Multipulse AC–DC Converters for Improving Power Quality: A Review

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***Abstract*—Three-phase multipulse ac–dc converters (MPC) are developed for improving power quality to reduce harmonics in ac mains and ripples in dc output. This paper deals with the multipulse ac–dc converter configurations, state of art, their performance, power quality aspects, components selection considerations, latest trends, future developments, and potential applications. It is targeted to provide broad perspective on multipulse converter technology to the researchers, engineers, and designers dealing with them. A classified list of more than 250 research publications on the subject is also given for quick reference.**

***Index Terms*—AC–DC converters, harmonics reduction, multipulse, power quality, rectifiers.**

I. Introduction

SOLID state ac–dc converters are widely used in a number of applications such as adjustable speed drives (ASDs), high voltage dc (HVDC) transmission, electro-chemical processes such as electroplating, telecommunication power supplies, battery charging, uninterruptible power supplies (UPS), high-capacity magnet power supplies, high-power induction heating equipments, aircraft converter systems, plasma power supplies, and converters for renewable energy conversion systems. These converters, which are also known as rectifiers, are generally fed from three-phase ac supply in power rating above few kilowatts and have the problems of power quality in terms of harmonics injected, caused poor power factor, ac voltage distortion and rippled dc outputs. Because of these problems in ac–dc conversion, several standards and guidelines are laid down [1]–[8] which are to be referred by designers, manufacturers, and users. Therefore, various methods are used to mitigate these problems in ac–dc converters. Normally, filters are recommended in already existing installations, which may be passive, active, or hybrid types depending upon rating and economic considerations. These filters have been developed from small power to large power ratings to reduce the power quality problems of ac–dc converters. However, in some cases, the ratings of these filters are close to the converter rating which not only increases the cost but it also increases the losses and component count resulting in reduced reliability of the system. However, in future installations, it is preferred to modify the converter structure at design stage either using active or passive (magnetic) wave shaping of input currents. These techniques of improving converter systems are well reported nowadays in the texts, research publications, and review articles [9]–[31]. Active wave shaping technique of ac–dc converters is widely used in a number of applications; however, passive wave shaping technique of these converters is considered a simple and economical method of improving the power quality in some applications. The passive wave shaping technique is normally based on magnetics in three-phase ac systems and corresponding developed systems are known as multipulse or multiphase ac–dc converters (MPCs). The number of novel configurations of multipulse ac–dc converters are developed in view of their potential applications for unidirectional and bidirectional power flow starting from 12 to a large number of pulses. Therefore, it is considered a timely attempt to present a comprehensive state of art on status of multipulse ac–dc converters for engineers using them and dealing with power quality issues.

This paper aims at presenting an extensive review on the multipulse ac–dc converters. More than two hundred publications [1]–[252] are reviewed and classified on the basis of power flow, number of pulse used, isolated and nonisolated topologies, and various techniques used to improve ac current profile and output dc voltage wave form. The paper is divided into ten parts. Starting with introduction, other sections cover state of art of multipulse ac–dc converters, configurations, classification, magnetics, and selection of components, their performance, power quality aspects, selection consideration with potential applications, comparative features and other options, latest trends, future developments, and conclusive remarks.

II. State of the Art

MPCs are developed to matured level for ac–dc conversion with reduced harmonic currents and reactive power burden, low EMI, RFI at input ac mains and good quality reduced rippled dc output with unidirectional and bidirectional power flow for feeding loads from a few kilowatts to several hundred megawatts. These MPCs evolved in the last half century with varying configurations, reduced magnetics, circuit integration, different concepts such as pulse multiplication [153], [155], [171], [219], [224], [227], [230], phase staggering [249], [251],

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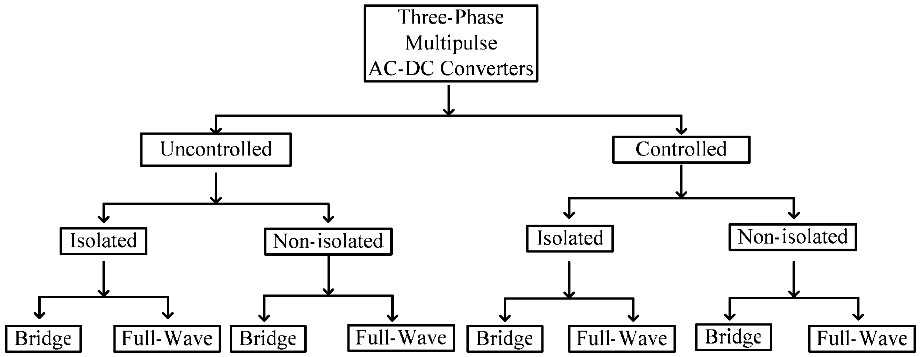

Fig. 1. Classification of three-phase multipulse ac–dc converters.

varying connections such as T connection [69], [85], [200], [201], [239], zigzag [57], [167], [223], fork [18], [35], [77], extended delta and double star [250], [252], polygon [18], reduced rating autotransformers [18], optimum interphase reactors [202], pu1se doubling circuits [44], [111], [112], [113], [126], and active interphase reactors [36], [150]. A number of circuit configurations of MPCs are explored to meet exact requirements of vast varying applications while maintaining a high level of quality at ac mains and output dc loads.

In some applications, a unidirectional power flow is required from ac source to dc loads; therefore, these MPCs are developed using diode rectifiers and transformer circuit configurations in isolated and nonisolated topologies starting with 12-pulse to 18, 24, 30, and higher number of pulses to maintain low total harmonic distortion (THD) of ac mains current and ripple-free dc output. Moreover, the concepts of full-wave (mid point) rectifiers with double star, zigzag, T connection, tapped winding in transformers and bridge rectifiers with compact autotransformers, multiple secondaries for phase shifting and pulse doubling, pulse multiplication using interphase transformers, and additional devices are adopted to suit vast varying requirements of applications from few a kilowatts power supplies to hundreds of kilowatts large rating variable-frequency ac motor drives used in fans, compressors, blowers, pumps, etc. Therefore, these unidirectional ac–dc converters are classified into full-wave and bridge converters based on the number of pulses and isolated and nonisolated circuits between ac input and dc output.

However, in some applications, a bidirectional power flow is required into ac–dc conversion from a few kilowatts dc motor drives to several megawatt HVDC transmission systems. These MPCs with bidirectional power flow are developed using classical robust thyristors and special arrangement of magnetics through auto, multiwinding transformers and interphase transformers, tapped reactor of optimum values and additional thyristors and capacitors with the concept of pulse multiplication to reduce THD of ac mains current and controlled with reduced-rippled dc output to feed wide varying rating loads.

The major breakthrough in the technology of MPCs is due to phase shifting process through transformers to convert from original three-phase ac supply to multiphase ac supply to result in a higher number of pulses in dc output for reducing in ripple and a high number of steps in ac mains current to make it close to sinusoidal with reduced and acceptable THD. The concept of zigzag, polygon, T connection, tapped winding, plurality of winding of isolated multiwinding transformers and autotransformers is used to achieve the desired phase shift to cancel, eliminate, and to reduce harmonics in input ac mains feeding ac–dc converters. Pioneers' attempts [18], [45], [54] have been made to reduce size, weight, and cost of magnetics (transformers) in MPCs and increased wide acceptability in a number of additional applications. The optimum value of dc link inductor and leakage reactance of input transformer drastically reduce the values of THD of ac mains current, thus resulting in improved power quality. Moreover, multipulse technology is considered superior to PWM technology because it not only eliminates some harmonics but also reduces other harmonics. It has also reduced EMI, RFI, and switching losses due to low-frequency soft switching caused by line/natural commutation, which results in high efficiency and low noise levels in the converter system. These converters are more robust, reliable, and simple in construction.

III. Configurations

MPCs can be classified based on power flow, number of pulses, and the isolated and nonisolated topologies. Fig. 1 shows the tree of such classification of MPCs. These converters are developed in such vast varying configurations to fulfill the exact requirements of a wide range of applications. Figs. 2–24 show basic circuit configurations of three-phase MPCs of different categories for ac–dc conversion.

A. *Unidirectional AC–DC Converters [32]–[146]*

The unidirectional ac–dc converters have only unidirectional power flow i.e. ac input to dc output and are used in variable-frequency ac drives for fans, compressors, pumps, waste water treatment plants, electroplating, telecommunication power supplies, etc. These converters are normally developed using diodes and transformers with other additional components. It is further subclassified into different number of pulses, which are much in use because of cost, reliability, and power quality considerations.

1) 12-Pulse AC–DC Converters [18], [36], [46], [49], [103], [123], [124], [130], [171], [223], [248]: These 12-pulse unidirectional converters are extensively used in both isolated and nonisolated circuit topologies depending upon voltage levels on the input ac mains and dc output. If there is much lower dc output voltage required such as in electroplating, then isolated topologies are preferred from the protection point of view, and

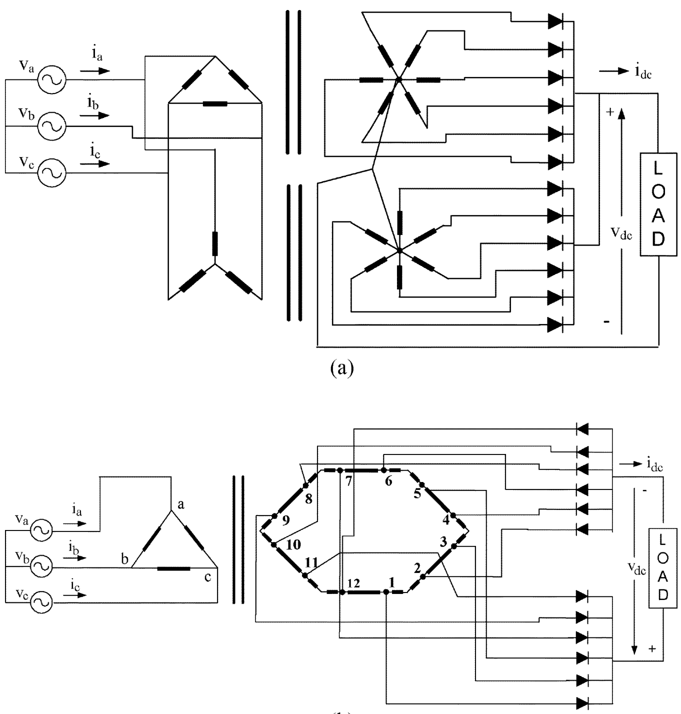

Fig. 2. (a) Three-phase unidirectional 12-pulse full-wave ac–dc converter using isolated two transformers (delta/double-star and star/double-star) [176]. (b) Three-phase unidirectional 12-pulse ac–dc converter using isolated single-polygon transformer [18].

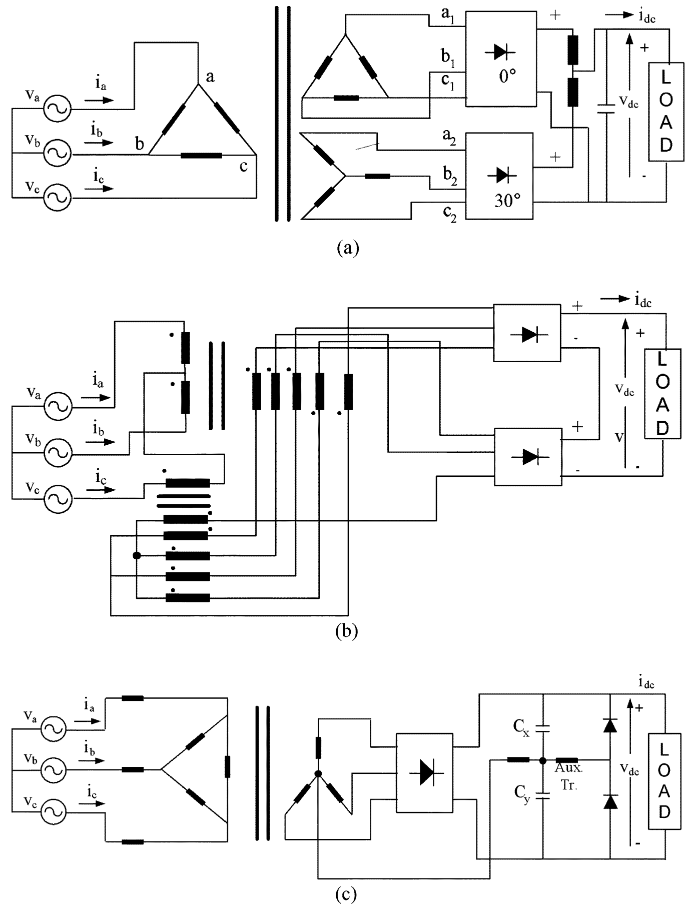

Fig. 3. (a) Three-phase unidirectional 12-pulse bridge ac–dc converter using isolated single delta/delta-star three winding transformer [18], [110]. (b) Three-phase unidirectional 12-pulse bridge ac–dc converter using isolated two Scott transformers [130]. (c) Three-phase unidirectional 12-pulse bridge ac–dc converter using isolated transformer and auxiliary transformer with two capacitors and diodes [123].

isolated multiwinding transformer is used before feeding it to the diode rectifier. However, if the voltage difference between input and output is not much, then nonisolated topologies are used through different types of autotransformers to reduce the size, cost, weight, and losses in the magnetics before it is fed to uncontrolled diode rectifiers. Therefore, these types of MPCs are further classified as follows.

