IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)
e-ISSN: 2278-1676,p-ISSN: 2320-3331, Volume 5, Issue 5 (May. - Jun. 2013), PP 57-67
www.iosrjournals.org

Back to Back Connected Multilevel Converters: A Review

Amit Ojha[1], Pradyumn K. Chaturvedi[2], Arvind Mittal[3], Shailendra K. Jain[4]
[1](Department of Electrical Engineering, MANIT, Bhopal, [2](Department of Electrical Engineering, SATI,Vidisha
[3](Department of Energy, MANIT, Bhopal, [4](Department of Electrical Engineering, MANIT, Bhopal

Abstract: *The new power converter topologies i.e multilevel converter is major breakthrough in power conditioning applications. The role of multilevel converters for AC-AC conversion when connected Back to Back is now proving an achievement of mile stone in the field of high power conversion. In view of this a comprehensive review of Back to Back connected multilevel converters is presented in this paper, which focus mainly on its topologies, control strategies and real time industrial applications. The aim of this review is to group and review the recent publications, in order to establish the current state of the art and trends of the Back to Back connected multilevel power converters (MPCs) to provide researchers meaningful information about this technology.*
Keywords- *Bi-directional converters, BTB connection, Front End Converters, Improved Power Quality, MPCs, Multilevel Topologies, SPWM.*

I. Introduction

` AC-AC converters, used in application ranging from few MW to several MW are playing key role in the field of power conditioning. AC-AC converters are broadly classified based on direct conversion (direct link) or indirect conversion (dc link). The former one i.e. phase controlled cycloconverters (direct link converters) having a big disadvantage of generation of complex harmonics in load and line along with poor line DPF. Whereas the later one i.e. dc link converters in which two converters connected back to back through dc link is an effective way to get variable frequency in the output with reasonably good power quality[1].

The front end converter in dc link AC-AC converter as shown in Fig.1 may be either line commutated converter or active front end converter. But the line commutated front end converter is suffering from serious problem of power quality issues such as injection of harmonics in to the system & requirement of reactive power [2]. So the choice available is active front end converter for the rectification [3].

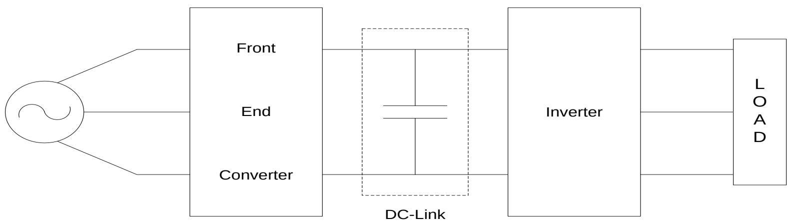

Fig.1 AC-AC converter

However there is an acute competition between the use of classic power converter topologies (2-level) using high voltage semiconductors [4] and new converter topologies (multilevel) [5, 6] using medium voltage devices in high power applications as shown in Fig.2.

