

October 2013

## MULTILEVEL POWER CONVERTERS: A SURVEY

A.NAVEEN KUMAR

*CVR College of Engineering, Hyderabad, India, naveenkumar.rk83.harsha@gmail.com*

KIRAN KUMAR CH

*CVR College of Engineering, Hyderabad, India, kiranch21983.harsha@gmail.com*

B. BASAVARAJA

*GITAM University, Hyderabad, India, banakara36@gmail.com*

Follow this and additional works at: <https://www.interscience.in/ijpsoem>



Part of the [Power and Energy Commons](#)

---

### Recommended Citation

KUMAR, A.NAVEEN; CH, KIRAN KUMAR; and BASAVARAJA, B. (2013) "MULTILEVEL POWER CONVERTERS: A SURVEY," *International Journal of Power System Operation and Energy Management*. Vol. 2 : Iss. 4 , Article 3.

Available at: <https://www.interscience.in/ijpsoem/vol2/iss4/3>

This Article is brought to you for free and open access by Interscience Research Network. It has been accepted for inclusion in International Journal of Power System Operation and Energy Management by an authorized editor of Interscience Research Network. For more information, please contact [sritampatnaik@gmail.com](mailto:sritampatnaik@gmail.com).

# MULTILEVEL POWER CONVERTERS: A SURVEY

A.NAVEEN KUMAR<sup>1</sup>, KIRAN KUMAR CH<sup>2</sup>, R.H.VARDAN<sup>3</sup> & B.BASAVARAJA<sup>4</sup>

<sup>1,2,3</sup>Electrical and Electronics Engineering Department,  
Department, CVR College of Engineering, Hyderabad, India

<sup>4</sup>Electrical and Electronics Engineering, GITAM University, Hyderabad, India.  
E-mail: naveenkumar.rk, kiranch219, 83.harsha@gmail.com, banakara36@gmail.com

---

**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).

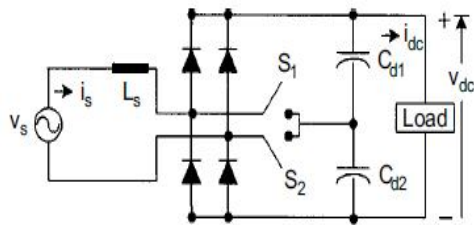


Figure1. Midpoint multi level converter

**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 applications 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).

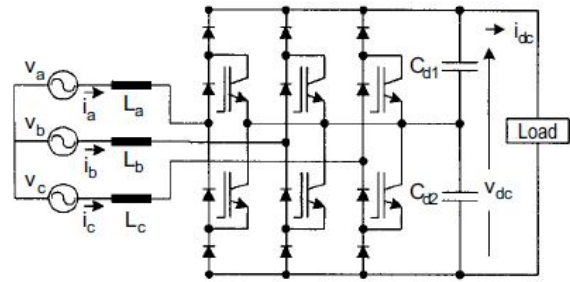


Figure 2. Three level unidirectional converter

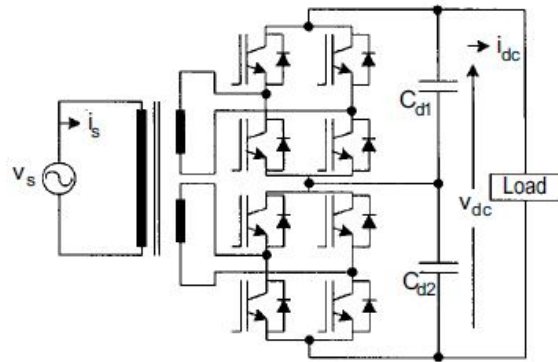


Figure 3 Single Phase Bidirectional Converter

**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 .

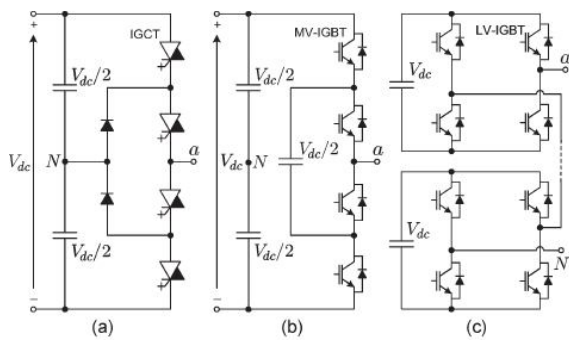


Figure. 4 Classic multilevel converter topologies (with only one phase shown).(a) 3L-NPC featuring IGCTs. (b) Three-level FC featuring MV-IGBTs.(c) Five-level CHB featuring LV-IGBTs.

