MULTILEVEL POWER CONVERTERS: A SURVEY

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Abstract- Multilevel static power conversion (MSPC) technology has ability to process high voltages and generate multi-tier voltage waveforms with high spectral quality. This technology is increasingly being used in ac- dc, dc-ac converters and power conditioning applications. In view of this, a comprehensive review of MSPC technology is presented in this paper, which includes configurations, control strategies and highlighting key areas of research .It is aimed to provide a framework of references and broad spectrum of MSPC technology to researchers, application engineers and educators dealing with Multilevel Power Converters (MPC).

Keywords- *Multilevel power conversion; Power quality; Harmonic reduction; multilevel rectifiers; multilevel inverters.*

I. INTRODUCTION

The field of high power devices has been one of the most active area in research and development of power electronics in the last decades. Several industrial processes have increased their power level needs, triggering the development of new power semiconductors, converter topologies, and control methods. In order to meet the industrial demand, series connection of power switches is the solution for dealing with large voltages. Nevertheless, achieving static and dynamic voltage sharing among those switches becomes a problem which led to the development of the new family of multilevel converters. Even though the idea of utilizing multiple voltage levels to perform electric conversion was patented almost thirty years ago[1,2], the term multilevel starts with the three level inverter introduced by Nabae et.all in 1981[3]. Subsequently, several multilevel converter topologies have been developed [4-11]. However, the elementary concept of a multilevel converter to achieve high power is to use a series of power semiconductor switches with several low voltage sources to perform the conversion by synthesizing a staircase voltage waveforms.

Multilevel inverter technologies have reached a mature level and plentiful converter topologies have been proposed during the last few decades. Application of MLI with bidirectional power flow in electric drive forms an important area of interest in multilevel power conversion.

Nowadays, multilevel inverters are becoming increasingly popular in power industry due to their ability to meet the increasing demand of power ratings and power quality associated with reduced harmonic distortion and lower electromagnetic inference. A multitude of factors driving research interest in MLIs can be summarized as: i).multilevel inverters not only generates the output voltage with very low distortion, but also can reduce the dv/dt stresses; therefore electromagnetic capability(EMC) problem can be solved. ii). MLIs produce smaller common mode voltage; then the stress on the bearing of a motor connected to inverter can be reduced. iii). Voltage handling capacity of MLIs is not restricted by voltage rating of power devices. Where as the semiconductor impose a limit on voltage rating of conventional converter leading to high design of the system, which limits the power rating and increases losses. iv).Voltage and current harmonics are significantly reduced in MPCs. Multilevel PWM and step modulation methods have been proposed to synthesize voltages with high spectral quality even at low switching frequency. This is an important criterion if GTOs and other high power devices are used, as well as high efficiency is desired in converters. v). High voltage handling capability and improved spectral performance reduce the need for step-down and multi-pulse/poly- phase transformers which are used in two level and multi-pulse converters in high voltage applications. Substantial reduction in cost, size, weight and losses are possible by reduction of transformers.

Unfortunately, MLIs do have some disadvantages. One particular disadvantage is the greater number of power semiconductor switches needed. Although lower rated switches can be utilized in a MLIs, each switch requires a related gate drive circuit. This may cause the overall system to be more complex and expensive.

II. CONFIGURATIONS

Circuit configurations of MPCs are classified on the basis of number of phases , power flow capability and switching frequency[12]. The category consists of single-phase[14,15] unidirectional power flow , three-phase[13,16] unidirectional power flow ,Single phase Bidirectional power flow and three-phase MPCs with bi-directional power flow.