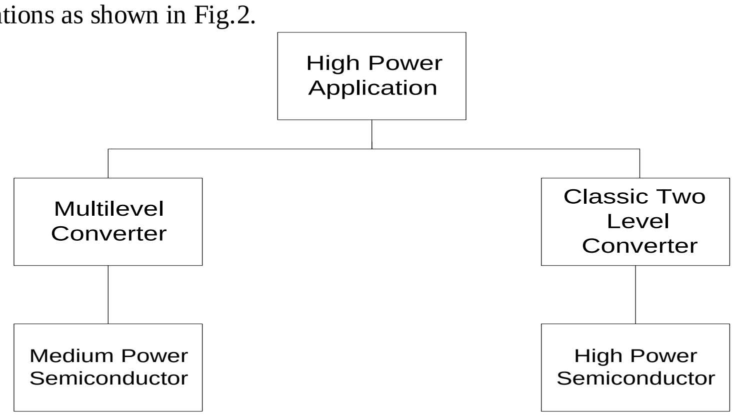

Fig.2 Classification of semiconductor family for high Power Application

Large dv/dt, device voltage stress, common mode voltage, high switching frequency etc. are reasons for using multilevel converters in dc link AC-AC converters (converters connected Back to Back) in place of 2-level conventional converters. Multilevel power converters are now finding increased attention in industry and academia as one of the preferred choices of electronic power conversion for medium/high power application [4] like high power AC motor drives. The main objective of using multilevel converter in high power application is to eliminate heavy costly transformers from the motor drive. Another advantage of using multilevel converters are nearly sinusoidal current waveform, lower common-mode voltage & lower dv/dt that lead to reduce stress on motor bearings & windings [8,9].

Looking in to the importance of multilevel converter in AC-AC conversion, this study is carried out to provide concrete information about this technology. In this review more than 70 papers are studied. All these papers basically deal with multilevel converters, their topologies & their control for specific applications.

The paper is organized as follows: The need for Back to Back connected converters is discussed in section II. A brief overview of multilevel converter topologies is outlined in section III to present basic concepts. Section IV gives information about the components required for AC-AC conversion in which MPCs are connected Back to Back. Section V covers the latest trends in multilevel modulation technique for BTB connections. New and future promising applications of multilevel converters using BTB connection are described in section VI. Challenges before this technology is covered in section VII followed by concluding remarks in section VIII.

II. Need of Back to Back Connected Multilevel Power Converters

With the advancement in the field of power electronics it has been well established that multilevel inverter is the most widely used static power converters for alternating current applications which includes variable speed industrial electric drives, electric vehicles, reactive power compensation in large distribution and transmission systems, electric traction drives and interfacing of renewable energy sources (photovoltaic and fuel cell) with the utility. Many of these application required bidirectional operation of the multilevel converters [10]. Unfortunately, the standard diode/thyristor rectifiers at the input side have serious problems of low input power factor, high THD in input currents and harmonic pollution on the grid. There is one literature [11] in which performance of 3-level neutral point clamped rectifier is compared with 2-level conventional rectifier in terms of input power factor, input current THD and ripple factor of the regulated dc output voltage. The study shows that multilevel rectifier for proposed control scheme is far superior to its counterpart 2-level rectifier and gives better performance like unity input power factor, negligible input current THD, reduced rippled regulated dc load voltage at a lower switching frequency and reduced voltage stress of the power semiconducting devices. These benefits of multilevel rectifier over conventional rectifier make multilevel rectifier a favorite choice as a DC source for multilevel inverters. This sort of connection of multilevel converters for AC-DC-AC conversion is commonly known as Back-to-Back Configuration (BTB) as shown in Fig.3. There is another advantage of BTB configuration is that, it provide power controllability at both machine and grid side. Looking in to the significant role of Back to Back connection technology for high power applications in industries, this study is carried out to provide concrete information about this technology.

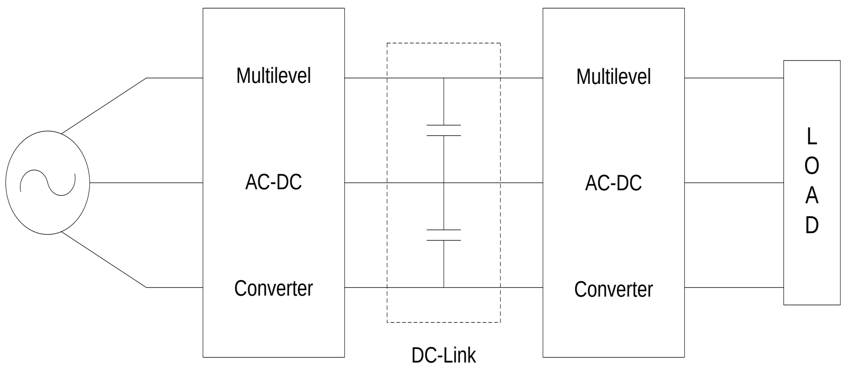

Fig.3 Back to Back connected multilevel converters.