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 converters.

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].

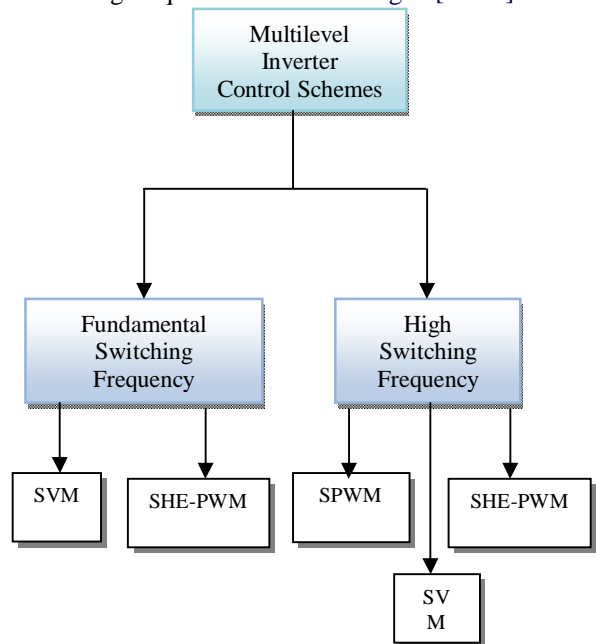


Figure.5 Classification of multilevel inverter control schemes

### 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 MPCs Authors 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.

## REFERENCES

- [1] R.H.Baker and L.H.Bannister, “Electric Power Converter”, U.S.Patents 3867643, Feb.18,1975.
- [2] R.H.Baker, “High-Voltage converter circuit”, U.S.Patent 4203151, May 13, 1980.

- [3] A.Nabae, I.Takahashi, and H.Akagi, “A new neutral point clamped PWM inverter”, IEEE Trans. Ins.Appl., vol. IA-17, no.5, pp.518-523, Sep-Oct.1981.
- [4] B.Singh, B.N.Singh, A.Chandra, K.Al-Haddad, A.Pandey, and D.Kothari, “A review of three phase improved power quality AC-DC converters”, IEEE Trans.Ind.Electron., vol.51, no.3, pp.641-660, June.2004.
- [5] N.Choi, J.Cho, and G.Cho, “A general circuit topology of multilevel inverter”, in Proc.IEEE Power Electronics Specialists Conf. PESC, Cambridge, MA, USA,24-27 June 1991.
- [6] T.A.Meynard and H.Foch, “Multi-Level conversion: high voltage chopper and coltage source inverter”, in Proc.IEEE Power Electronics Specialists Conf. PESC, vol.1, Toledo, Spain, 29 Jun-3Jul. 1992, pp.397-403.
- [7] J.Lai and F.Z.Peng, “Multilevel converters-A new breed of power converters”, IEEE Trans. Ind. Appl., vol 32, no 3, pp. 509-517, May-June 1996.
- [8] J.Rodriguez, J.S.Lao and F.Z. Peng, “Multi level inverters: a survey of topologies, controls and applications”, IEEE Trans Ind Electron., vol 49, no. 4, pp 724-738, Aug 2002.
- [9] K.A. Corzine, “Operation and desing of multilevel inverters”, University of Missouri-Rolla, Tech.Rep., 2005.
- [10] T.Bruckner and D.Homles, “Optimal pilse width modulation for three level inverters”, IEEE Trans. Power Electronics, vol 20, no 1, pp. 82-89, Jan 2005.
- [11] M.Fracchia, T.Ghiara, M.Marchesoni, and M.Mazzucchelli, “ Optimized modulation techniques for the generalized N Level converter” in Proc. IEEE Power Electronics Specialists Conf. PESC, vol 2, Toledo, Spain, 29 June-3 Jul, 1992, pp.1205-1212.
- [12] Samir Kouro, Mariusz Malinowski, K. Gopakumar, Josep Pou, Leopoldo G. Franquelo, Bin Wu, Jose Rodriguez, Marcelo A. Pérez, and Jose I. Leon, “Recent Advances and Industrial Applications of Multilevel Converters”, IEEE Trans. Ind. Ele., Vol. 57, No. 8, Aug 2010
- [13] K O'Brien, R Teichmann and S Bernet. ‘Active Rectifier for Medium Voltage Drive Systems.’ Proceedings on IEEE APEC '2001, 2001, pp 557-562
- [14] M T Zhang, Y Jiang, F C Lee and M M Jovanovic. ‘Single-phase Three-level Boost Power Factor Correction Converter.’ Proceedings on IEEE APEC'95, 1995, pp 434-439.
- [15] B R Lin and H H Lu. ‘Single-phase Three-level Rectifier with High Power-factor.’ European Transaction on Electric Power, vol 11, January/ February 2001, pp 31-37.
- [16] K Oguchi and Y Maki. ‘A Multilevel-voltage Source Rectifier with a Three-phase Diode Bridge Circuit as a Main Power Circuit.’ Proceedings on IEEE IAS'92, 1992, pp 695-702.
- [17] B R Lin, C N Wang and H H Lu. ‘Multilevel ac/dc/ac Converter by using Three-level Boost Rectifier and Five-level Diode Clamped Inverter.’ in IEEE PEDS'99, 1999, pp 444-448.
- [18] B Mwyniwiwa, Z Wolanski, Y Chen and B T Ooi. ‘Multimotor Multilevel Converters with Input/output Lineary.’ IEEE Transactions on Ind Applicat, vol 33, September/October 1997, pp 1214-1219.
- [19] B S Suh and D S Hyun. ‘A New N-level High Voltage Inversion System.’ IEEE Transaction on Ind Electron, vol 44, February 1997, pp 107-115.
- [20] S Halasz, A A M Hassan and B T Huu. ‘Optimal Control of Three-level PWM Inverters.’ IEEE Transaction on Ind Electron, vol 44, February 1997, pp 96-106.

