A Review on Multilevel Converter Topologies for Electric Transportation Applications

Pouria Qashqai[1], Abdolreza Sheikholeslami[1] and Hani Vahedi[2]

[1]*Babol Noshirvani University of Technology, Babol, Iran*

[2]*Ecole de Technologie Superieure, University of Quebec, Montreal, Canada*

*Corresponding Author's E-mail: Pouria.qashqai@gmail.com

Abstract

This paper presents some popular multilevel converter topologies and associated modulation techniques considering advantages for electric transportation (ET) applications including electric vehicles (EVs), charging stations, wireless charging, etc. Cascaded H-Bridge (CHB), Flying Capacitors (FC) and Neutral Point Clamped (NPC) are analyzed. Moreover, mostly used switching techniques in multilevel converters including Sinusoidal Pulse Width Modulation (PWM) and Space Vector Modulation (SVM) are explained and investigated comprehensively. Various advantages of multilevel converters such as generating low harmonic waveforms, low common mode voltage and low switching frequency would be reviewed to show their capability in medium and high power ET applications such as car or train.

1. Introduction

Multilevel Inverters are getting increasingly used and studied because of their interesting features. Different topologies have been proposed in the literature since three of the most popular topologies are: CHB, FC and NPC. These are often known as classic topologies. Many newer topologies like PMP, PUC and CSC have been introduced lately. Each one of these topologies has its own pros and cons which give a great flexibility to select the right topology for each application. Also many modulation methods have been proposed which cover a wide range of switching frequencies. Low frequency methods like selective harmonic elimination (SHE) and selective harmonic mitigation (SHM) usually work with the fundamental frequency while medium frequency methods like SPWM and SVM work with frequencies much higher than the fundamental frequency. Just like different topologies, variety of modulation techniques gives an opportunity to select the best fitted technique for each application [12, 14, 33, 35]. Multilevel converters are successfully replacing old-fashioned two-level inverters with high power losses and bulky filters [53]. Nowadays they have covered a wide range of low, medium and high power applications. High power applications such as mining applications as regenerative conveyor, medical purposes like MRI gradient coil driver, hydro pump storage, STATCOM, FACTS, distributed generation, ship propulsion, train traction, aerospace and renewable energy conversion (wind and photovoltaic) [7, 17, 20, 38]. Multilevel inverters are gaining more interest than before in low and medium power applications like active filters because of their smooth output waveform [28]. The development of electric and hybrid-electric vehicles will offer many new opportunities and challenges to the power electronics industry, especially in the development of the main traction motor drive, charging stations, wireless charging, low EMI converters, etc [14]. Heavy trucks and many

military vehicles that have large electric drives need high-power converters (>250KW). Development of electric drives for these large vehicles will result in increased fuel efficiency, lower emissions, and likely better vehicle performance (acceleration and braking). As well, hybrid electric vehicle (HEV) is an emerging technology In the modern world because of the fact that it mitigates environmental pollutions and at the same time increases fuel efficiency of the vehicles.[55]. Moreover, charging stations including wired and wireless systems require high efficiency, low harmonic and low loss converters. Due to decreasing cost of semiconductor switches, multilevel Inverters are appropriate for these kinds of applications due to their distinguished characteristics including but not limited to: low switching frequency, low harmonic voltage waveforms low voltage stress on switches and low common mode voltage.

In the following sections, a comprehensive literature review of multilevel inverters and their switching techniques are performed. Moreover, their applications in ETs are investigated.

2. Multilevel wave concept

Based on output waveforms, inverters can be classified into four main categories: 1-Square wave inverters, 2-Quasi-square wave inverters, 3-Two-level PWM inverters and 4-multilevel inverters [6]. Typical output waveforms of these inverters are illustrated in Fig. 1 [14]. In the recent decades, multilevel inverters have attracted more interest both in industrial applications and research areas. Main idea of multilevel inverters (also called as MLI's) is based on generating a staircase waveform voltage at the output using power semiconductor devices and medium-voltage DC sources. Capacitors, batteries and renewable energy resources may be used as DC links as well [54]. Since high-voltage outputs are synthesized based on different combinations of input voltage levels, voltage rating of switches would be low and close to voltage level of input DC sources. Thus voltage stresses of semiconductors in MLI's are smaller than a conventional two-level inverter whose voltage stresses are almost near output voltage level. The most important advantages of MLI's according to the literature are listed below [8, 11, 12, 29, 33, 35, 49, 56]:
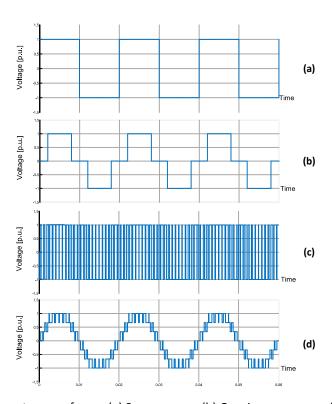

Figure 1: Typical inverter waveforms: (a) Square wave; (b) Quasi-square wave; (c) Two-level PWM waveform; and (d) Multilevel PWM waveform

1. The staircase output waveform results in lower harmonic and smaller dv/dt and consequently reduction (and sometimes elimination) of bulky filters, which is a great feature in design of onboard electrical chargers.