Isolated unidirectional 12-pulse AC–DC converters [18], [123], [130], [167], [171], [248]: As it is already mentioned above that if the voltage levels are quite different in input ac mains and dc output, then normally isolated multiwinding transformers are used before it is converted into dc through diode rectifiers. Moreover, it can be subclassified depending upon whether it uses a full-wave or bridge rectifier in output stage and accordingly transformer secondary connections are selected. Figs. 2 and 3 show isolated full-wave and bridge-type uncontrolled 12-pulse ac–dc converters.

As shown in Fig. 2(a) [176] and (b) [18], these types of full-wave MPCs can also be further classified whether it uses double star or tapped polygon transformer secondaries to create twelve phases to feed full-wave diode rectifiers. Both types of MPCs [Figs. 2(a) and (b)] have relative merits and demerits in terms of device utilization, transformer utilization, etc. However, these two types of converters offer almost the same level of performance in input ac mains in terms of THD of current and power factor and ripples in dc output.

Fig. 3 shows only three circuits of bridge type 12-pulse isolated ac–dc converters. However, there are possibilities of many configurations in such converters using star, delta, zigzag, Scott

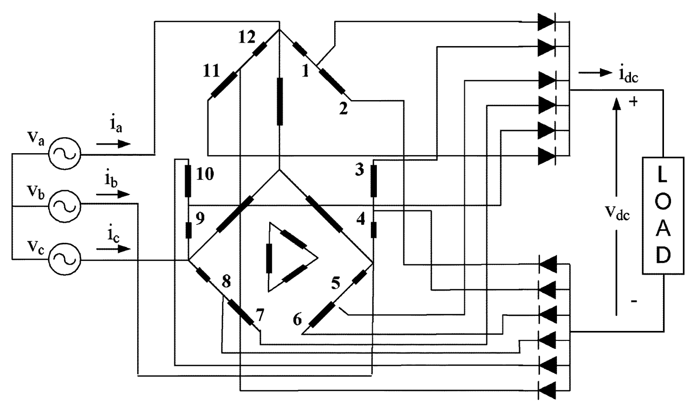

Fig. 4. Three-phase unidirectional 12-pulse ac–dc converter using differential fork autotransformer with closed delta winging [18].

connections, etc. in primary and secondaries in the transformers. Fig. 3(a) [18], [110] shows this type of 12-pulse bridge ac–dc converter in which a single transformer with delta primary and two secondaries, one in star and the other in delta for 30°-phase shift, is used to feed dual three-phase diodes bridge rectifiers with interphase reactor and optional capacitance filter. However, Fig. 3(b) [130] shows such a 12-pulse converter with two

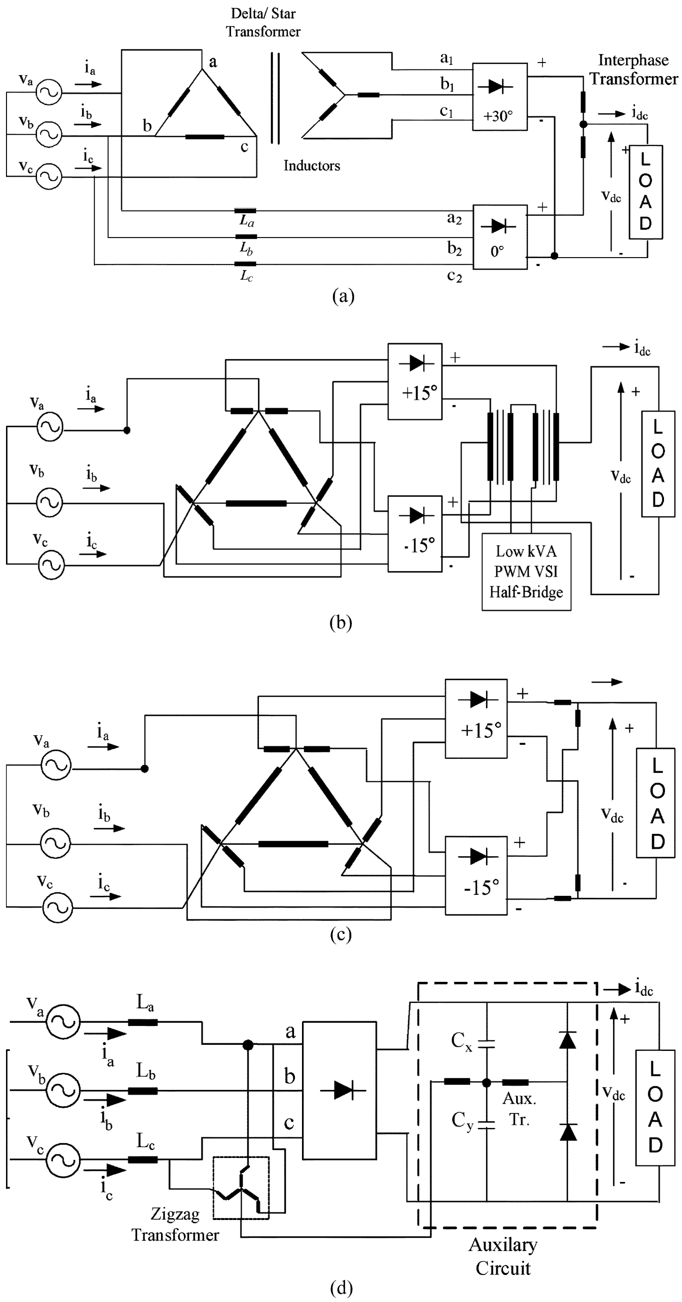

Fig. 5. (a) Three-phase unidirectional 12-pulse bridge ac–dc converter using delta-star connected transformer [18]. (b) Three-phase 12-pulse bridge ac–dc converter with active interphase reactor [36]. (c) Three-phase unidirectional 12-pulse bridge ac–dc converter [134]. (d) Three-phase unidirectional 12-pulse bridge ac–dc converter using zigzag transformer, auxiliary transformer, two capacitor, and additional diodes [124].

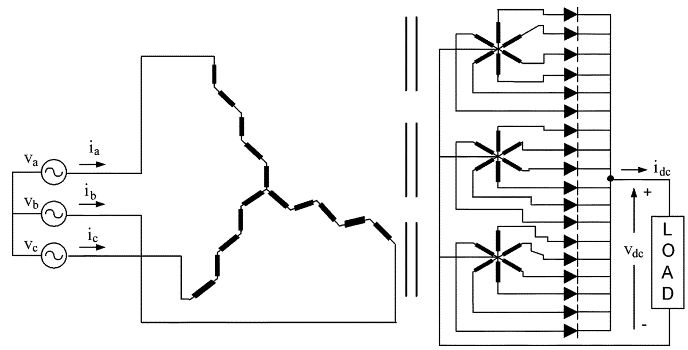

Fig. 6. Three-phase unidirectional full-wave 18-pulse ac–dc converter using zigzag/triple double-star isolation transformer [248].

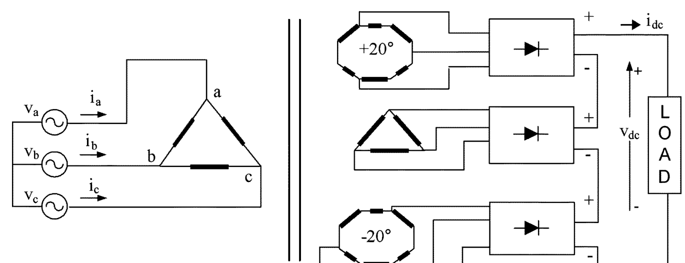

Fig. 7. Three-phase unidirectional 18-pulse bridge ac–dc converter using isolated delta/delta/double polygon transformer [18].

Scott-connected isolated transformers to feed dual-bridge rectifiers. Fig. 3(c) [123] shows another such type of converter in which only one diode bridge is used, and pulse multiplication is made using an auxiliary circuit consisting of couple of capacitors, interphase transformer, and a couple of additional diodes on the dc side with star point of isolated single transformer. All these circuit configurations offer the same level of performance on ac input and dc output.

Nonisolated unidirectional 12-pulse AC–DC converters [18], [39], [46], [49], [103], [124]: In case voltage levels of input ac and output dc is very close and isolation is not required between ac input and dc output, then these converters shown in Figs. 4 and 5 of full-wave and bridge-type are used with the drastic reduction in weight, volume, cost, size, and losses in magnetics using autotransformers configurations. Because of these features, these converters are finding increased applications due to simplicity with high efficiency and high level of power quality. These MPCs can also be further classified into full-wave and bridge configurations.

As shown in Fig. 4 [18], an autotransformer with fork connection is used to feed a full-wave converter with a small isolated delta connected secondary for tripplen and other harmonics.

Fig. 5 shows these 12-pulse ac–dc converters with diode bridge rectifiers. In these MPCs, there are possibilities of more than ten configurations; however, only four are given due to space. Fig. 5(a) [18] shows a circuit with a two-winding transformer to feed one bridge with a phase shift of 30° and other bridge is fed directly through small ac reactors to adjust input ac inductances in both bridges with an interphase transformer on dc side to realize 12-pulse in the dc output.

Fig. 5(b) [36] shows a 12-pulse ac–dc converter in which a set of phase shift of ±15° is achieved using an extended delta connection to feed two sets of three-phase diode rectifiers with interphase transformers on the dc side with small (2%) rating active PWM current source to improve its performance in terms of THD of less than one percent of ac mains current. These are also called active interphase reactors and use a half bridge with two self-commutating devices along with its self-supporting dc bus voltage source converter. It only needs these types of transformers of less than 20% of load rating.