- [21] J H Suh, B S Suh and D S Hyun. 'A New Snubber Circuit for High Efficiency and Over Voltage Limitation in Three-level GTO Inverter.' IEEE Transactions on Ind Electron, vol 44, April 1997, pp 147-156.
- [22] M. Marchesoni and P. Tenca, "Theoretical and practical limits in multi-level mpc inverters with passive front ends," in Proc. EPE, Graz, Austria, Aug. 2001.
- [23] J. Pou, R. Pindado, and D. Boroyevich, "Voltage-balance limits in four-level diode-clamped converters with passive front ends," IEEE Trans. Ind. Electron., vol. 52, no. 1, pp. 190-196, Feb. 2005.
- [24] S. Busquets-Monge, S. Alepuz, J. Bordonau, and J. Peracaula, "Voltage balancing control of diode-clamped multilevel converters with passive front-ends," IEEE Trans. Power Electron., vol. 23, no. 4, pp. 1751-1758, Jul. 2008.
- [25] Z. Cheng and B. Wu, "A novel switching sequence design for five-level NPC/H-bridge inverters with improved output voltage spectrum and minimized device switching frequency," IEEE Trans. Power Electron., vol. 22, no. 6, pp. 2138-2145, Nov. 2007.
- [26] T A Maynard, M Fadel and N Aouda. 'Modelling of Multilevel Converter.' IEEE Transactions on Ind Electron, vol 44, June 1997, pp 356-364.
- [27] N P Schibli, T Nguyen and A C Rufer. 'A Three-phase Multilevel Converter for High-power Induction Motors.' IEEE Transactions on Power Electronics, vol 13, 1998, pp 978-986.
- [28] G Joos, X Huang and B T Ooi. 'Direct Coupled Multilevel Cascaded Series VAR Compensators.' IEEE Transactions on Ind Applicat, vol 34, September/October 1998, pp 1156-1163.
- [29] F Z Peng and J W McKeever. 'A Power Line Conditioner using Cascade Multilevel Inverters for Distribution Systems.' IEEE Transactions on Ind Applicat, vol 34, November/December 1998, pp 1293-1298.
- [30] J Rodriguez, L Moran, A Gonzalez and C Silva. 'High Voltage Multilevel Converter with Regeneration Capability.' Proceedings on IEEE PESC'99, pp 1077-1082.
- [31] Çolak I, Kabalci E. A review on inverter topologies and developments. In: Proceedings of Eleco'2008 electric, electronics and computer engineering symposium, Bursa (Turkey); 2008.
- [32] Xu L, Agelidis VG. Active capacitor voltage control of flying capacitor multilevel converters. IEEE Electr Power Appl 2004;151:1179-84.
- [33] Feng C, Liang J, Agelidis VG, Green TC. A multi-modular system based on parallel-connected multilevel flying capacitor converters controlled with fundamental frequency SPWM. In: Proceedings of IEEE 32nd conf on ind elec, Paris (France); 2006.
- [34] Song BM, Kim J, Lai JS, Seong KC, Kim HJ, Park SS. A multilevel soft-switching inverter with inductor coupling. IEEE Trans Ind Appl 2001;37:628-36.
- [35] Bose BK. Modern power electronics and AC drives. NJ, USA: Prentice Hall; 2001.
- [36] Rashid MH. Power electronics handbook. Florida, USA: Academic Press; 2001.
- [37] Mohan N, Undeland TM, Robbins WP. Power electronics-converters, application and design. New York: John Wiley & Sons Inc.; 1995.
- [38] Williams BW. Power electronics, devices, drivers, applications, and passive components. 2nd ed. McGraw Hill; 1992.