III. Multilevel Converter Topologies for Back to Back Connection

MPCs topologies are classified on the basis of number of phases and power flow capability as shown in the Fig.4. There are two categories, first category consists of single phase and three phase non regenerative MPCs whereas second category consists of single phase and three phase regenerative MPCs.

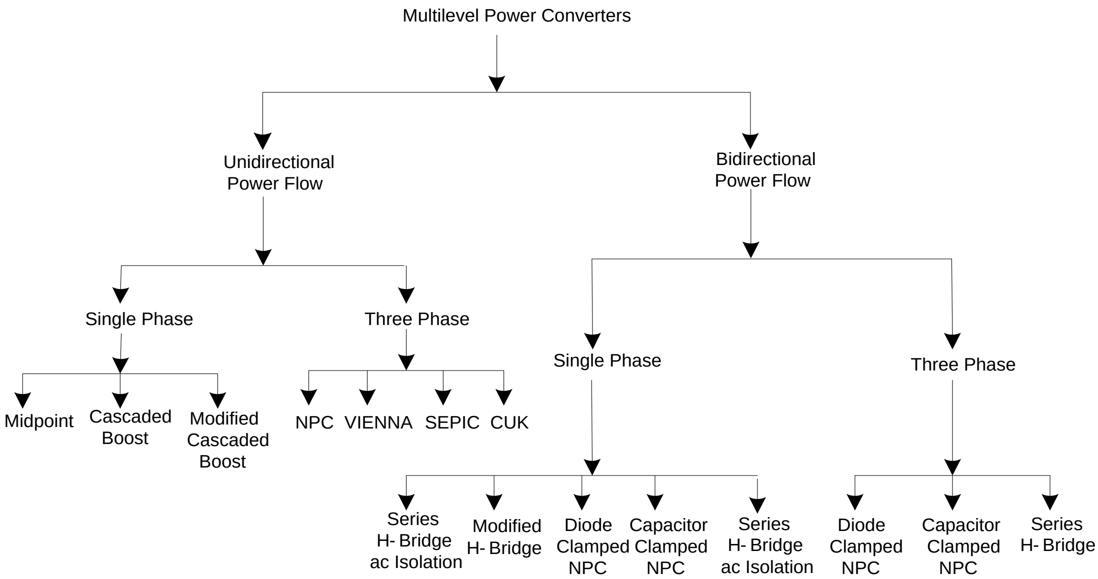

Fig.4 Classification of power multilevel converters [12]

In order to focus the content of this paper on Back to Back connection of converters for high power applications and ongoing research in this field, well-established three phase bi-directional topologies will only be briefly introduced and referred to existing literature.

i) Diode clamped MPCs

This circuit configuration provides excellent control over power flow and most adopted topology in real time applications [12-17]. Three and five level diode clamped bi-directional converter is shown in Fig.5 & Fig.6 which addresses the important issue of unequal sharing of voltages in clamping diodes in diode clamped converters with higher number of levels. Back to Back connected diode clamped converters (Fig.10) provide four-quadrant operation with inherent neutral point voltage balance and is most applied topology for ac motor drives and utility applications.