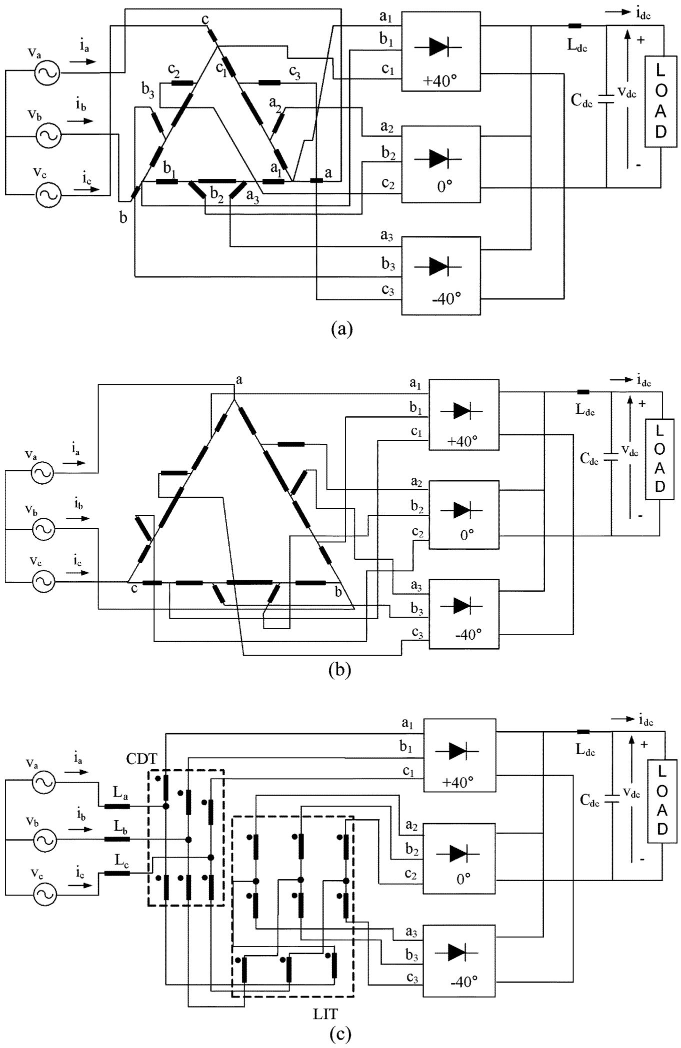

Fig. 8. (a) Three-phase unidirectional 18-pulse bridge ac–dc converter using phase shifting delta-zigzag autotransformer [191]. (b) Three-phase unidirectional 18-pulse ac–dc converter using tapped delta connected autotransformer [42]. (c) Three-phase unidirectional 18-pulse bridge ac–dc converter using current divider transformer (CDT) and line side interphase transformer (LIT) [103].

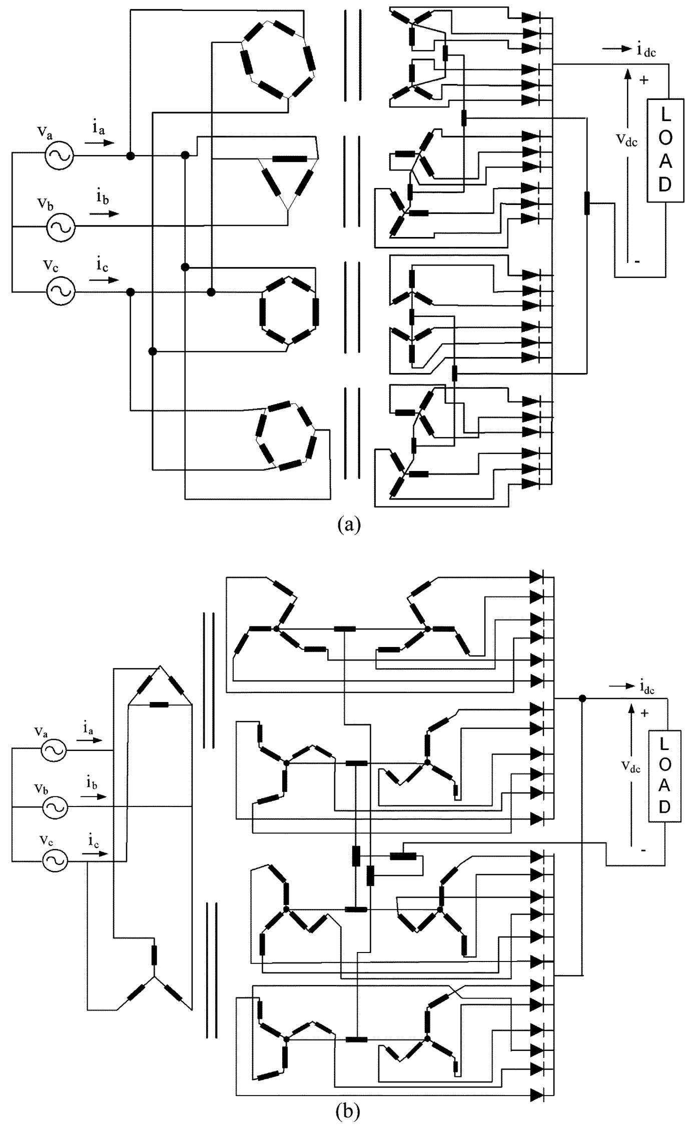

Fig. 9. (a) Three-phase unidirectional 24-pulse full-wave ac–dc converter using isolated parallel double star staggered transformers [249]. (b) Three-phase unidirectional 24-pulse full-wave ac–dc converter using isolated delta-star/zigzag transformers with seven interphase reactors [245].

2) 18-Pulse AC–DC Converters [18], [42], [46], [57], [103], [106], [164], [248]: Eighteen-pulse ac–dc converters are developed to achieve improved performance in terms of low THD of ac mains current and have low value of output voltage ripples. These are also used both in isolated and nonisolated topologies depending upon the requirements of specific applications. These 18-pulse uncontrolled ac–dc converters are classified into the following categories.

Isolated unidirectional 18-pulse AC–DC converters [18], [248]: These are used to provide isolation between input ac mains and dc loads with varying configurations. These 18-pulse converters are also further subclassified as full-wave and bridge configurations as shown in Figs. 6 and 7.

Fig. 6 [248] shows a full-wave 18-pulse ac–dc converter in which three isolated transformers with zigzag primary windings in series and secondaries windings in double star are connected to feed 18 diodes in full-wave configuration with the return path through the star points of three double-stars connected together. In this configuration, series-connected zigzag primaries result in proper current sharing with the 18-pulse in the dc output and close to sinusoidal currents in the ac mains.

Fig. 7 [18] shows one typical circuit of bridge-type 18-pulse isolated ac–dc converter in which a multiwinding transformer with primary in delta and three secondaries using one in delta with zero-phase shift and two polygon windings having a phase shift of $\pm 20°$ are used to feed three sets of three-phase diode bridge rectifiers connected in series for dc output. It has the advantage of avoiding interphase components and insensitive ac mains voltage harmonics.

Nonisolated 18-pulse AC–DC converters [18], [42], [46], [50], [54], [58], [103], [106], [176]: There are a number of developed pioneering circuits of this type of MPCs to get high level of performance typically less than 2% THD of ac mains current [18] with proper design and reduced rating of extended connected delta-zigzag autotransformer as shown in Fig. 8(a) [191]. Similar converters can also be developed using tapped

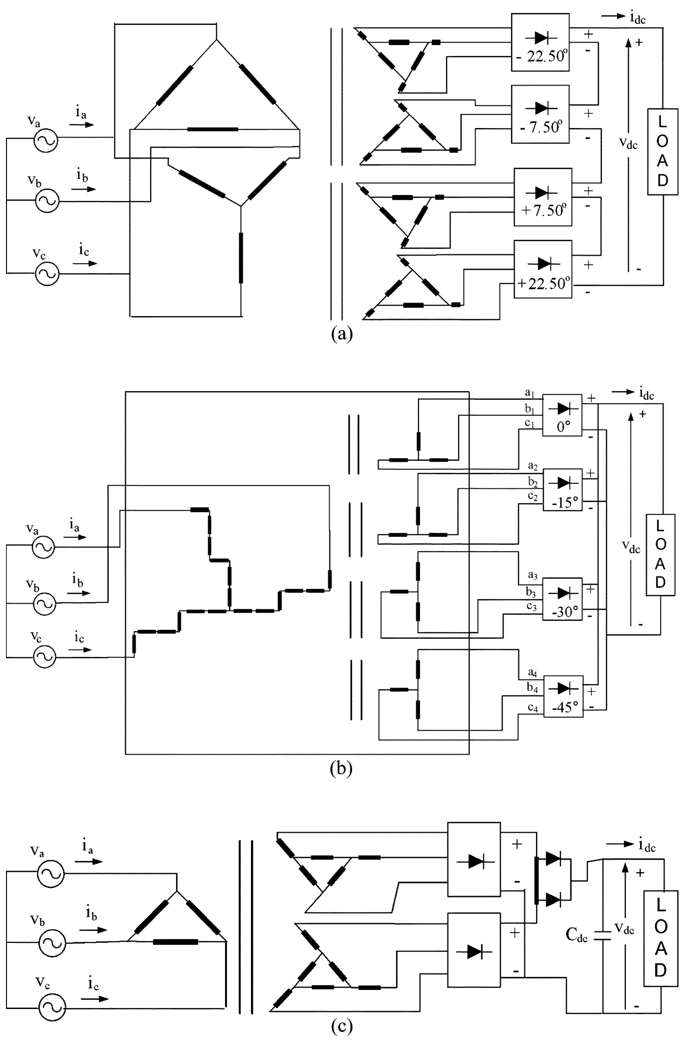

Fig. 10. (a) Three-phase unidirectional 24-pulse bridge ac–dc converter using isolated star-delta/extended delta transformers [119]. (b) Three-phase uncontrolled 24-pulse bridge ac–dc converter using isolated T connected transformers [201]. (c) Three-phase unidirectional 24-pulse bridge ac–dc converter using isolated three winding transformer with two diodes and interphase transformer [113].

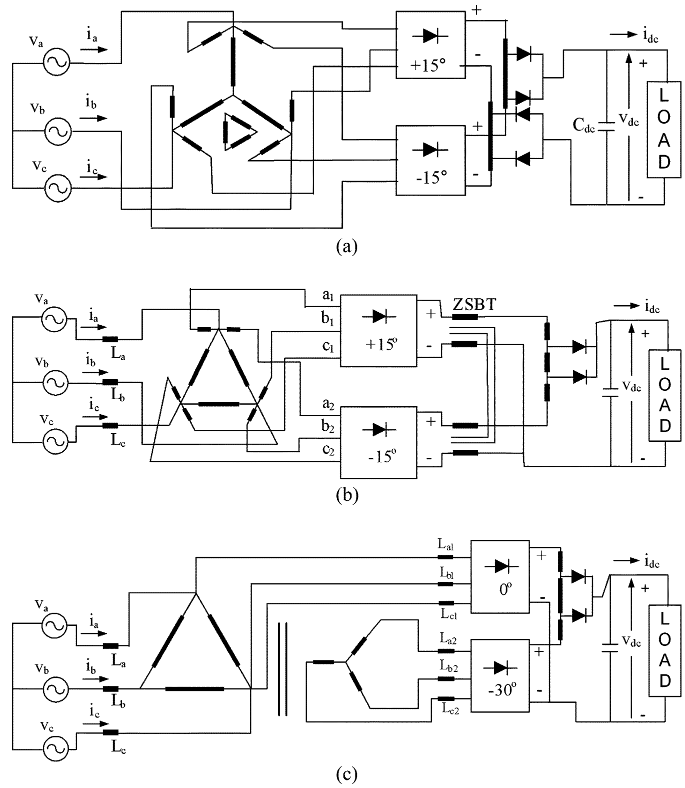

Fig. 11. (a) Three-phase unidirectional 24-pulse ac–dc converter using star-fork autotransformer with four diodes and two interphase transformers [18], [41]. (b) Three-phase unidirectional 24-pulse bridge ac–dc converter using delta fork autotransformer with zero sequence blocking transformer (ZSBT) and two diodes [112]. (c) Three-phase unidirectional 24-pulse bridge ac–dc converter using two winding transformer, two diodes and interphase transformers [109].

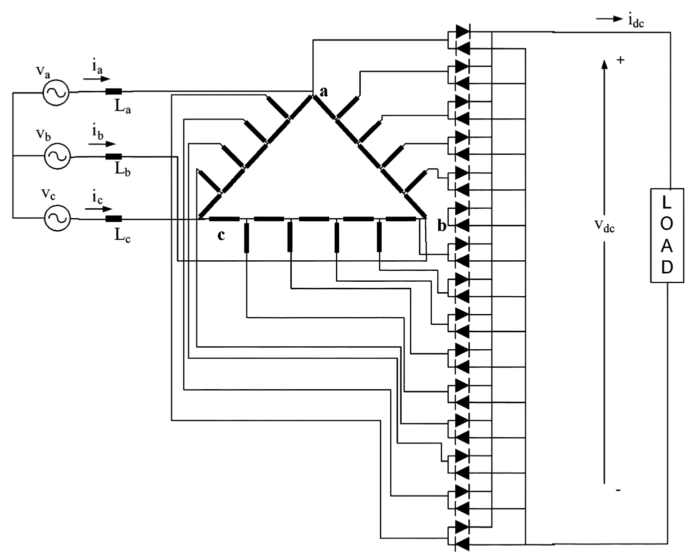

Fig. 12. Three-phase unidirectional 30-pulse ac–dc converter using tapped delta autotransformer [175].

delta winding as shown in Fig. 8(b) [42]. A similar performance can also be achieved using a CDT and an LIT as shown in Fig. 8(c) [103]. All these circuits use three diode bridge rectifiers with zero and ±40° phase-shifted nine phase ac input obtained from three-phase ac mains using these arrangements of transformers. There are a number of circuit configurations of this type of MPC and may be referred to in the [18], [42], [46], [50], [54], [58], [103], [106], [176].