A. Single-phase Unidirectional MPC

As power levels reach multiple kW in single-phase applications, multilevel techniques have been proposed in single-phase ac-dc power conversion with unidirectional power flow for two-quadrant rectifier- inverter drives and high voltage front-end power factor pre- regulators. Use of low voltage power devices in these power factor correction (PFC) converters allows high switching frequency operation required for PFC. Single-phase Unidirectional MPC are configured as midpoint , cascaded boost and modified cascaded MPCs .Converters in this category have been proposed as an alternative to conventional two level boost rectifier for high voltage/power applications. The main advantage is increase in efficiency and performance as the current ripple is significantly reduced leading to reduction in the size and core losses of the inductor and use of power devices with low voltage ratings with better overall performance. This requires a rule-based non-linear control with large number of sense variables for current control and output voltage regulation as well as neutral point voltage balance. These topologies also lack modularity and increase in number of levels requires use of line frequency transformers[17]. The main configuration of this category is shown in Figure(1).

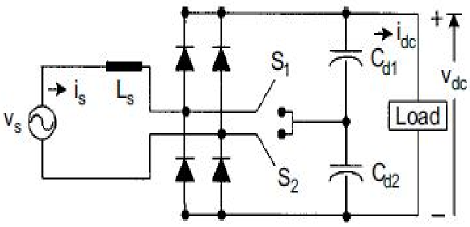

Figure1. Midpoint multi level converter

B. Three-phase Unidirectional MPC

A Three-phase MPCs with unidirectional power flow have been proposed for high performance power supplies and rectifiers in non-regenerative ac drive applications.Three-phase three level converters are configured as Boost, Cuk, NPC, SEPIC and VIENNA converters. These converters achieve partial or full de-coupling of input voltages resulting in improved control of input current. The main configuration of this category is shown in Figure (2).

C. Single-phase Bi-directional MPC

Topologies proposed for three phase applications including diode clamped, capacitor clamped NPC converters and series H-bridge converter with dc isolation have been adapted for Single phase pplications and are reconsidered next. Two configurations of this category are adapted half bridge and series H-Bridge converter with ac side isolation .Basic circuit under this category is shown in figure(3).

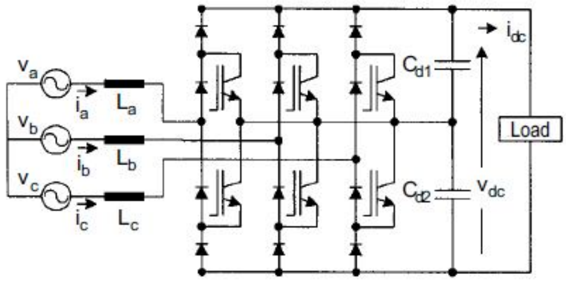

Figure 2. Three level unidirectional converter

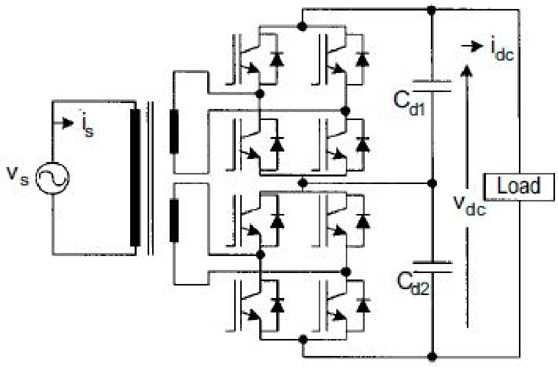

Figure 3 Single Phase Bidirectional Converter

D. Three-phase Bi-directional MPC

Extensive research has been reported in this category as they cater to a number of application areas of MPC viz drives ,FACTS, HVDC etc. These converters classified as diode clamped [18-21], capacitor clamped NPC converters [26] and series H-Bridge converters [27-30]. Diode clamped converters provide excellent control over power flow and are topologies of choice in most applications[22-25]. Further enhancement of voltage handling capability has been possible by increasing number of voltage levels . Adapted diode clamped NPC topology shown in figure4(a) addresses an important issue of unequal sharing of voltages in clamping diodes in diode clamped converters with higher number of levels. Paralleling of switches and legs has been proposed to enhance the current handling capability of diode clamped topology. Back to Back intertie topology provides inherent neutral point voltage balance and four quadrant operation.