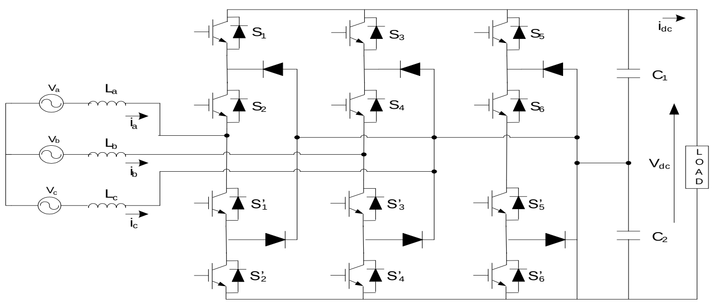

Fig.5 Three level diode clamped bi-directional converter

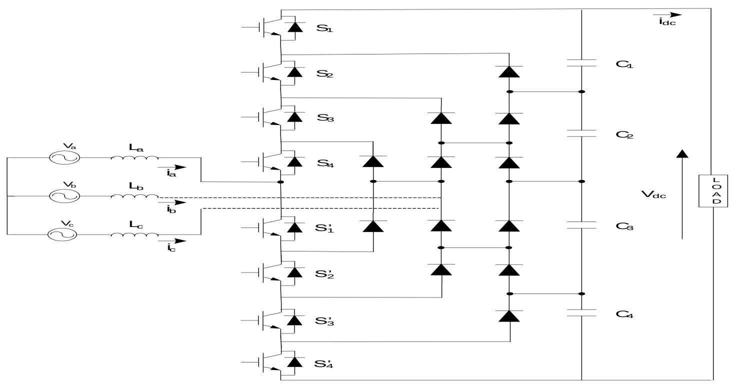

Fig.6 Five level diode clamped bi-directional converter

ii) Capacitor clamped MPCs

This is basically modification of diode clamped topology, which is proposed to simplify the neutral point voltage balancing and to eliminate clamping diodes. But the problem in this topology is that the power flow is very much complex and pre-charging of capacitors for ac-dc operation requires dedicated circuitry [12, 13]. The scope of this topology for high power applications is limited due to large current stresses on the capacitors. Three and Five level flying capacitors bi-directional converter is shown in Fig.7 & Fig.8.

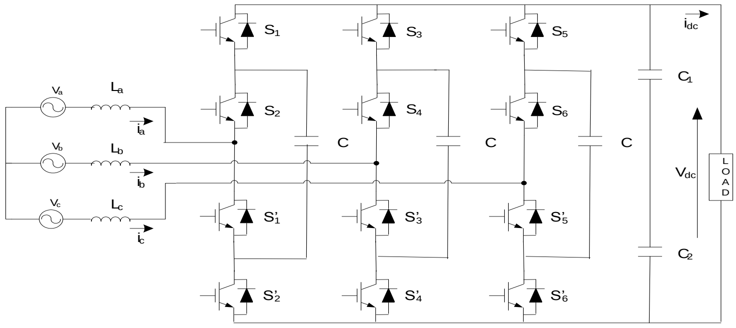

Fig.7 Three level flying capacitor bi-directional converter

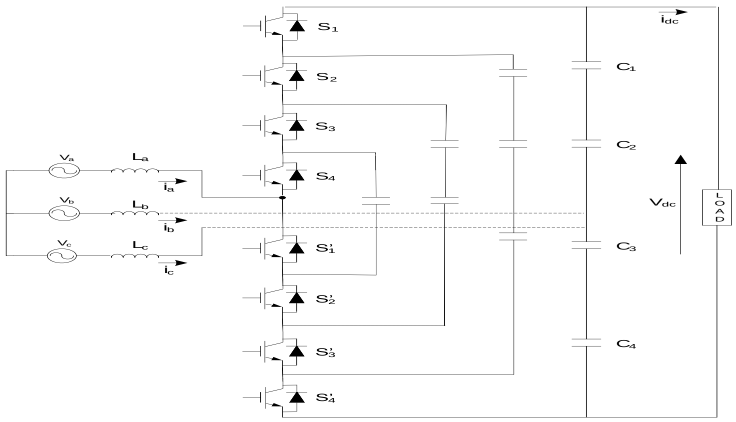

Fig.8 Five level flying capacitor bi-directional converter

iii) H-Bridge converter

Another important topology is H-bridge converter which requires isolated dc source for each level[12,13,18]. It finds its application in inverter fed electric vehicle drives and grid interface for PV generators where isolated dc sources are available. Fig.9 shows one leg of series H- bridge converter with dc link isolation.