3) 24-Pulse AC–DC Converters [41], [109], [112], [113], [119], [201], [245], [249]: Twenty-four-pulse ac–dc converters are used in high power rating applications where the use of a large number of devices is acceptable. It provides ripple-free dc output and almost sinusoidal ac current in the ac mains. Since these 24-pulse uncontrolled MPCs are developed in a number of configurations, they can be classified into the following categories.

Isolated unidirectional 24-pulse AC–DC converters [113], [119], [201], [245], [249]: These MPCs are developed with isolation between input ac mains and dc output through transformers to feed loads at optimum voltages. These 24-pulse ac–dc converters can also be further classified as full-wave and bridge configurations as shown in Figs. 9 and 10. Fig. 9(a) [249] shows a full-wave 24-pulse ac–dc converter using four isolation transformers with delta and staggered polygon primaries and

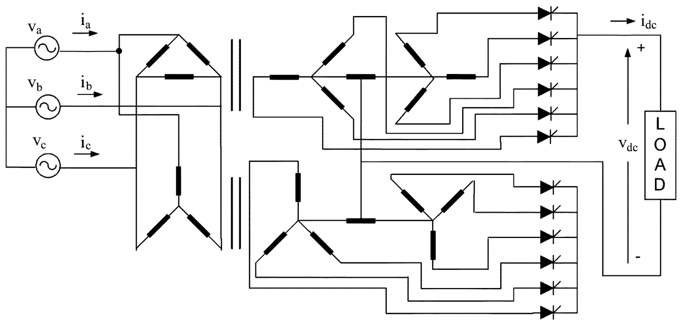

Fig. 13. Three-phase bidirectional 12-pulse full-wave ac–dc converter using isolated delta-star/double star three windings transformers [250].

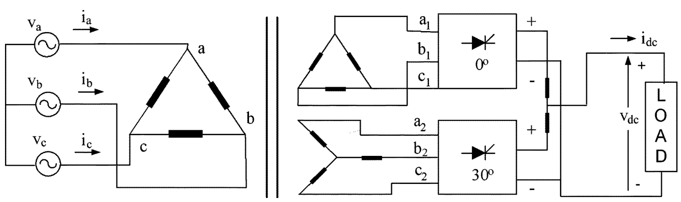

Fig. 14. Three-phase bidirectional 12-pulse ac–dc converter using isolated delta/delta and delta/star with optimum interphase reactor and transformer leakage inductances [202], [214].

double star secondaries with seven interphase reactors and 24 diodes, whereas Fig. 9(b) [245] shows full-wave 24-pulse ac–dc converter using two transformers having primaries in delta and star with secondaries in zigzag with seven interphase reactors and 24 diodes. These full-wave ac–dc converters have the advantage of having a common negative terminal of dc output, which can be used as a base or neutral point in a number of applications.

Fig. 10(a) [119] shows an isolated bridge 24-pulse ac–dc converter using four series-connected three-phase bridges and using two isolation transformers with primaries in delta and star and secondaries in extended delta to have a phase shift of 15° resulting in an ac of 12 phases to provide 24-pulses in the dc output. However, Fig. 10(b) [201] shows a 24 pulse ac–dc converter using a T connected transformer to provide a phase shift of 15° in each set of isolated secondaries from each other. Fig. 10(c) [113] shows a 24-pulse converter using single transformer with a primary in delta and two secondaries in extended delta to feed two sets of a three-phase diode bridge rectifier with a pulse multiplication circuit consisting of an interphase transformer and two additional diodes.

Nonisolated unidirectional 24-pulse AC–DC converters [41], [109], [112]: Nonisolated topologies of ac–dc converters are used with the view to reduce cost, weight, size, volume, and losses in the transformers by either adopting autotransformers of reduced rating and reduced number of devices. Fig. 11 shows such circuits of 24-pulse ac–dc converters. Fig. 11(a) [18], [41] shows a fork-based autotransformer with two sets of a three-phase diode bridge rectifier with a pulse doubling circuit consisting of interphase transformers and four diodes. Similarly, Fig. 11(b) [112] shows another circuit with a delta fork autotransformer and two three-phase diode bridge rectifiers with two zero sequence blocking transformers (ZSBT) and one interphase transformer with two additional diodes for

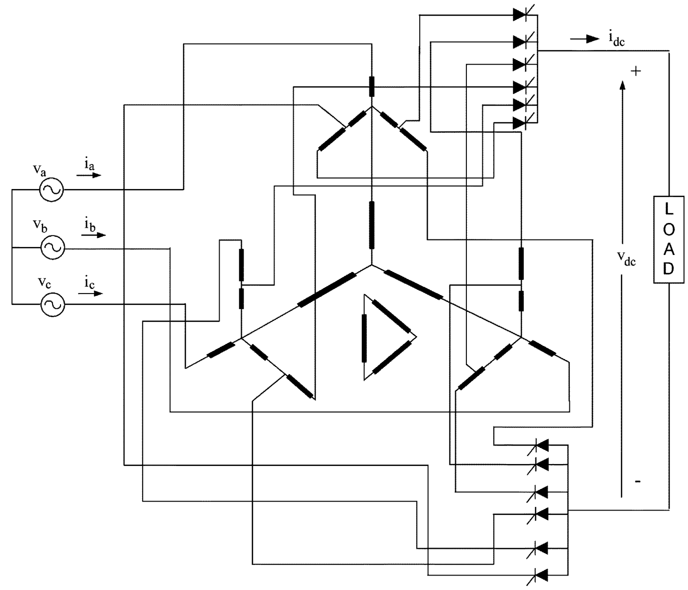

Fig. 15. Three-phase bidirectional 12-pulse full-wave ac-dc converter using fork connected autotransformers [18].

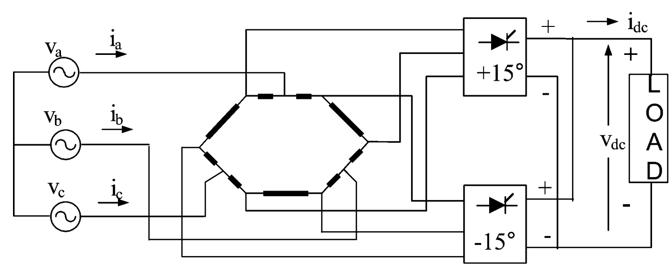

Fig. 16. Three-phase bidirectional 12-pulse bridge ac–dc converter using auto polygon transformers [178].

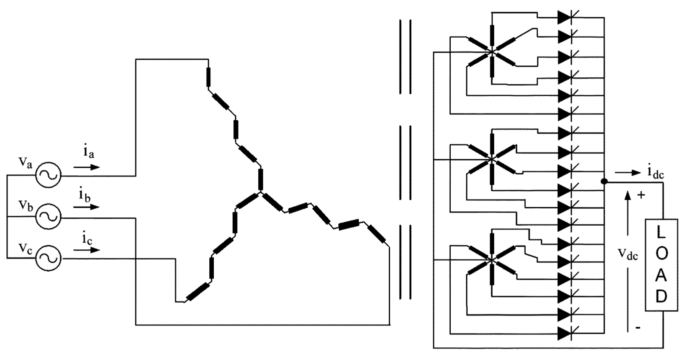

Fig. 17. Three-phase bidirectional 18-pulse full-wave ac–dc converter using isolated zigzag/double star transformer [248].

pulse doubling. However, Fig. 11(c) [109] shows two windings with a delta and star connection for 30° phase shift and with a pulse doubling circuit which reduces the number of diodes and associated input transformers.

4) 30-Pulse AC–DC Converters [175]: Fig. 12 [175] shows a 30-pulse ac–dc converter using a tapped delta connected autotransformer to convert from three-phase AC mains to 15-phase ac source to feed 30 diode circuits to provide a dc 30-pulse output. The circuit is quite cost effective because of an autotransformer, and no other components are required. It results in

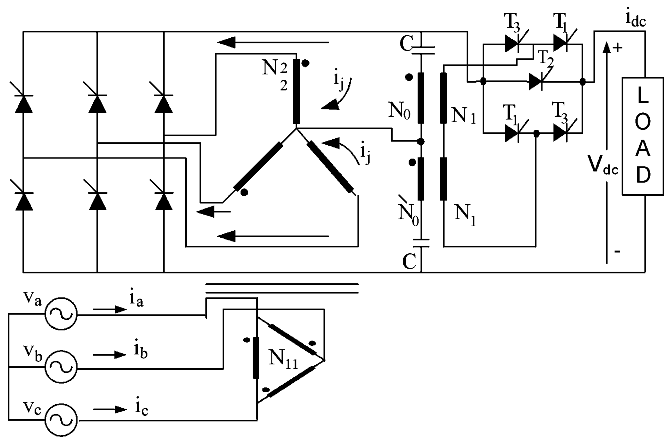

Fig. 18. Three phase bidirectional 18 pulse bridge ac–dc converter using isolated delta/star transformer with interphase transformer, five thyristors, and two capacitors [194].

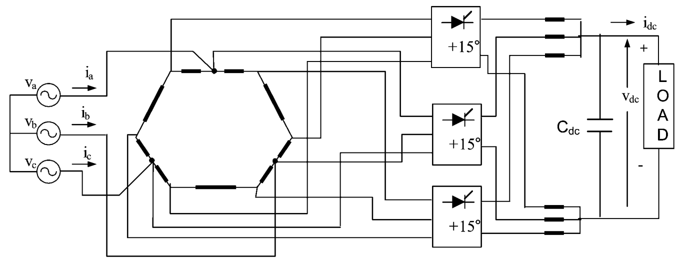

Fig. 19. Three-phase bidirectional 18-pulse bridge ac–dc converter using polygon autotransformer [178].

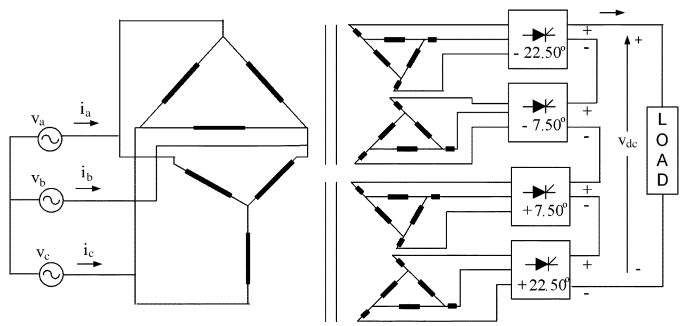

Fig. 20. Three-phase bidirectional 24-pulse bridge ac–dc converter using isolated star, delta/extended delta transformers [141].

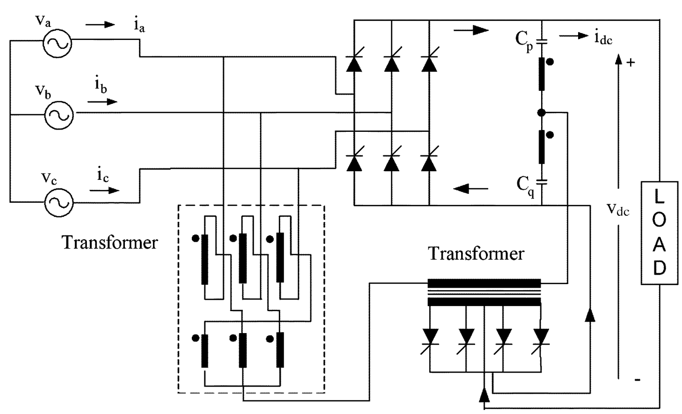

Fig. 21. Three-phase bidirectional 24-pulse with mid point reactor converter with zigzag transformer, four thyristors, and two capacitors [153], [155].

a high level of performance with a low value of THD of ac mains current with almost unity power factor and dc output with negligible ripple voltage.