2. Voltage stress among power semiconductors is much lower than that of a conventional inverter which makes it possible to have high voltage outputs using low-voltage semiconductors which is useful in fast charging systems.

3. Common mode voltage is smaller in MLI's thus the stress on bearings of motors used in electrical vehicles (EV's) can be significantly reduced.

4. Input current of MLI's has low distortion.

5. Renewable energy sources like: photovoltaic cells, wind turbines and fuel cells are well integrated with these inverters (e.g. for hybrid solar vehicles).

6. EMI in multilevel inverters is lower and broadly speaking their electromagnetic compatibility is better than conventional two-level inverter.

Increasing the number of levels results in better voltage and current quality both at input and output but increases overall cost and complexity of the system [47, 50]. Output waveforms of typical two-level, three-level and five-level inverters are illustrated in Fig. 2 and their corresponding harmonic spectrums as well as their total harmonic distortion (THD) are shown in Fig. 3. As it is clear in figures, with increasing the number of levels, output waveform becomes smoother and more sinusoidal thus THD gets lower. Choosing the right number of levels totally depends on the application, size and cost. Anyways there must be a trade-off between cost, complexity and quality of voltages and currents tied to a multilevel inverter.
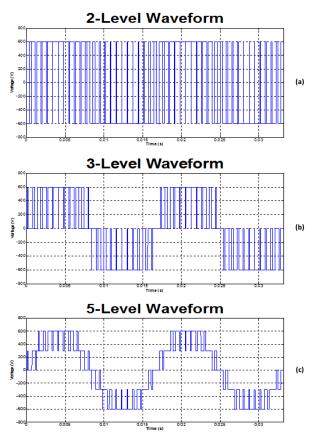

Figure 2: Typical multilevel inverter waveforms: (a) Two-level waveform; (b) Three-level waveform; (c) Five-level waveform

3. Multilevel Inverter Topologies

In 1975, first patent of a multilevel topology which was able to produce a staircase waveform at its output using several separated DC sources at the input introduced by Baker and Bannister [3]. This topology that is formed by connection of single-phase inverters in series is currently known as Cascade H-bridge (CHB) converter.

This topology is interesting to use in Hybrid Electrical Vehicles since they have separated DC sources like batteries and fuel cells which can be used as power sources of their inverters [55].

A few years later in 1980, Baker introduced another multilevel topology [2] which unlike CHB, needed only one separated DC source as its input. This structure that produces multilevel output waveform by several neutral-point-connected clamping diodes is mostly known as Neutral Point Clamped (NPC) or simply Diode Clamped inverter. Structure of a three-level and a five-level NPC is illustrated in Fig. 5-a and Fig. 5-b respectively.

In the same year Nabae et al, implemented NPC topology using a PWM switching method [27, 50]. After this achievement for over a decade, researchers put their effort on three-level NPC and its controlling methods. Another popular topology which is called Flying Capacitor (FC) / Capacitor Clamped, introduced by Meynard, Foch [26] and Lavieville [18] in 1990s. FC topology is very similar to NPC but it provides more redundant switching states [36, 52]. This redundancy is very important in voltage balancing and safe operation, but results in requiring a more complex controlling method thus this topology could not attract industries. Structure of a three-level and five-level flying capacitor inverter have been illustrated in Fig. 6-a and Fig. 6-b respectively.

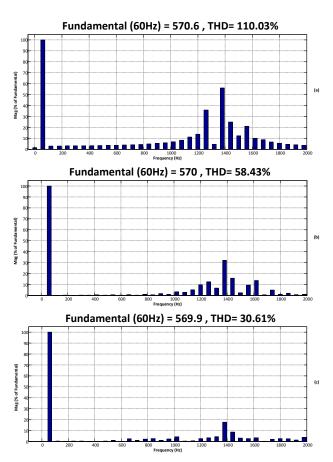These three topologies are usually known as "Classic Topologies" in the literature.

Figure 3: Typical Voltage THD of multilevel inverters: (a) Two-level waveform; (b) Three-level waveform; (c) Five-level waveform

Newer topologies have also been introduced in the last decades. Some modifications have been done on NPC in the literature. For instance, active NPC has been introduced to make the components losses equal while increasing the number of active switches [4]. As well, the anti-parallel IGBTs have replaced the clamping diodes of NPC [13]. However, the number of semiconductor switches didn't change. A three-level three-phase BNPC has been invented in 1987 using bidirectional switch (BS) which is made of a diode bridge and an IGBT [41]. Afterwards, a multilevel inverter based on BNPC generating higher levels has been introduced which employs more BSs [10]. Vahedi and Al-Haddad introduced PMP topology which had fewer switches and
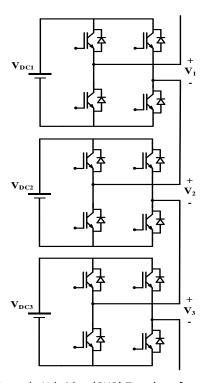