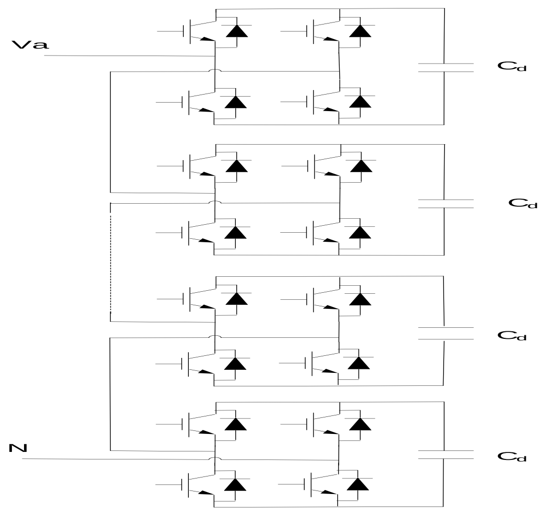

Fig.9 One leg of series H- bridge converter with dc link isolation.

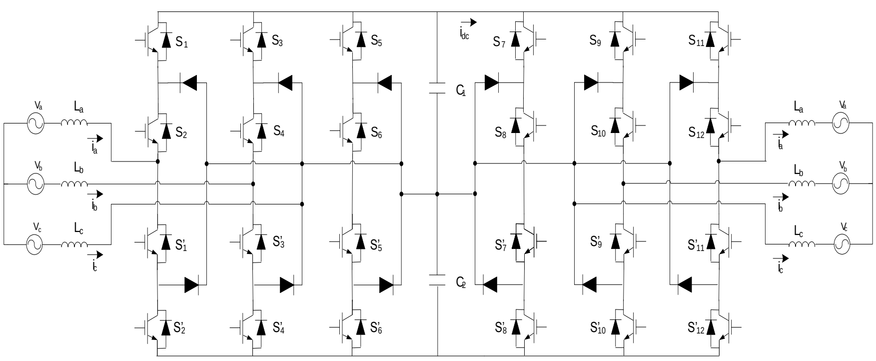

Fig.10 Back to Back connected diode clamped converter

These converters are commercialized by several manufacturers [19-32], offering different power ratings, front-end configurations, cooling systems, semiconductor devices, and control schemes, among other technical specifications. Significant features of three phase bi-directional MPCs are summarized in Table.1.

Table 1
Summary of three-phase bi-directional MPC topologies[7].

Topology	Diode-Clamped (3-Level)	Capacitor-Clamped (3-Level)	Series H-Bridge (Isolated dc link) 3-Leve
Number of Power Switches	12	12	8
Switch Diodes	12	12	12
Clamping Diodes	6	0	0
Clamping Capacitors	0	3	0
Dc Link Capacitors	2	2	3
High Side Switches	9	9	4
Neutral Point Voltage Balance	Complex	Simple	Very Simple
Transformer	No	No	Dc link isolation
Redundancy	No	No	Yes
Modularity	Complex	Complex	Simple
Bi-directional Power Flow	Simple	Complex	Very Complex
Figure	5	7	9

Operating principles, multilevel waveform generation, characteristics, modulation schemes and other relevant information about these topologies are very well explained in the earlier publications [33-41], therefore it is not covered in this paper. The diode clamped topology is most used topology as it requires reduced number of energy storage capacitors and lack of multiple isolated DC power supplies, when it is compared with flying capacitors topology and cascaded H-bridge topology respectively. Lot of literature is available with diode clamped topology for Back to Back connection, though it is having worse power quality issue [6]. The problem of power quality in diode clamped topology can be reduced by increasing the number of levels and by selecting proper control technique which is presented in section V.

IV. Components of Back to Back Connected Multilevel Power Converters

The power circuit of MPCs connected Back-to-Back consists of several solid state power devices such as diodes, MOSFET, IGBT, IGCT etc and series connected capacitors. Table 2 highlights the recent development & contribution of power devices, controllers, and sensors etc required for the reliable operation of MPCs connected Back to Back.