5) Other High-Pulse AC–DC Converters [106], [186]: It has been reported by a number of investigators that the number of pulses can be increased to a higher number such as 38 pulses [106] by using autotransformer arrangements, and it can be increased to further higher numbers but at the cost of complexity in the circuit and increased number of components. Moreover, another method based on pulse multiplication can also be used to increase the pulses in these converters. However, it has also been reported that a high level of performance in terms of THD of ac mains current can be achieved, less than 2%, using an 18-pulse converter with a proper design of components and modified circuits [18]. Therefore, the commercial development of these converters has been up to 24-pulse converters to get quite a satisfactory level of performance of these MPCs.

B. Bidirectional AC–DC Converters [147]–[252]

The bidirectional ac–dc converters have the power flow from ac mains to dc output or vice versa and normally use thyristors with phase angle control to obtain wide varying dc output voltages. In these converters, harmonic reduction is made with pulse multiplication using magnetics. The use of a higher number of phases through the input of a multiple winding transformer and pulse multiplication using tapped reactors, interphase, and injection transformer with additional components and optimum value of interphase reactors [214] reduces THD of ac mains current and ripples in the output dc voltages. These MPCs are used to feed dc motor drives, synchronous motor drives, and to realize an ideal dc current source to feed the current source inverter fed ac motor drives. These MPCs are also used in HVDC transmission systems and power supplies for magnets, plasma, and a number of other applications. Figs. 13–24 show a few typical circuits of multipulse bidirectional ac–dc converters. These are classified into different number of pulses, which are much in use because of a high level of power quality, reliability, and overall cost of the system.

1) 12-Pulse AC–DC Converters [18], [201], [214], [250]: Twelve-pulse bidirectional converters are widely used in isolated and nonisolated circuit topologies depending upon the requirement of applications. Therefore, these MPCs are further classified as follows.

Isolated bidirectional 12-pulse AC–DC converters [201], [214], [224], [250]: Since some applications require isolation between three-phase ac mains and dc output, these are realized using isolation transformers which are also used to increase the number of phases for providing higher pulses in thyristor rectifiers to reduce THD of ac mains current and ripple in output dc voltage. However, these MPCs are realized using two types of rectifiers, namely full-wave and bridge circuits and may be subclassified into these two types as shown in Figs. 13 and 14.

Fig. 13 [250] shows a three-phase bidirectional full-wave 12-pulse ac–dc converter using isolated delta/double star and star/double star transformers, twelve thyristors connected in

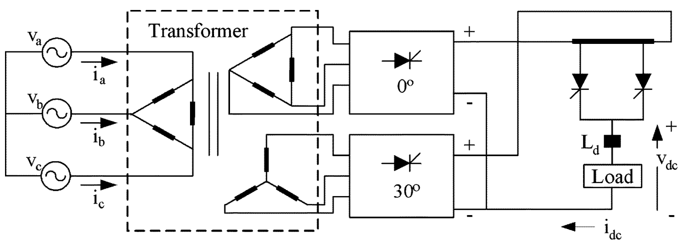

Fig. 22. Three-phase bidirectional 36-pulse ac–dc converter using isolated three winding transformer with interphase transformer and three additional thyristors [182].

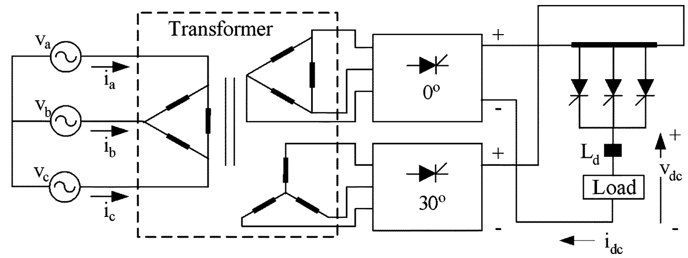

Fig. 23. Three-phase bidirectional 36-pulse ac–dc converter using isolated three-winding transformer with interphase transformer and three additional thyristors [230].

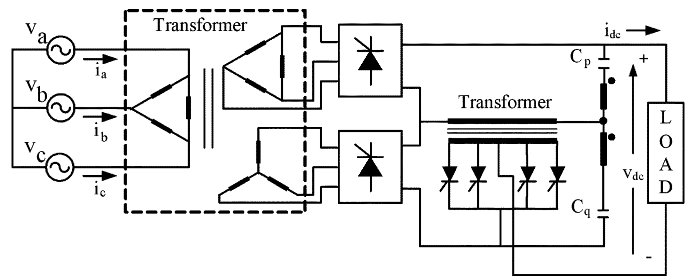

Fig. 24. Three-phase bidirectional 48-pulse bridge ac–dc converter using isolated delta/star-delta transformer with interphase transformer with four additional thyristors [224].

full-wave configurations, and two interphase reactors. It has been used for electro-winning copper plants [250] for 62-V dc at 20 kA, in which isolation is an important factor because of safety and a large difference in input (4.16 kV) and output voltages (104 V ac).

Fig. 14 [214] shows a bidirectional ac–dc converter using one isolated transformer with one primary in delta and two secondaries in delta and star with an interphase reactor. The proper design of the interphase reactor reduces its value, size, cost, losses, and the THD of ac mains current around one percent which is comparable to classical 36-pulse converters.

Nonisolated bidirectional 12-pulse AC–DC converters [18], [150]: In cases of nonisolated converters, the size, cost, and weight of magnetics using autotransformers can be drastically reduced with the same level of performance. These MPCs can also be subclassified as full-wave and bridge converters.

Fig. 15 [18] shows a circuit of a three-phase bidirectional full-wave 12-pulse ac–dc converter using a fork-connected autotransformer with open delta-connected winding and twelve thyristors.

Fig. 16 [178] shows a bidirectional bridge 12-pulse ac–dc converter with a phase shift of $\pm 15^\circ$ for feeding two three-phase bridges using polygon and extended delta connected autotransformers with effective harmonic cancellation in ac mains current.

2) 18-Pulse AC–DC Converters [178], [194], [195], [248]: These 18-pulse ac–dc converters are implemented both in isolated and nonisolated topologies similarly to uncontrolled MPCs to meet the requirements of a variety of applications. These MPCs are classified as follows.

Isolated bidirectional 18-pulse AC–DC converters [194], [248]: These 18-pulse ac–dc converters are developed both in full-wave and bridge configurations as shown in Figs. 17 and 18 with zigzag/double star and pulse multiplication circuits to achieve a low value of THD of ac mains current and less ripples in dc output voltage.

Fig. 17 [248] shows a full-wave 18-pulse ac–dc converter using primary windings connected in zigzag and secondaries in double star with 18 thyristors. This configuration of MPCs avoids interphase reactors and is well suited for low-voltage and high-current applications such as electrolysis, melting, electroplating installations, and traction.

Fig. 18 [194] shows a three-phase bidirectional bridge type 18-pulse, isolated ac–dc converter using only one three-phase transformer with delta/star-connected windings, a single three-phase thyristor bridge rectifier, and a pulse multiplication circuit consisting of two capacitors, an interphase transformer, and five additional thyristors to provide 18 pulses in output dc voltage and low THD in ac mains current. The concept of dc ripple injection is employed to eliminate the harmonics and is recommended for use in HVDC and variable-frequency ac power generated by variable-speed generators into dc.

Nonisolated bidirectional 18-pulse AC–DC converters [178]: There are numbers of configurations of these types of MPCs with reduced size of magnetics using autotransformers. Fig. 19 [138] shows a typical 18-pulse ac–dc converter using polygon autotransformer with three sets of three-phase thyristor bridges and six interphase reactors to have cost-effective conversion to feed dc and ac motor drives.

3) 24-Pulse Bidirectional AC–DC Converters [115], [119], [153], [155], [209], [249]: These MPCs are used in high-power applications such as HVDC, large-rating dc motor drives, renewable energy conversion systems, etc. with a high level of performance on ac mains and dc output to be realized as a current source. These MPCs are also realized in a number of circuit configurations and can be classified as follows.

Isolated bidirectional 24-pulse AC–DC converters [115], [119], [211], [249]: These ac–dc converters are developed to have isolation between input three-phase ac mains and output dc voltage and current at an optimum level through multiwinding transformers. Since these converters have circuit configurations of full-wave and bridge thyristor rectifiers and can be classified as follows.

Fig. 20 shows a 24-pulse isolated ac–dc converter employing isolated transformers with primary windings connected in star and delta while secondary windings are arranged in extended-delta fashion. Such rectifier configurations are described in the

TABLE I
POWER QUALITY PARAMETERS OF NONISOLATED, UNCONTROLLED AC–DC CONVERTERS

Full-Wave/ Bridge Rectifier	No. of Pulse	Fig. No.	AC mains current, I_a (A)	THD of I_a (%)	THD of V_a (%)	Displacement Factor, DPF	Power Factor, PF	DC Voltage, V_{dc}	Ripple Factor, RF (%)	DC Current, I_{dc}
Bridge	12	Fig.5c	5.876	13.9	0.5412	0.9993	0.9898	558.7	1.125	7.164
			29.04	12.51	1.746	0.9973	0.9894	556.6	1.336	35.68
	18	Fig.8b	6.031	8.018	1.282	0.9979	0.9946	577.5	0.678	7.366
			29.41	5.762	3.837	0.9923	0.9894	570.8	0.908	36.40
	24	Fig.11b	5.56	6.277	0.3597	0.9989	0.997	567.5	0.353	6.677
			27.35	5.707	1.086	0.9969	0.9952	564.5	0.576	33.21
	30	Fig.12	5.96	3.798	1.182	0.9977	0.9969	646.6	0.3476	6.218
			28.86	2.107	2.378	0.994	0.9935	639.4	0.9806	30.73

literature [119], [141], [211] where all secondary windings are extended delta.

Nonisolated bidirectional 24-pulse AC–DC converters [153], [155]: There are a number of circuit configurations developed in nonisolated topologies with reduced rating of magnetics through the use of various new concepts. Fig. 21 [153], [155] shows a typical nonisolated bidirectional 24-pulse ac–dc converter which employs a single three-phase thyristor bridge with a pulse multiplication circuit consisting of a couple of interphase transformers with four additional thyristors, two capacitors, and a three-phase zigzag transformer of around 20% rating of input power. It can also be operated in six-pulse, 12-pulse and 20-pulse mode.

Fig. 22 shows a pulse doubling scheme [182] for 12-pulse ac–dc converters that employs two six-pulse-controlled bridges having 30° phase-shifted inputs. It has an interphase reactor tapped with two thyristors for dc ripple reinjection that make it 24 pulses and improves power quality at the input.

4) 36-Pulse Bidirectional Converters [219], [230]: Fig. 23 [230] shows a typical 36-pulse ac–dc converter using a single, three-phase transformer with three windings having a primary in delta and two isolated secondaries, one in delta and other in a star to feed two sets of three-phase thyristor bridges with a pulse multiplication circuit having tapped interphase reactors and three additional thyristors. It is recommended to realize a dc current source to feed a 5300 hp (around 40 MW) synchronous motor drives. It can be operated with a 12- to 36-pulse converter. It provides a high level of performance in terms of harmonic reduction in ac mains and ripple less controlled dc output.

5) 48-Pulse Bidirectional AC–DC Converters [187], [224]: There can be a number of configurations of 48-pulse ac–dc converters using the concept of phase shifting and pulse multiplication. A 48-pulse ac–dc converter based on the dc ripple reinjection technique is described in [187]. Another typical circuit of a three-phase, bidirectional 48-pulse ac–dc converter using a single transformer with a primary in delta and two secondaries, one in star and other in delta, to feed two sets of series-connected three-phase thyristor bridges is shown in Fig. 24 [187] for high-power and high-voltage applications. This configuration is based on dc current reinjection that employs an auxiliary circuit, as shown, for pulse multiplication. It can be operated with 12, 24, 36, and 48-pulse converters. It is recommended for use in HVDC with a high level of performance in terms of harmonic reduction in the ac mains and reduced ripples in dc output.