- [39] Rodriguez J, Hammond P, Pont J, Musalem R. Method to increase reliability in 5-level inverter. Electron Lett 2003;39:1343-5.
- [40] Rodriguez J, Lai S, Peng FZ. Multilevel inverters: a survey of topologies, control and applications. IEEE Trans Power Electron 2002;49:724-38.
- [41] Su Gui-Jia. Multilevel DC-link inverter. IEEE Trans Ind Appl 2005;41:848-54.
- [42] Jinghua Z, Zhengxi L. Research on hybrid modulation strategies based on general hybrid topology of multilevel inverter. In: Proceedings of int symp power elect, elec drives, motion, Ischia (Italy); 2008.
- [43] Manjrekar MD, Lipo TA. A hybrid multilevel inverter topology for drive applications. In: Proceedings of IEEE applied power elec conference; 1998.
- [44] Veenstra M, Rufer A. Control of a hybrid asymmetric multilevel inverter for competitive medium-voltage industrial drives. IEEE Trans Ind Appl 2003;41:655-64.
- [45] Gopalarathnam T, Manjrekar MD, Steimer PK. Investigations on a unified controller for a practical hybrid multilevel power converter. In: Proceedings of IEEE appl power elec conf, Texas (USA); 2002.
- [46] Lopez M, Moran L, Espinoza J, Dixon J. Performance analysis of a hybrid asymmetric multi-level inverter for high voltage active power applications. In: Proceedings of the 29th annual conference of the IEEE ind elec society; 2003.
- [47] Rech C, Pinheiro JR. Hybrid multilevel converters: unified analysis and design considerations. IEEE Trans Ind Electron 2007;54.
- [48] Lin BR. A novel control scheme for the multilevel rectifier/inverter. Taylor and Francis Int J Electron 2001;88:225-47.
- [49] Kincic S, Chandra A, Babic S. Multilevel inverter and its limitations when applied as statcom. In: Proceedings of 9th Mediterranean conference on control and automation, Dubrovnik (Croatia); 2001.
- [50] Leon JI, Portillo R, Vazquez S, Padilla JJ, Franquelo LG, Carrasco JM. Simple unified approach to develop a time-domain modulation strategy for single-phase multilevel converters. IEEE Trans Ind Electron 2008;55:3239-48.
- [51] Chiasson J, Tolbert L, McKenzie K, Du Z. Real-time computer control of a multilevel converter using the mathematical theory of resultants. Elsevier Math Comp Simul 2003;63:197-208.
- [52] Celanovic N, Boroyevic D. A fast space vector modulation algorithm for multilevel three-phase converters. In: Proceedings of conf rec IEEE-IAS annual meeting, Phoenix (USA); 2001.
- [53] Rodríguez J, Correa P, Morán L. A vector control technique for medium voltage multilevel inverters. In: Proc IEEE applied power elec conf APEC 2001, Anaheim CA (USA); 2001.
- [54] Lakshminarayanan S, Gopakumar K, Mondal G, Dinesh NS. Eighteen-sided polygonal voltage space-vector based PWM control for an IM drive. IEEE Electr Power Appl 2008;2:56-63.
- [55] L.Li, D. Czarkowski, Y. Liu, and P. Pillay, "Multi level selective harmonic elimination PWM technique in series connected voltage inverters", IEEE Trans. Ind. Appl., vol. 36, no. 1, pp. 160-170, Jan.-Feb. 2000.
- [56] S. Sirisukprasert, J.-S. Lai, T.-H. Liu, "Optimum harmonic reduction with a wide range of modulation indexes for multilevel converters," IEEE