Table 2
Summary of Components of MPC connected Back to Back

	Components	Important Features	Manufacturers /Model
Power devices	New solid state self commutating devices such as MOSFETs, IGBTs, GTO, IGCT, Silicon-Carbide Power	Devices with high power ratings and low conduction losses. Availability of high voltage ,high frequency SiC devices.	ABB, Renesas, IXYS etc. The DARPA Wide Bandgap Semiconductor Technology High Power Electronics

	Devices		program is spearheading the development of HV-HF SiC power semiconductor technology [38]
Controllers	DSPs, Microcontrollers, PLDs, FPGA,dSpace etc.	Availability of high speed DSP optimised for solving complex algorithms in real time drive application. Important feature of the high speed DSP is its low cost.Low cost PLDs (programmable logic devices) is the best option available for non-linear controllers which replaces the lookup table stored in the memories of slow digital processors.FPGA is characterised by its short design cycle, low cost and high flexibility in terms of programmability.	Texas Instruments Inc., VeriSilicon,Vitesse Semiconductor Corporation,Analog Devices, XILINX, Lattice Semiconductor, NEC, QuickLogic etc
Sensing devices	Voltage & Current Sensors	Isolated hall effect current and voltage sensors are available which are very much required for the reliable operation of MPCs due to the use of digital controllers	LEM,Lindsey,MAGNELAB,Electrohms, Honeywell,Rongtech Industry (Shanghai) Inc., ENTES etc.
Device drivers	Power device drivers	High performance isolated power devices drivers and hybrid ICs are being now commercially available.	SCHURTER, Avago Technologies, SEMIKRON, ARCEL,FAIRCHILD semiconductor, CLARE etc.

V. Control Strategies of Multilevel Power Converters

The control strategy of MPC is the heart of the whole system, it actually decide the performance of MPC designed for particular application. The basic aim of the control is to produce multilevel voltages with good spectral quality in MPCs. By this review the authors tried to present some of the important and recent development in the field of control of MPCs used for Back to Back connections. As the control part plays an important role in the working of MPCs, it is worth to present some of the basics for the effective implementation of the control strategy. Normally control is implemented in following three steps.

i) Sensing of variable used in control like voltage, supply current, output dc voltage etc.
ii) Implementation of control algorithm responsible for the high level transient and steady state performance of MPCs.
iii) Deriving of the gate signals for the solid state devices.

It is found in the review that multilevel power converters require explicit control of capacitor voltages to avoid unequal voltages due to symmetrical charging and discharging of capacitors [43-46]. Unwanted harmonics in output voltage waveforms will appear due to the loss of neutral point voltage balance (NPVB) and capacitors can fail if this unbalance leads to voltage stresses beyond their rated limits. An important method for NPVB involves embedded NPVB control in the modulation strategy involving use of redundant switching state [45, 47, and 48]. The important modulation techniques used in multilevel power converter can be classified as shown if Fig. 11

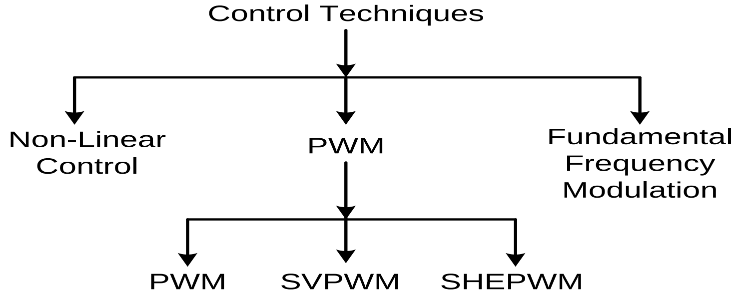

Fig.11 Classification of control techniques for MPCs connected Back to Back.

Not all the modulation techniques are suitable for each topology of multilevel converters [7]. Table 3 show, which modulation technique is suitable for different multilevel converter topologies. This will be important for selecting particular modulation technique for BTB connection of multilevel converters.

