real boost to these IPQCs in the near future.

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