- Trans.Ind.Electron.,vol.49,no.4,pp.875-881,Aug.2002.
- [57] J.Rodriguez,L.Moran,P.Correa,and C.Silva,"A Vector control technique for medium-voltage multilevel inverters,"IEEE Trans.Ind.Electron.,vol.49,no.4,pp.882-888,Aug.2002
- [58] J.Rodriguez,L.Moran,J.Pontt ,P.Correa,and C.Silva,"A high-performance vector control of an 11-level inverter," IEEE Trans.Ind.Electron.,vol.50,no.1,pp.80-85,Feb.2003
- [59] A.Hava, R.Kerkman, and T.Lipo,"Simple analytical and graphical methods for carrier based PWM-VSI drives," , IEEE Trans.Power Electron.,vol.14,no.1,pp.49-61,Jan.1999.
- [60] L.M.Tolbert and T.G.Habetler,"Novel Multi level inverter carrier-based PWM method,"IEEE Trans.Ind.Appl.,vol.35,no.5,pp.1098-1107,Sep.-Oct.1999.
- [61] B.McGrath and D.Holmes,"Multi carrier PWM strategies for multilevel inverters", ,IEEE Trans.Ind.Electron.,vol.49,no.4,pp.858-867,Aug.2002.
- [62] H.Vander Broeck, H.Skudelny, and G.Stanke," Analysis and realization of a PWM based on voltage space vector", IEEE Trans.Ind.Appl.,vol.2,no.1,pp.142-150,Jan.-Feb.1988.
- [63] M.M.Prats L.G.Franquelo, J.I.Leon, R.Portillo, E.Galvan, and J.M.Carrasco, " A-3-D space vector modulation generalized algorithm for multi level converters", IEEE Power Electron.Lett. , vol.1,no.4,pp.110-114,Dec.2003
- [64] W.Hill and C.Harbourt ,,"Performance of medium voltage multi level inverters,"in Proc.IEEE Industry Applications Conf.,IAS Annual Meeting vol.2,Pheonix,AZ,3-7 Oct.1999,pp. 1186-1192.
- [65] J.Kelley,E.Strangas,and J.Miller,"Multi phase inverter analysis," in Proc.IEEE Inter.Electric machines and Drives conf.IEMDC,Cambridge,MA,17-20 Jun.2001,pp.147-155.
- [66] O.Ojo and G.Dong,"Generalized discontinuous carrier based PWM modulation scheme for multi-phase converter – machine systems,"in Proc.IEEE Industry Applications Conf.,IAS Annual Meeting,vol.2,Hongkong,china,2-6 Oct.2005,pp.1374-1381.
- [67] A.Iqbal,E.Levi,M.Jones, and S.N.Vukosavic,"Generalised sinusoidal PWM with harmonic injection for multi-phase VSIs,"in Proc.IEEE Power Electronics Specialists Conf.PESC,Jeju,Korea,18-22 Jun.2006,pp.2871-2877.
- [68] L.Hou,Y.Su,and L.Chen,"DSP based indirect rotor flux oriented control for multi phase induction machines,"in Proc.IEEE Inter.Electric machines and Drives conf.IEMDC,Madison,WI,1-4 Jun.2003,pp.976-980.
- [69] A.Iqbal,E.Levi,M.Jones, and S.N.Vukosavic ,,"A PWM scheme for a five phase VSI supplying a five -phase two - motor drive,"in Proc.IEEE Industrial Electronics Society Conf.IECON, Paris,France,6-10 Nov.2006,pp. 2575-2580.
- [70] S. Bowes and P. Clark. Regular-sampled harmonic-elimination PWM control of inverter drives. IEEE Trans. Power Electronics, 10(5):521–531, September 1995.
- [71] Sidney R. Bowes. Advanced regular-sampled PWM control techniques for drives and static power converters. IEEE IECON'93, pages 662–669, 1993.
- [72] P. N. Enjeti, P. D. Ziogas, and J. F. Lindsay. Programmed PWM techniques to eliminate harmonics: a critical evaluation. IEEE Trans. Industry Applications, 26(2):302–16, March-April 1990.
- [73] G. A. Goodarzi and R. G. Hoft. GTO inverter optimal PWM waveform. 1987 IEEE Industry Applications Society Annual Meeting, 1:312–16, 1987.