Table 3
Applicability of modulation technique to MPCs topologies.

Topology	Diode-Clamped (3-Level)	Capacitor-Clamped (3-Level)	Series H-Bridge
Space Vector PWM	Y	Y	Y
Level Shift-PWM	Y	Y	-
Phase Shift-PWM	N	Y	Y
Hybrid Modulation	N	N	Y
Selective Harmonic Elimination	Y	Y	Y
Space Vector Control	-	Y	Y
Nearest Level Control	-	Y	Y

Y- Applicable, N- Not Applicable, - Applicable but Not Recommended

A large number of researches have already been documented in the area of control of MPCs. More than 50 publications have been reviewed and classified in this study to explain the vital role of control in the multilevel converter technology for AC-AC conversion. Some of the important publications particularly deals with the control of MPCs, connected Back to Back are tabulated in Table 4. and the idea behind this is to provide the information about recent advances in control technique used for MPCs, connected Back to Back.

Table 4
Recent advances in control technique for MPCs connected Back to Back.

Objective	Methodology
3-level NPC rectifier is compared with 2-level conventional rectifier in terms of input power factor, input current THD etc.	Using simplified control scheme based on SPWM [11]
6.6 kV transformerless BTB system using two five-level diode clamped PWM converters for motor drives	SPWM with carrier frequency of 3 kHz and voltage balancing control of the common four dc capacitors connected in series using buck-boost choppers [49]
DC voltage control strategy for a five-level converter	Control circuit uses multiband hysteresis comparators to simplify the control of the main circuit [50]
Balancing the DC capacitor voltage divider in back-to-back multilevel converters	A new method to balance dc bus capacitors voltages by exploiting the redundant space vectors and using the dc bus average power flow direction [51]
Limits of the neutral-point balance in back-to-back-connected three-level converters	Explorers the limitations of NP current control for balancing the voltage in 3-level NPC converters [52]
NPP regulator reducing voltage and current harmonics along with the second harmonic.	Using Simple carrier-based neutral point potential regulator for three-level diode clamped inverter [53]
Dual 5-Level Inverter-Fed Induction Motor Drive with CMV Elimination and DC-Link Capacitor Voltage Balancing using Switching-State Redundancy—Part II	A simple control scheme based only on the switching state redundancy is proposed as a solution to the operating limitation of the open loop control scheme [48]
Back-to-Back Connected Five-Level Diode-Clamped PWM Converters for Motor Drives	DC link voltage can be balanced by using two bi-directional buck-boost choppers [54]
Conventional SVM technique has been compared with the single-phase modulator for multilevel converters	The single-phase modulator for multilevel converters [55]
A space vector PWM modulation scheme for BTB	Proposes a modulation strategy for back to back

three-level diode-clamped converters	NPC converters[56]
Switching loss analysis of modulation methods used in neutral point clamped converters	A tool where switching losses can be calculated for different modulation technique[57]
Reduction of switching losses due to redundant vectors in SVPWM modulation technique to allow for capacitor balancing in BTB configuration	To overcome this problem, a switching scheme has been proposed in which not only balances the DC-link capacitors but also reduces the switching frequency [58]
Control electronic platform based on floating-point DSP and FPGA for a NPC multilevel back-to-back converter	Design, implementation and test of novel real time controller for a NPC 3-level multilevel converter based on floating point DSP and on FPGA by operating in co-operative way[59]
Frequency reduction schemes for back-to-back connected, diode-clamped multilevel converters	Two new switching schemes for BTB DCC proposed. Result shows 35% reduction in switching frequency along with the balanced voltage across the DC-link capacitors [60]
Balancing of DC link voltage for Diode –Clamped five level Back to Back connected five level converters	A novel SPWM modulation control method is proposed for balancing of Dc-link voltage of multilevel converters connected back to back[61]
Reduction of switching losses in Hybrid-Clamped multilevel inverters.	A novel PWM control method is proposed which reduces the devices switching on-off within broad range of modulation index[62]

The study clearly shows that SVPWM technique is the most studied technique for Back to Back connected MPCs based applications. A common characteristic to all SVPWM-based schemes is that the modulation algorithm is divided into three stages:

i) A set of switching states or vectors needs to be selected for modulation
ii) Computation of duty cycles of each vectors to achieve the desired reference over time average
iii) Sequence in which the vectors are generated.