A capacitor clamped configuration (FC-MLI) is an important modification to diode clamped topology shown in figure 4(b), proposed to simplify the neutral point voltage balancing and to eliminate clamping diodes[31-34].The most important advantages of FC-MLI topology are preventing the filter demand, and controlling the active and reactive power flow besides phase redundancies. Although these advantages, the increment of m level will restrain the accurate charging and discharging control of capacitors. The cost of inverter will increase and device will be more enlarged due to increased number of capacitors. However pre-charging of capacitor for ac-dc operation requires dedicated circuitry and packaging of capacitors is a challenge. Due to large current stresses on capacitors applicability for high power applications is limited.

Another important configuration, series H-Bridge converter requires isolate dc source for each level shown in figure 4(c). H-Bridge converter provides a modular structure, adds redundancy and is uniquely suited for the applications drawing power from independent batteries and fuel cells. These converters are uniquely suited for electric vehicles and grid interface for PV generators. Converters with higher number of levels are being reported in this category for their ability to provide good spectral performance at line frequency switching using GTOs .

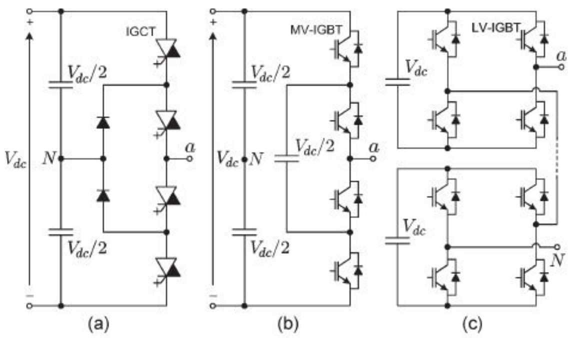

Figure. 4 Classic multilevel converter topologies (with only one phase shown).(a) 3L-NPC featuring IGCTs. (b) Three-level FC featuring MV-IGBTs.(c) Five-level CHB featuring LV-IGBTs.

The hybrid and asymmetric hybrid inverter configuration have been developed according to the combination of existing MLI topologies or applying different DC bus levels respectively [35-40] The hybrid multilevel topologies are constituted by using combination of two basic topologies utilize the DC-MLI or FC-MLI to replace the H-bridge as the basic module of the CHB-MLI in order to reduce the number of the separated DC sources. The asymmetric hybrid MLIs synthesize the output voltage waveforms with reduced harmonic content [42,43]. This advantage is achieved by using distinct voltage levels in different modules, which can generate more levels in output voltage waveform and reduces the THD ratio, while preventing to increase the number of switching devices and sources. Each power module of a hybrid MLI can be operated at distinctive DC voltage and switching frequency improving the efficiency and THD compensation characteristics of inverter. Nevertheless, conventional PWM strategies, which generates switching frequency at fundamental frequency are not appropriate for AH-MLIs due to switching devices of the higher voltage modules, would have to operate at high frequencies only during some inverting instants. To achieve this control strategy, hybrid modulation methods have been proposed that provide to get higher power cells switched at low frequency and low power cells switched with high frequency [44-47].

III. COMPONENTS OF MPC

The circuit of MPC consists of several series connected capacitors and solid state devices with a number of operating modes. Reliable operation of these converters requires control strategies[48-51] with large number of sense variables necessitating high speed digital controllers, PLDs, sensors and gate drivers. Development in power devices , controllers including DSP and Micro controllers, PLD will have significant impact on the applicability of MPCs.

Integrated power modules (IPM) can greatly simplify packaging of large number of devices in MPCs. High Speed DSPs can provide I single chip low cost solution for most computationally intensive real time control required for MPCs. Hall effect current and voltage sensors have been traditionally used for current and voltage sensing in high performance convertors.