- [74] J. X. Lee and W. J. Bonwich. On-line suboptimal PWM strategy for AC driver. In Australasian Universities Power Engineering Conference, volume 1, pages 182–187, September 1994.
- [75] H. S. Patel and R. G. Hoft. Generalised techniques of harmonic elimination and voltage control in thyristor inverters: Part I — harmonic elimination. IEEE Trans. Industry Applications, IA-9(3):310–317, May 1973.
- [76] H. S. Patel and R. G. Hoft. Generalised techniques of harmonic elimination and voltage control in thyristor inverters: Part II — voltage control techniques. IEEE Trans. Industry Applications, IA-10(5):666–673, September 1974.
- [77] A Nabae, I Takahashi and H Akagi. 'A New Neutral-point-clamped PWM Inverter.' IEEE Transaction Industry Applicat, vol IA-17, September/ October 1981, pp 518-523.
- [78] P M Bhagwat and V R Stefanovic. 'Generalized Structure of a Multilevel PWM Inverter.' IEEE Transaction Industry Applicat, vol IA-19, November/ December 1983, pp 1057-1069.
- [79] Peng FZ, McKeever JW, Adams DJ. Cascade multilevel inverters for utility applications. In: Proceedings of 23rd international conference on industrial elect. control and inst, New Orleans (USA); 1997.
- [80] Manjrekar MD, Lipo TA. A hybrid multilevel inverter topology for drive applications. In: Proceedings of IEEE applied power elec conference; 1998.
- [81] Joos G, Huang X, Ooi BT. Direct-coupled multilevel cascaded series VAR compensators. In: Proceedings of IEEE ind appl society 32nd meeting; 1997.
- [82] Tolbert LM, Peng FZ, Habetler TG. Multilevel inverters for electric vehicle applications. In: Proceedings of IEEE workshop on power electronics in tran, Michigan (USA); 1998.
- [83] Bendre A, Krstic S, Meer JV, Venkataramanan G. Comparative evaluation of modulation algorithms for neutral point clamped converters. IEEE Trans Ind Appl 2005;41:634–43.
- [84] K Matsui, Y Kawata and F Ueda. 'Application of Parallel Connected NPC-PWM Inverters with Multilevel Modulation for ac Motor Drive. IEEE Transactions Power Electron, vol 15, September 2000, pp 901-907.
- [85] Y Shakweh. 'MV Inverter Stack Topologies.' IEE Power Engineering Journal, June 2001, pp 139-149.
- [86] T Ishida, K Matsuse, K Sasagawa and L Huang. 'Five-level Double Converters for Induction Motor Drives.' IEEE Ind Applicat Mag, July/August 2001.
- [87] C Hochgraf, R Lasseter, D Devan and T A Lipo. 'Comparison of Multilevel Inverters for Static VAR Compensation.' Proceedings on IEEEIAS'94, 1994, pp 921-928.
- [88] G C Cho, G H Jung, N S Choi and G H Cho. 'Analysis and Controller Design of Static VAR Compensator Using Three-level GTO Inverter.' IEEE Transactions on Power Electronics, vol 11, 1996, pp 57-65.
- [89] F Z Peng, J W McKeever and D J Adams. 'Cascade Multilevel Inverters for Utility Applications.' Proceedings on IEEE IECON'97, 1997, pp 437-442
- [90] G Joos, X Huang and B T Ooi. 'Direct Coupled Multilevel Cascaded Series VAR Compensators.' IEEE Transactions on Ind Applicat, vol 34, September/October 1998, pp 1156-1163.
- [91] F Z Peng and J W McKeever. 'A Power Line Conditioner using Cascade Multilevel Inverters for Distribution Systems.' IEEE Transactions on Ind Applicat, vol 34, November/December 1998, pp 1293-1298.
- [92] L M Tolbert, F Z Peng and T G Habetler. 'A Multilevel Converter-based Universal Power Conditioner.' IEEE