Review suggests that SVPWM technique reduces the switching frequency, common mode voltage, THD, losses etc. Despite of having so many advantages the SVPWM technique is not dominant in industrial applications because of complicated real time implementation of above mention stages involved in SVPWM technique. Still SPWM technique is most used technique in the industries due to its less complexity in the implementation and low computational cost.

VI. Applications

In this review some specific and important applications on BTB connection are presented which clearly shows that this technology is now capable enough to handle the pressure of fast moving technology in this area and this is only possible due to major development in multilevel topologies, modulation technology and control methodology[63-77]. Some important applications are tabulated in Table 5. to show the relevance of MPCs technology for the Back to Back connection along with their important feature.

Table 5
Recent Advances in Applications of MPCs connected Back to Back

Area of Application	Applications of Back to Back connected MPCs	Rating	Important Features
Energy & Power System	Wind Energy [6,63,76,77]	Upto 5MW	It’s simple, low cost and reliable front end.
	HVDC[6,73]	1000MW	Improved efficiency & power system stability with reactive power control
	Hydropumped energy storage system[6]	200 MVA	Improved efficiency & power system stability with reactive power control
Production	Regenerative Conveyors[63]	Each drive of 2.5MW	Fully regenerative operation, low input current harmonic content & adjustable input power factor.
Transportation	Tanker propulsion power	Each drive	Overall cost is reduced.

	syste[61]	of 6.15 MW	
	Variable Speed electric marine propulsion system[6]	30MW	Power quality is improved
	Transrapid system[63,74,75]	12 converters units of 15.6 MVA	Regenerative braking and the power level of the application makes Back to Back connected MPCs an effective solution.

VII. Challenges & Future Development

Due to the advancement in the field of power electronics, the MPCs technology has reached to certain level of maturity with wide range of applications. Still there certain challenges before the Back to Back connected MPCs and these challenges are shown in Table 6 along with their benefits.

Table 6
Challenges before Back to Back connected MPCs

Challenges	Benefits
Reduction of number of variables to be sensed	There will be an elimination of sensor offsets, size of converter system also reduced, and system become noise insensitive & economically sound.
Power Quality Improvement (%THD & Power Factor)	Elimination of lower order harmonic with low voltage distortion and high power factor at the input side. Reduction in filter size.
Reduction of Common Mode Voltage	Reliable operation of electric drive system. Less premature bearing failures & Low EMI.
Balancing of Neutral Point Potential Voltage	Reliable operation of power devices, Reduced voltage stressed across the devices. Improved quality of voltage and current.
Effective Control of MPCs	Improved performance of the system in terms of power quality, efficiency & reliability.
Packaging of MPCs	Reduced size and complexity.
Switching losses	Effective cooling system can be designed with improved power quality & overall efficiency
Fault Tolerance Capabilities	Improved reliability & performance as the fault tolerance capabilities of NPC multilevel converter is poor.

VIII. Conclusion

This paper has reviewed the present state of the art of multilevel converter, connected Back to Back by presenting the most recent contribution on topologies, modulation & high power applications. It is found that diode clamped topology is the topology used for the Back to Back connection. Lot of research has already been done which deals with control of Back to Back connected MPCs are presented in this paper, shows that still there is scope of improvement in the performance of MPCs connected Back to Back. Applications of Back to Back connected MPCs shows that now this technology has reached to certain level of maturity especially in the field of wind energy and high power AC drives. But existence of challenges before this technology indicates that still long way to go for this technology to gain remarkable achievement in the field of high power conversion.

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