IV. CONTROL OF MPC

MPCs require explicit control of capacitor voltages to avoid runaway voltages due to asymmetrical charging and discharging of capacitors. Loss of neutral point voltage balance can cause unwanted harmonics in output voltage and capacitors can fail if this unbalance leads to voltage stresses beyond their rated limits. All space vector modulation and non linear current control strategies incorporate voltage imbalances in overall current regulations strategy. The modulation methods used in multilevel inverters can be classified according to switching frequencies as seen in Fig. 5 [52-54].

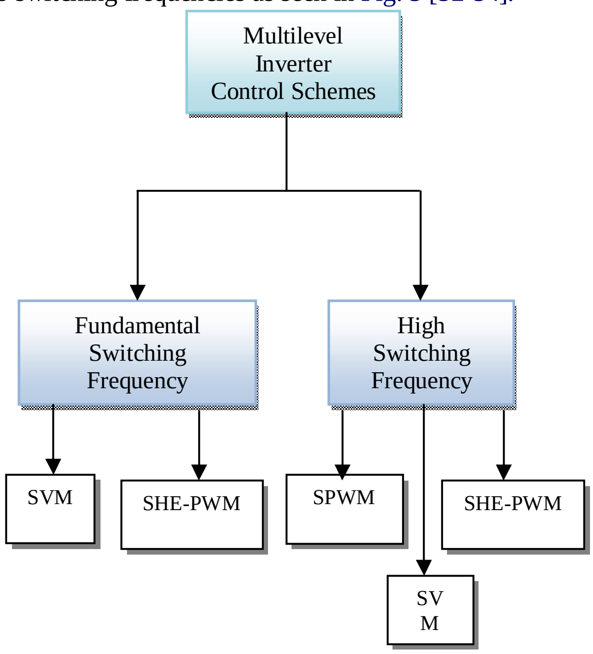

Figure.5 Classification of multilevel inverter control schemes

A. Nonlinear control

This is essentially rule-based control mainly applied to single phase unidirectional system because of inherent non-linearity in the system. The control decision is based on several factors such as magnitude of input voltage, voltage level in individual capacitors and current tracking requirement.

B. Fundamental switching frequency methods.

Fundamental switching frequency methods generally perform one or two commutations of the power semiconductors during one cycle of the output voltages generating a staircase waveform. Hence, the switching losses are kept low but the output voltage have a high low order harmonic currents in the motor drive applications. Representative techniques of this family are the multilevel selective harmonic elimination [56,57] and the space vector control [58,59]. In the former technique, the switching instants are calculated to eliminate the most significant low order harmonics whereas the high frequency harmonics must be removed by using additional filters. The objective in the latter technique is to deliver to the load a voltage vector that minimizes the space error or distance to the reference vector. This method is simple and attractive for high number of levels, nevertheless, when the number of levels decreases, the error increases and the current ripple becomes higher.

In a high switching frequency can be accommodated then the low order voltage harmonics can be reduced at expense of higher switching losses. Most popular methods in industrial applications are

1. Carrier based sinusoidal PWM.
2. Selective Harmonics Elimination PWM.
3. Space vector PWM.

C. Carries based sinusoidal PWM

A very common practice when SPWM is used in three phase industrial applications for the multilevel inverter is the injection of a third harmonic to increase the output voltage and improve the dc bus utilization[24,60,65]. Likewise, in multiphase VSIs it is also possible to improve the dc bus utilization by injecting the appropriate zero sequence harmonic into leg voltage reference[66,67,97-100]. Nevertheless, this improvement reduce as the number of phases increases[68]. The gain in maximum fundamental in the linear modulation region is only 5.15% for five-phase VSI and 2.57% for a seven phase VSI, while it is 15.47% in the three phase VSI[43].

When compared with the other techniques, the main advantage of the SPWN technique is the easiness of implementation. This advantage becomes more and more pronounced as the phase number increases because this technique controls each phase separately. Hence its implementation in multi phase converter rather straightforward [69]. Another advantageous feature of multilevel SPWM is that the switching frequency of each transistor can be lower than the effective converter output switching frequency, thus reducing the switching losses and filter requirements.