- Transactions on Industry Applicat, vol 36, March/April 2000, pp 596-602.
- [93] V Aburto, M Schneider, L Moran and J Dixon. 'An Active Power Filter Implemented with a Three-level NPC Voltage-source Inverter.' Proceedings on IEEE PESC'97, pp 1121-1126.
- [94] C J Hatziaodiu, F E Chalkiadakis and V K Feiste. 'A Power Conditioner for a Grid Connected Photo-voltaic Generator Based on a3-level Inverter.' IEEE Transactions on Energy Conversion, vol 14, December
- [95] L M Tolbert and F Z Peng. 'Multilevel Converters as a Utility Interface for Renewable Energy Systems.' IEEE Power Engineering Society Summer Meeting, July 15-20, 2000, pp 1271-1274.
- [96] Josh, F.T.; Jerome, J.; Wilson, A." The comparative analysis of multicarrier control techniques for SPWM controlled cascaded H-bridge multilevel inverter ", Proceedings on ICETECT'2011,2011, pp 459 – 464.
- [97] Dong Dong; Thacker, T.; Cvetkovic, I.; Burgos, R.; Boroyevich, D.; Wang, F.F.; Skutt, G, "Modes of Operation and System-Level Control of Single-Phase Bidirectional PWM Converter for Microgrid Systems ", IEEE Trans on Smart Grid, Vol 3, 2012, pp 93-104
- [98] Baimel, D. ; Tomasik, J. ; Zuckerberger, A. "Series Space Vector Modulation For Multi-Level Cascaded H-Bridge Inverters", Iet Trans On Power Electronics, Nov 2010, Vol 3, Pp 843 – 857.
- [99] Patel, P.J., Patel, V. ; Tekwani, P.N. ." Pulse-Based Dead-Time Compensation Method For Selfbalancing Space Vector Pulse Width-Modulated Scheme Used In A Three-Level Inverter-Fed Induction Motor Drive", Iet Trans On Power Electronics, July 2011, Vol 4, Pp 624 – 631.
- [100] Durgasukumar, G.; Pathak, M.K., "THD reduction in performance of multi-level inverter fed induction motor drive" ,IEEE conference proceedings of IICPE 2010, 2011, pp 1-6.
- [101] Sandulescu, P.; Idkhajine, L.; Cense, S.; Colas, F.; Kestelyn, X.; Semail, E.; Bruyere, A., "FPGA implementation of a general Space Vector approach on a 6-leg voltage source inverter", IEEE conference proceedings of IECON 2011, 2011, pp 3482 - 3487.
- [102] Ben Abdelghani, H.; Ben Abdelghani, A.B." Fault tolerant SVM strategy for 3-level NPC inverter ",IEEE conference proceedings of SSD 2011, pp 1-6.
- [103] Dey, A.; Ramchand, R.; Rajeevan, P.P.; Patel, C.; Mathew, K.; Gopakumar, K., "Nearly constant switching frequency hysteresis current controller for general n-level inverter fed induction motor drive", IEEE conference proceedings of IECON 2011, 2011, pp 4451 – 4456.
- [104] Bodo, N.; Jones, M.; Levi, E, "Multi-level space-vector PWM algorithm for seven-phase open-end winding drives ",IEEE conference proceedings of ISIE 2011, 2011, pp 1881 - 1886.
- [105] Dahidah, M.S.A.; Konstantinou, G.S.; Agelidis, V.G., "Single-phase nine-level SHE-PWM inverter with single DC source suitable for renewable energy systems ", Vehicle Power and Propulsion Conference (VPPC), 2011 IEEE , 2011 , pp 1 – 6.
- [106] Haghdar, K.; Shayanfar, H.A.; Alavi, M.H.S., "Selective Harmonics Elimination of Multi Level Inverters via Methods of GPS, SA and GA", Power and Energy Engineering Conference (APPEEC), 2011 Asia-Pacific , 2011 , pp 1 – 5.
- [107] Wanmin Fei; Xiaoli Du; Bin Wu , "A Generalized Half-Wave Symmetry SHE-PWM Formulation for Multilevel Voltage Inverters", IEEE Transaction on Industrial Electronics, Volume 57 , 2010 , pp 3030 – 3038.
- [108] Flourentzou,N., Agelidis, V.G. , "Multimodule HVDC System Using SHE-PWM With DC Capacitor Voltage Equalization", IEEE Transactions on Power Delivery, Volume 27 , Issue 1 , 2012 ,pp 79 – 86.
- [109] Pulikanti, S.R.; Dahidah, M.S.A.; Agelidis, V.G., "Voltage Balancing Control of Three-Level Active NPC Converter Using SHE-PWM ",IEEE Transactions on Power Delivery, Volume 26 , Issue 1, 2011, pp 258 – 267.