6) Other Higher Pulse AC–DC Converters [18]: It is proposed that the concepts of phase shifting using multiple windings in transformers and pulse multiplication on the dc side can be used to realize a further higher number of pulses for power quality improvements in terms of harmonic reduction in ac mains current and reduced ripples in dc output. However, increased complexity, components count, and economic considerations may not favor the use of a much higher number of pulses.

IV. COMPONENTS SELECTION AND THEIR RATINGS

The major components in MPCs are magnetics, solid-state devices, and capacitors. Normally used solid-state devices in uncontrolled ac–dc converters are diodes, and in a few cases some small rating MOSFETs and IGBTs are used to realize active dc link reactance, which improves the performance of MPCs tremendously. However, in bidirectional ac–dc converters, thyristors are used in full-wave and bridge circuit configurations and pulse multiplication circuits. Since these solid-state devices generally carry load current, their rating depends on the voltage and current rating of the loads. These solid-state devices operate at low (line) frequency with line commutation (soft switching); therefore, losses in devices are quite low compared to other types of converters. Moreover, other accessories such as heat sink and protective components depend upon the device rating.

The heart of these ac–dc converters is the magnetics used to increase the number of pulses for improving the performance in terms of harmonics reduction in ac supply currents and ripples in output dc voltages. The major magnetic components are transformers (isolation and auto) on the ac mains side and interphase transformers and reactors on the dc side. In most of the isolated topologies, multiwinding isolation transformers are used in the input side of converter, and their rating is equal to load rating or little higher; therefore, the size and weight of theses transformers are quite high. However, these are compulsions due to the requirements of applications to provide isolation between

TABLE II
POWER QUALITY PARAMETERS OF ISOLATED UNCONTROLLED AC–DC CONVERTERS

Bridge Rectifier	No. of Pulse	Fig. No.	AC mains current, I_a (A)	THD of I_a (%)	THD of V_a (%)	Displacement Factor, DPF	Power Factor, PF	DC Voltage, V_{dc}	Ripple Factor, RF (%)	DC Current, I_{dc}
Full-Wave	12	Fig 2a	6.349	12.05	0.34	0.9954	0.9883	232.3	1.249	18.36
			30.31	8.54	0.9	0.9824	0.9788	226	1.049	89.34
	18	Fig.6	7.607	5.019	0.822	0.9899	0.9886	173.0	0.782	30.75
			32.48	1.322	0.980	0.9514	0.9512	152.4	2.549	135.5
Bridge	12	Fig3a	6.082	12.82	0.3992	0.9971	0.9891	269	1.299	15.3
			27.85	10.45	1.046	0.991	0.9856	265.1	1.729	71.25
	12	Fig.3b	6.199	13.81	1.433	0.9977	0.9882	583.2	1.944	7.439
			30.03	10.88	4.081	0.9895	0.9829	572.6	2.108	36.52
	18	Fig.7	5.803	7.831	1.214	0.9979	0.9948	3351	0.640	1.192
			27.76	5.549	3.373	0.9942	0.9921	3310	0.563	5.887
	24	Fig.10a	6.035	3.316	0.578	0.9928	0.9922	2211	0.539	1.896
			27.74	2.028	1.071	0.965	0.9647	2094	1.053	8.974
	24	Fig.10b	6.756	4.926	1.057	0.9978	0.9965	254.8	0.599	17.69
			28.7	2.379	2.115	0.9941	0.9936	223.5	2.155	77.55
	24	Fig10c	5.181	5.861	0.2691	0.8331	0.8331	273.3	0.3925	12.85
			29.35	4.747	0.79	0.8014	0.8005	269.6	0.781	73.85

ac mains and dc loads, especially when the voltage difference is large between input and output. Moreover, it is also essentially required from safety and protection points of view.

In case of a nonisolated ac–dc converter, the size, cost, weight, and losses of magnetic components can be reduced drastically. There are novel configurations in which the rating of autotransformers can be reduced less than 20% of the load rating. Moreover, in some cases, the input main transformer is avoided, and auxiliary or only interphase transformers are required. Therefore, there is a tremendous scope of reducing the rating of input transformers by using new circuit concepts and a number of phase-shifting techniques. The techniques of pulse multiplication on the dc bus, optimum value selection of dc link reactors, and method of active interphase reactor on the dc side have the direct impact on the rating and size of input transformer in these ac–dc converters. These methods reduce the number of input transformers, number of devices, overall size, losses, and cost of the converters, which have made them acceptable in additional applications.

The magnetic components on the dc side of these ac–dc converters are interphase transformers, reactors. and filter inductors. In some configurations, their size can be reduced or they can be eliminated especially in series-connected converters. The design of these components is quite crucial due to dual excitation of them with ac and dc fluxes. However, the size of the filter inductors is automatically reduced due to the increased number of pulses on the dc side and even low values of higher order harmonics on the ac side.

Other required components in the power circuit of these MPCs are the capacitors required in the pulse multiplication circuit, at output dc, and optional ac filters on input ac mains, and their size and requirements are reduced with increasing the number of pulses in the converters. Moreover, they can also be eliminated if the level of performance is acceptable and within satisfactory limits by increasing the number of pulses.

V. PERFORMANCE OF MULTIPULSE CONVERTERS

These multipulse ac–dc converters are designed and modeled using MATLAB software along with SIMULINK and Power System Blocksets (PSB) toolboxes. The performance of some ac–dc converters in each category in terms of power quality indices is given in Tables I–IV. The simulations are carried out for a 20-kW R-L load with three-phase input supply voltage of 415 V, 50 Hz having 3% source impedance. The power quality indices such as total harmonic distortion of ac mains current (THDi), distortion factor (DF), Displacement power factor (DPF), power factor (PF), and ripple factor (RF) can be compared at full-load and light-load (20% of full-load). In case of controlled ac–dc converters, the power quality indices are given at 10° and 30° firing angles. The input current waveform for these converters along with their harmonic spectrum and THD are shown in Figs. 25–40. It can be seen that the input current in 18-pulse and higher pulse converters meets IEEE-519 standard requirements without any filters.

VI. POWER QUALITY CONSIDERATIONS

One of the major objectives to increase the number of pulses in ac–dc converters is to improve the power quality at input ac mains and output dc load in a wide variety of applications. The main drawbacks of conventional ac–dc converters have been harmonic injection into ac mains which results in a number of problems such as poor power factor, poor utilization of the distribution system, increased losses, EMI and RFI, increased noise, distortion in voltage wave forms at the point of common coupling (PCC), disturbance to neighboring consumers, etc. Similarly ripples in dc output voltage causes derating of loading equipment, additional losses in the load, etc. These power quality problems are increasing at a fast rate due to the enhanced use of solid-state converters. There are a number of options for power quality improvement, and multipulse ac–dc

TABLE III
POWER QUALITY PARAMETERS OF NONISOLATED CONTROLLED AC–DC CONVERTERS

No. of Pulse	Fig. No.	Firing Angle (degrees)	AC mains current, I_a (A)	THD of I_a (%)	THD of V_a (%)	Displacement Factor, DPF	Power Factor, PF	DC Voltage, V_{dc}	Ripple Factor, RF (%)	DC Current, I_{dc}
12	Fig.5c with thyristors	10	6.014	14.74	3.037	0.9845	0.9735	570.1	2.741	7.323
		10	29.55	12.89	6.952	0.9822	0.9718	564.7	2.053	36.27
		30	5.313	16.9	4.67	0.8731	0.86	501.4	8.183	6.442
		30	26.12	15.37	10.5	0.8733	0.8584	497.0	5.897	31.92
24	Fig.11b With thyristors	10	5.475	6.763	2.013	0.9823	0.9799	538.0	1.144	6.868
		10	26.77	5.968	4.166	0.9766	0.9741	528.7	1.534	33.72
		30	4.877	8.968	3.239	0.8742	0.8702	477.7	3.638	6.093
		30	23.8	6.456	6.863	0.8718	0.868	469.3	3.13	29.93

TABLE IV
POWER QUALITY PARAMETERS OF ISOLATED CONTROLLED AC–DC CONVERTERS

Full-Wave/ Bridge Rectifier	No. of Pulse	Fig. No.	Firing Angle, (degrees)	AC mains current, I_a (A)	THD of I_a (%)	THD of V_a (%)	Displacement Factor, DPF	Power Factor, PF	DC Voltage, V_{dc}	Ripple Factor, RF (%)	DC Current, I_{dc}
Full-Wave	12	Fig.13	10	6.158	13.46	1.765	0.9790	0.9701	58.11	1.838	71.54
			10	28.71	9.328	3.858	0.9652	0.9603	54.99	1.088	338.5
			30	5.162	15.92	2.663	0.8304	0.8198	48.61	6.606	59.84
			30	24.25	13.79	6.014	0.7982	0.7893	45.72	4.424	281.4
Bridge	12	Fig.14	10	6.174	5.563	0.605	0.9587	0.9573	531.2	2.448	7.589
			10	29.91	5.551	2.177	0.9627	0.9610	525.7	2.538	37.55
			30	5.474	4.43	0.246	0.8537	0.8529	470.7	5.62	6.724
			30	26.26	4.628	2.041	0.8429	0.8419	459.9	6.604	35.85
	36	Fig.23	10	5.148	4.452	0.074	0.9809	0.9799	270.2	1.343	12.69
			10	28.95	4.594	0.171	0.9728	0.9718	267.9	2.982	71.11
			30	5.269	4.911	0.122	0.8616	0.8606	237.0	3.126	12.97
			30	25.66	4.097	0.266	0.8548	0.8541	234.8	4.563	64.08

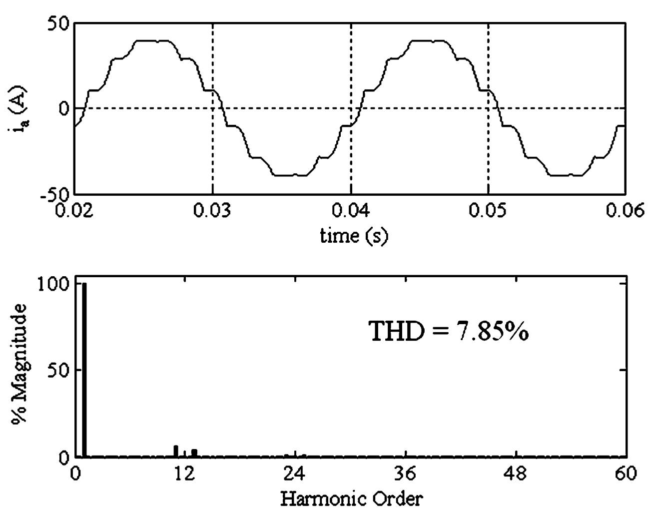

Fig. 25. Input current waveform and harmonic spectrum of Fig. 2(a) (three-phase unidirectional 12-pulse full-wave ac–dc converter using two isolated transformers (delta/double-star and star/double-star)).

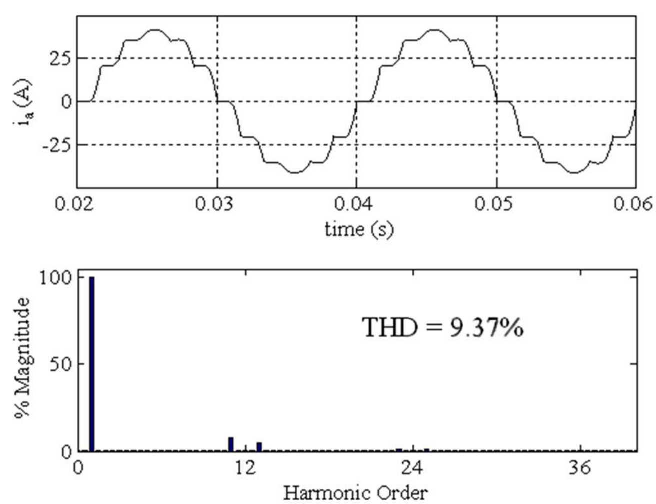

Fig. 26. Input current waveform and harmonic spectrum of Fig. 2(b) (three-phase unidirectional 12-pulse full-wave ac–dc converter using isolated single-polygon transformer [18]).

converters is one of among others, such as PWM converters, filters (passive, active, and hybrid), etc. MPCs are quite effective to improve power quality at input ac mains and output dc loads.