D. Space vector PWM

SVPWM arises from the vectorial description of the switching states of power converters. Since those switching states constitute a discrete set of space vectors, the continuous reference vector must be approximated by the time averaging of a space vector sequence[101-104]. The SVPWM technique is used to determine this sequence and to calculate the time interval corresponding to each vector. The way that the space vectors are selected and ordered in the sequence has a great effect on the output voltage harmonics and on the converter switching losses. Usually, the vector sequence is made with the space vectors nearest to the reference vector to reduce the output ripple. This modulation technique considers all phases of the converter as a whole, this being the main difference with carrier based methods. The number of available switching states in a P-phase converter changes to the law N^P where N is the number of levels. This means that, as the number of phases and levels increases, the problem of devising an adequate SVPWM scheme becomes more and more involved.

E. Selective Harmonic Elimination PWM

Selective Harmonic Elimination (SHE) and Selective Harmonic Minimisation (SHM) are two off-line (pre-calculated) non carrier based PWM techniques. SHE was proposed in a early paper by Patel and Hoft [75,76]. SHM minimises these harmonics, rather than eliminating them, according to some cost function (such as harmonic loss in an induction motor) to give a better overall result [73]. A summary of Harmonic elimination PWM techniques is presented by Enjeti et al. [72]. Optimal PWM or selected harmonic elimination PWM (SHE-PWM) seems attractive, but cannot react to transients quickly. This is because pulses do not occur at fixed intervals, that is, the switch period is not constant. Moving one edge may completely upset the optimised spectrum. Closed loop control using SHE/SHM is generally limited to cycle by cycle control of the fundamental frequency and modulation depth. Some work has been done on closing feedback loops around optimized PWM modulators to remove errors when they occur [32]. These techniques cannot compensate for distortions due to DC bus ripple, or switching imperfections. Recent work has been done on implementing regular sampled or on-line SHEPWM [70,71,74,105-109]. This work has shown that the positions of edges can be approximated relatively simply online given the modulation depth. The calculation gives their displacement from the "sampling points", the positions of the edges for a modulation depth of zero.

V. APPLICATIONS OF MPC

MPCs were initially proposed in ac motor drives applications due to their ability to generate low harmonics, multi-tier waveforms[77,78]. These converters have been extensively applied in ac motor drives in medium and high voltage ratings[84-86]

Several MPC topologies have been proposed for static power conversion applications[79-82], Permanent magnet brushless motor (PMSM) drives are used in high power three-phase industrial drives and as well as in single-phase traction drives . Series H-Bridge MLI with isolated dc sources for each level has been proposed for Electric Vehicle (EV) drives applications. Considerable research has been reported in application of MPC in utility systems including FACTS[87-92] , active filters[93] and grid interface for non -conventional energy sources[94,95]. Use of MPC can eliminate step-up transformers for interface with high voltage utility systems as they can handle sufficiently high.

VI. CHALLENGES AND FUTURE DEVELOPMENT

MPSC technology has reached a level of advancement and its wide applications are being reported. Some possible areas for further development could be: i). Reduction of sensed variables which offers elimination of offsets, insensitivity to noise and size reduction of converter. ii). Control of NPVB remains a complex issue especially in MPCs with higher voltage levels. iii) Further research and design of MPCs in low voltage applications is required to enhance Power Quality. iv). Development of IPM and power modules for various configurations can reduce the size and complexity of power circuit of MPCsAuthors and Affiliations.

VII. CONCLUSIONS

A number of configurations and control techniques for multi level converters have resulted widespread adaptation of MPC in varied applications for solid state power conversion .This comprehensive review will provide a clear broad perspective on various aspects of MSPC to researchers and engineers working in this field. Application base of these converters is expected to increase in high and medium voltage applications due to its excellent spectral performance and non-availability of power devices in high voltage ratings.

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