Three-phase unidirectional multipulse ac–dc converters are capable of reducing THD of ac mains current well below the limits specified in the several standards. For example, unidirectional 18-pulse ac–dc converters [18] are able to reduce THD of ac mains current below 2% with proper design and without any control. Similarly active interphase transformer in the dc bus [150] is able to reduce THD below 1% of ac mains current in

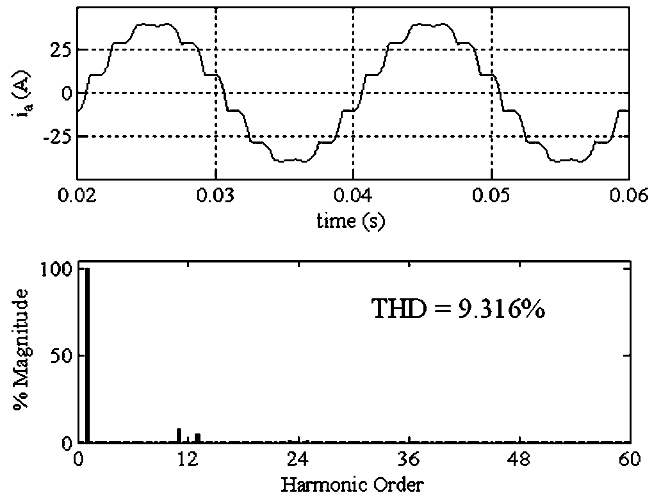

Fig. 27. Input current waveform and harmonic spectrum of Fig. 3(a) (three-phase unidirectional 12-pulse bridge ac–dc converter using isolated single delta/delta-star three winding transformer [18], [110]).

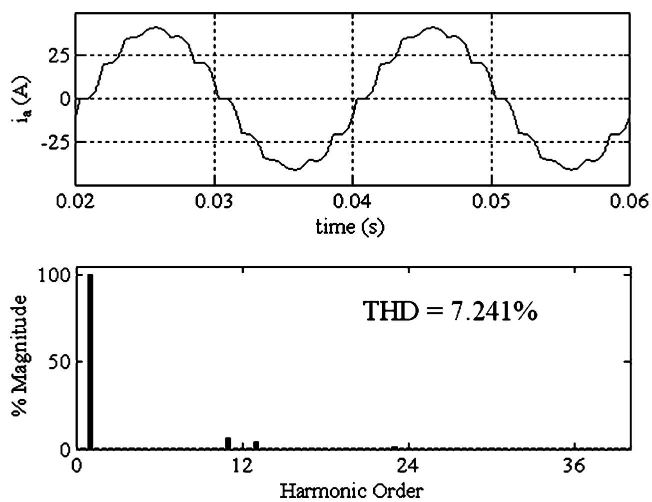

Fig. 28. Input current waveform and harmonic spectrum of Fig. 3(b) (three-phase unidirectional 12-pulse bridge ac–dc converter using isolated two Scott transformers [130]).

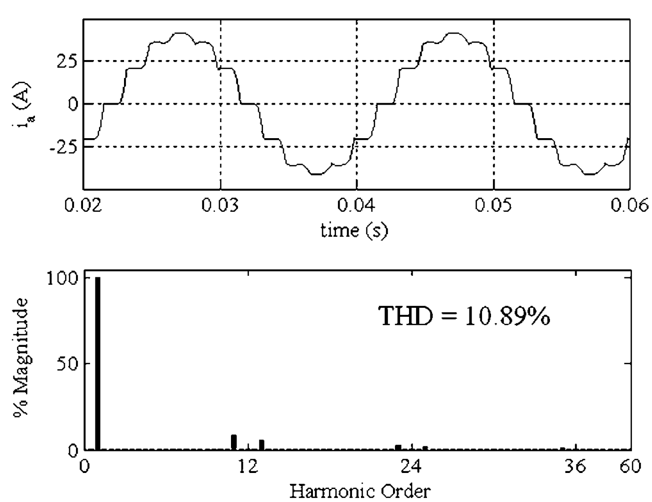

Fig. 29. Input current waveform and harmonic spectrum of Fig. 5(c) (three-phase unidirectional 12-pulse bridge ac–dc converter [36]).

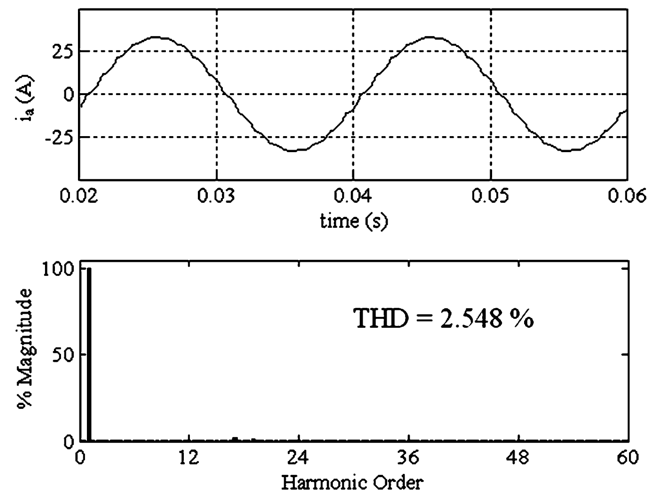

Fig. 30. Input current waveform and harmonic spectrum of Fig. 6 (three-phase unidirectional full-wave 18-pulse ac–dc converter using zigzag/triple double-star isolation transformer [248]).

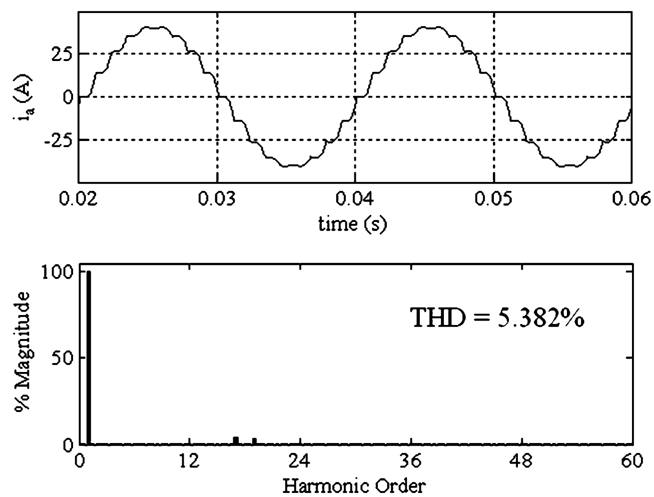

Fig. 31. Input current waveform and harmonic spectrum of Fig. 7 (three-phase unidirectional 18-pulse bridge ac–dc converter using isolated delta/delta/double polygon transformer [18]).

12-pulse ac–dc converters. The concept of improved magnetics with novel configurations of ac–dc converters is capable of providing a high level of power quality in terms of reduced THD of ac mains current well below 5% or around and almost ideal ripple-free dc output voltage to feed variety of loads.

The new design concepts and novel configurations of bidirectional ac–dc converters are capable of reducing THD of ac mains current [202] below 1% in 12-pulse converters. It does not improve only the power quality but reduces the cost, size, weight, and losses in the converters. Novel concepts of pulse multiplication are able to increase many times the pulses without increasing the size of magnetics to result in a high level of power quality.

A number of pioneering attempts have been made to increase the number of pulses in ac–dc converters for improving the power quality at input ac mains in terms of low THD of current and high power factor and almost ripple-free ideal dc output voltage to feed a number of loads. There are novel configurations of MPCs in which a number of pulses can be increased

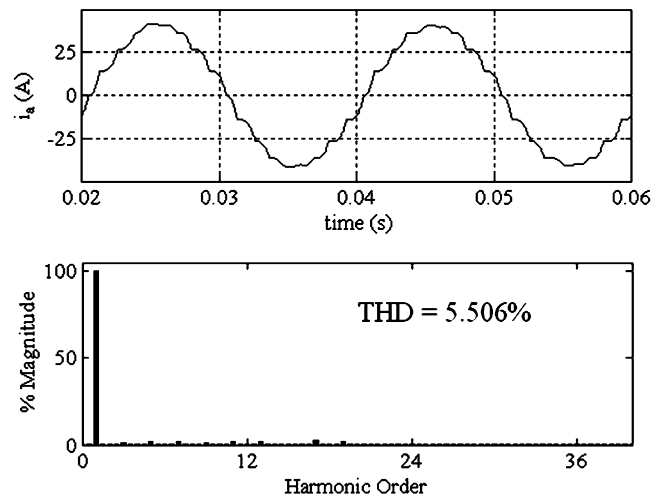

Fig. 32. Input current waveform and harmonic spectrum of Fig. 8(b) (three-phase unidirectional 18-pulse ac–dc converter using tapped delta connected autotransformer [42]).

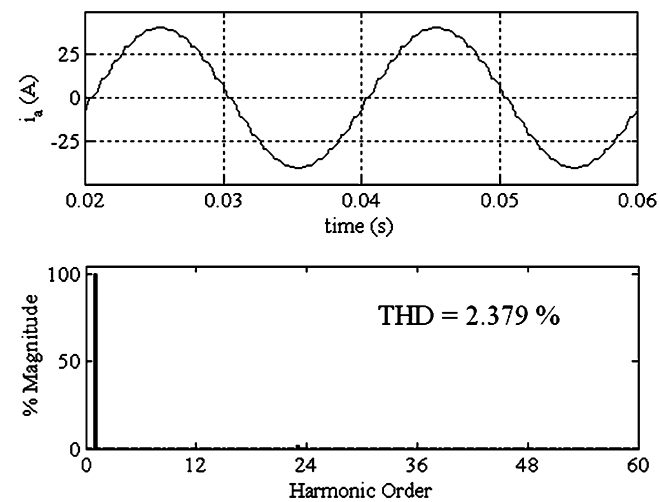

Fig. 34. Input current waveform and harmonic spectrum of Fig. 10(b) (three-phase uncontrolled 24-pulse bridge ac–dc converter using isolated T- connected transformers [201]).

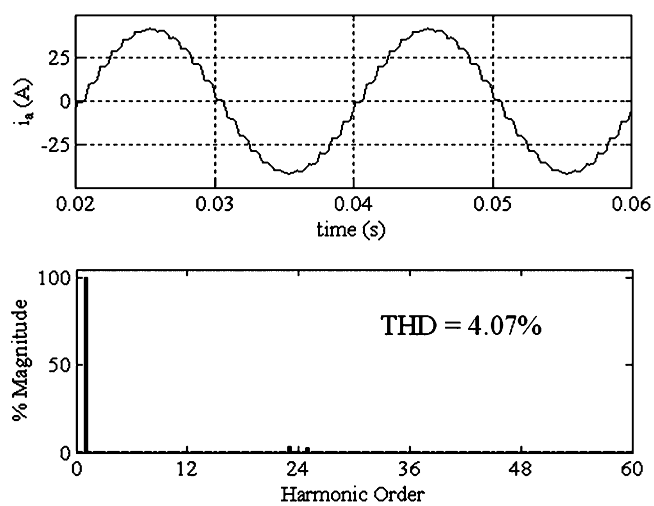

Fig. 33. Input current waveform and harmonic spectrum of Fig. 10(a) (three-phase unidirectional 24-pulse bridge ac–dc converter using isolated star-delta/extended delta transformers [95]) [178].

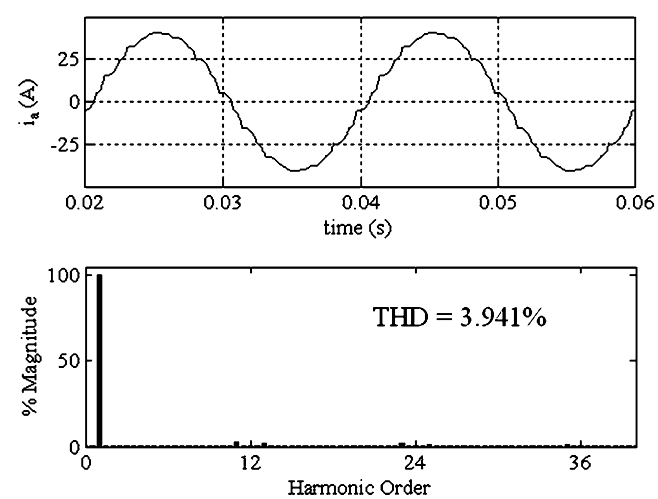

Fig. 35. Input current waveform and harmonic spectrum of Fig. 10(c) (three-phase unidirectional 24-pulse bridge ac–dc converter using isolated three winding transformer with two tapping diodes and interphase transformer [113]).

to any high value but certainly at the cost of additional components and complexity of the circuit configurations. Therefore, the designer has to use an ac–dc converter with an appropriate number of pulses, which satisfies the level of power quality, required in view of economic and reliability considerations. However, MPCs are certainly the cost-effective option compared to other methods of power quality improvements and are used extensively in a number of applications.

One of the very favorable aspects of MPCs is that by increasing the number of pulses, some of the harmonics are eliminated; along with it higher order harmonics are also drastically reduced due to the stepped wave of ac currents much closer to sinusoidal waveforms. Moreover, they have much less switching losses compared to PWM converters.

VII. Comparative Features and Other Options of Power Quality Improvement

The evolved configurations of MPCs mentioned in the previous section are developed to meet the requirements of varying applications and altogether have different features. For example, unidirectional MPCs are used in the applications which have power flow from ac source to dc load with typical examples of variable frequency ac motor drives for pumps, fans, compressors, and blowers, etc. without isolation between ac input to dc output. However, there are a few applications, which require isolation between ac and dc, such as electrochemical processes, etc. even with unidirectional power flow. Similarly, in bidirectional ac–dc converters, there are applications which do not need isolation, such as dc motor drives and synchronous motor drives,

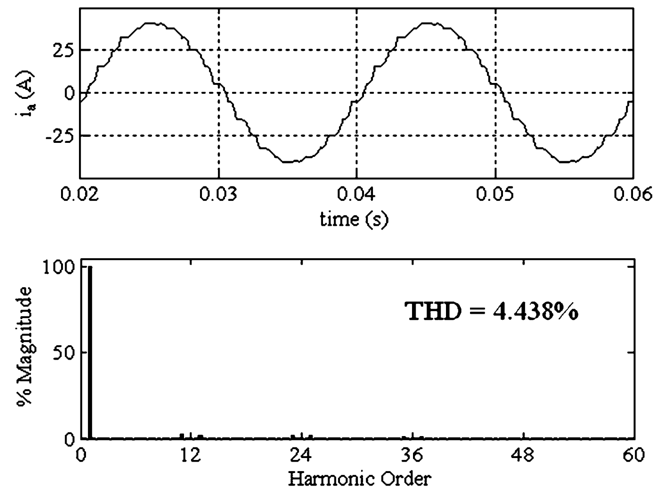

Fig. 36. Input current waveform and harmonic spectrum of Fig. 11(b) (three-phase unidirectional 24-pulse bridge ac–dc converter using differential delta autotransformer with zero sequence blocking transformer (ZSBT) and two diodes [112]).

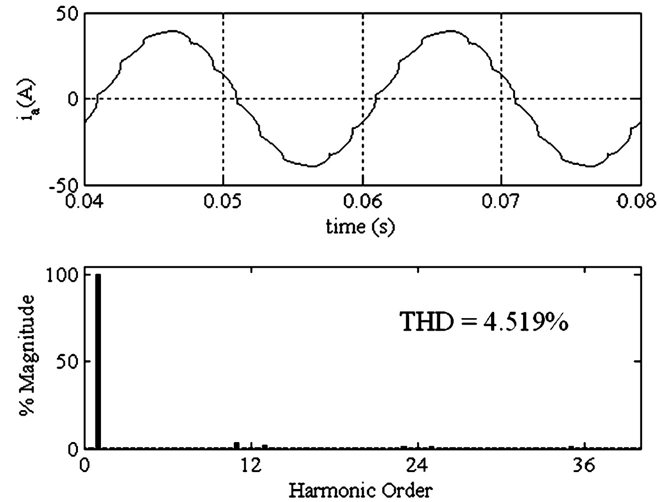

Fig. 38. Input current waveform and harmonic spectrum of Fig. 14 (three-phase bidirectional 12-pulse ac–dc converter using isolated delta/delta and delta/star with optimum interphase reactor and transformer leakage inductances [202]).

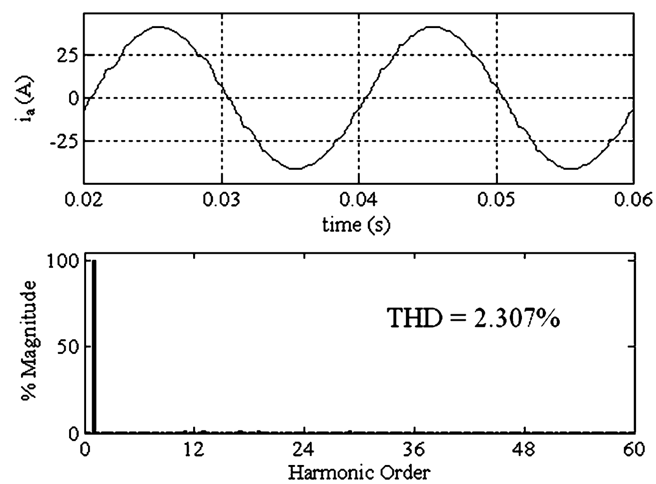

Fig. 37. Input current waveform and harmonic spectrum of Fig. 12 (three-phase unidirectional 30-pulse full-wave ac–dc converter using tapped delta autotransformer [175]).

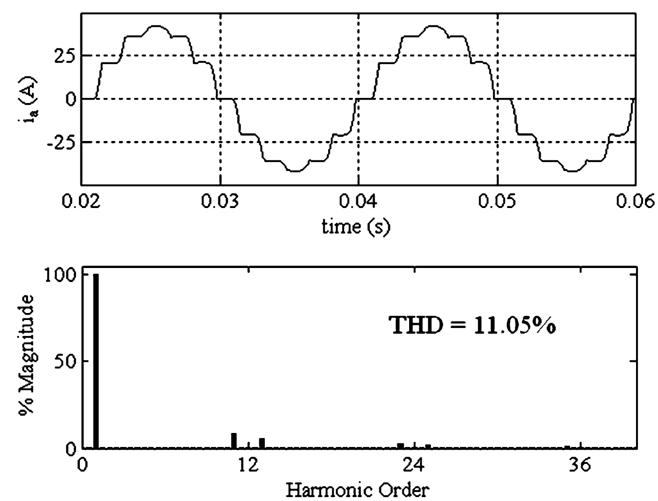

Fig. 39. Input current waveform and harmonic spectrum of Fig. 16 (three-phase bidirectional 12-pulse bridge ac–dc converter using auto polygon transformers [178]).

and some of them need isolation, such as HVDCs, etc. Therefore, there is clear demarcation among MPCs depending upon the requirements of the loads.

However, within the same category of MPCs, there are many configurations that have merits and demerits toward ideal characteristics. Moreover, different pulse configurations in the same type of MPCs provide a variety of options to the users. The designer has to select a best option of MPCs with a right pulse number depending upon rating of load, cost, efficiency, and requirement of level of power quality desired. Moreover, there are other options of power quality improvement such as filters and PWM converters. Further, in filters too, one may use passive, active, or hybrid filters. Since these filters are to be used along with some ac–dc converter; therefore, it will have additional components, material, increased losses, etc. The option of filters may be better for already existing installation of ac–dc converters for improving the power quality. However, for new installations, MPCs will certainly be a better option since it has improved power quality in the ac–dc conversion stage itself, and no separate attachment is required. Similarly, one may select PWM converters for ac–dc conversion, but these converters have complex control, higher switching losses, noise, and a high level of RFI and EMI. It may be true only in case if MPCs can meet the requirement of a particular application. It means one can have a number of options for power quality improvements in ac–dc conversion. The design engineer, therefore, must be aware of all possible options and their relative features to select the best option with required level of power quality from an overall point of view.

VIII. Selection Considerations of MPCS for Specific Applications

Selection of MPCs for a specific application is an important task for designer and users. The following are a few factors responsible for deciding on the right ac–dc converter topology for a particular application.

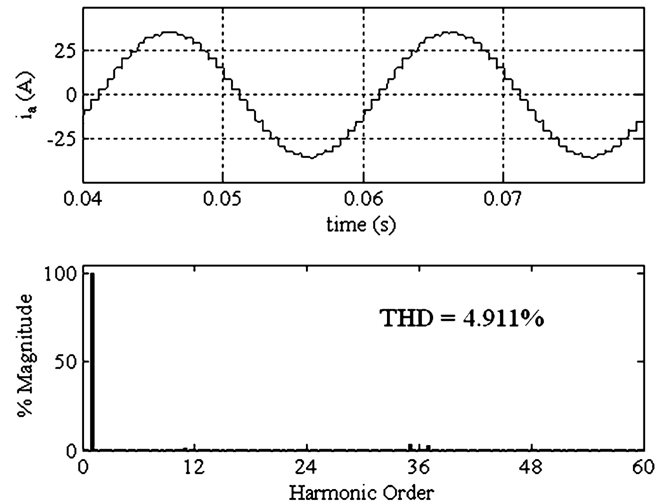

Fig. 40. Input current waveform and harmonic spectrum of Fig. 23 (three-phase 36-pulse AC–DC converter using isolated three-winding transformer with interphase transformer and three additional thyristors [187]).

Required level of power quality in input (permitted crest factor, THD, PF).

Required level of power quality in output (voltage ripple, voltage regulation).

Type of dc output voltage (constant, variable, etc.).

Power flow (unidirectional or bidirectional).

Nature of output (isolated or nonisolated between ac and dc).

Number of pulses.

Type of magnetics.

Type of dc load (linear, nonlinear).

Cost, size, weight.

Efficiency.

Noise level (EMI, RFI, sound level, etc.).

Rating (kW, MW etc.).

Environmental factors (ambient temperature, altitude, pollution level, humidity, types of cooling, etc.).

These are only few factors. Moreover, there are some other considerations such as comparative features of other options, types of protection, Standard to be followed, etc.

IX. Latest Trends and Future Developments in MPCs Technology

MPCs technology has been developed to a mature level and is finding wide-spread applications in variable-speed drives using variable frequency ac motor controllers and dc motors, power supplies, electrochemical, and HVDC transmission systems. However, there are consistent new developments in MPCs for further improving their performance through cost, size, weight, loss reduction, and enhancement of reliability by reducing the number of component counts. Newer configurations of MPCs are on the way to reduce the size of magnetics, number of components, and energy storage elements. A breed of transformer connections for the use in MPCs is being developed to improve the overall performance of these converters. The numbers of increased configurations of these converters are able to provide a good choice for the design engineers to meet exact requirements of a particular application. The concept of pulse multiplication in these converters has given a real boost to increasing the number of pulses for improving power quality without increasing much hardware. Similarly, the concept of the active interphase reactor has also made a drastic improvement in power quality by reducing THD of ac currents less than 1% even in 12-pulse converters. It is expected that such new inventions in MPCs will further improve the power quality in ac–dc conversion without increasing their costs, and they will find their use more and more common in the near future.

X. Conclusion

A comprehensive review of MPCs has been presented to explore a wide spectrum of different configurations of multipulse ac–dc converters. A broad classification of MPCs in several categories is expected to be good guidelines for easy selection of an appropriate converter for a specific application. These MPCs can be considered better alternatives for power quality improvement because of an inherent integrated converter with simple construction, reduced size of magnetics, and enhanced reliability due to lower components count compared to other means of power quality improvement. These converters improve the power quality at both ends, i.e., input ac mains and dc output load. Moreover, the use of these MPCs results in less noise, low EMI and RFI, low switching losses, and low cost due to the use of simple devices. It is hoped that this glimpse of multipulse ac–dc converters and their performance will be a useful reference to the designers, users, manufacturers, and researchers working on ac–dc converters dealing with power quality issues.

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