Figure 4: Cascade H-bridge (CHB) Topology for multilevel inverters

clamping diodes than the cascaded H-bridge (CHB) and neutral point clamped (NPC) inverters, moreover it has less bidirectional switches in comparison with the BNPC [54]. CSC topology which uses crossover switches to generate the maximum output voltage levels using only one single DC source is also introduced in [51]. One leg of a 5-level PMP and 9-level CSC is illustrated in Fig. 7-a and Fig. 7-b respectively. The PUC converter has been introduced in [1] which has less switches compared to other multilevel inverters
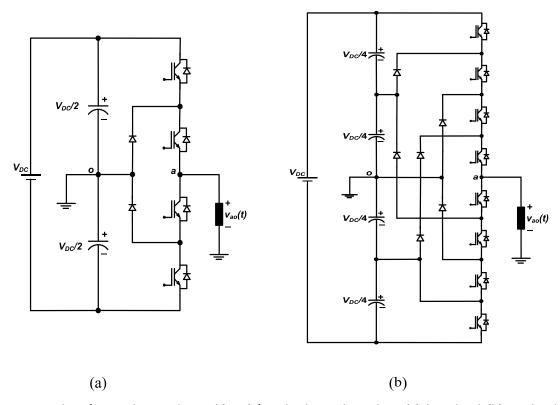
(a)   (b)

Figure 5: One leg of Neutral Point Clamped (NPC) / Diode Clamped Topology: (a)Three-level; (b) Five-level

while generating more voltage levels at the output. This topology is a blend of FC and CHB configuration [49]. A single-phase 7-level PUC configuration is illustrated in Fig. 8. As it is clearly seen, in comparison with classic topologies, less components are needed for creating the same number of levels.
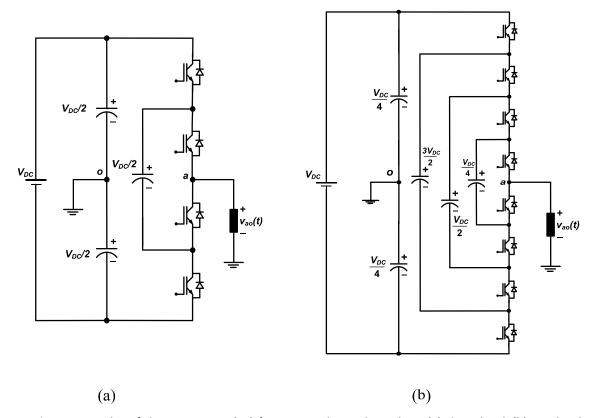

(a)   (b)

Figure 6: One leg of Flying Capacitor (FC) / Capacitor Clamped Topology: (a) Three-level; (b) Five-level

Nowadays Plug-in Electric Vehicles (PEVs) use a single-phase unidirectional converter in their chargers known as L1 or L2 models [42, 57]. But high-power PEVs need bidirectional three-phase structures. To provide such high power and voltage system with acceptable quality, using multilevel inverters is the best option aiming at lower THD, smoother waveforms, lower voltage stress across semiconductors, lower EMI, smaller common mode voltages and meanwhile they can produce a low-ripple DC output which is insensitive to source disturbances and load [5, 16, 23, 44, 46, 48].
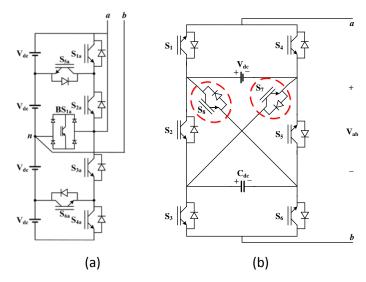

(a)   (b)

Figure 7: One leg of: (a) 5-Level PMP; and (b) 9-Level CSC Inverter
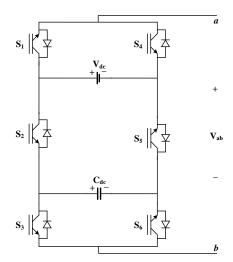

Figure 8: Single-Phase 7-Level PUC Inverter

4. Multilevel Switching Techniques

Modulation techniques of MLI's can be categorized into two main types based on their switching frequency. Some of those methods trigger their switches with fundamental frequency and are known as low frequency methods while switching frequency of the others are much higher than the fundamental frequency and are known as high frequency methods [34, 45]. As a high frequency method, Sinusoidal Pulse Width Modulation (SPWM) is one of the most popular switching techniques which is widely used in commercialized switching converters. In this technique, reference voltage is compared with one or more carrier signals (depends on number of levels) and produces desired gate signals as shown in Fig. 9. this method is quite popular due to its simplicity and robustness but has some drawbacks like inability in voltage self-balancing and incapability to provide maximum modulation index [37]. Another popular and well-known method is Space Vector Modulation (SVM)

which has overcome pre-mentioned drawbacks of SPWM. This method can be easily implemented on any multilevel topology [15, 21, 22, 25].

Reference vector and space vector diagram for a two-level, three-level and five-level inverter has been illustrated in Fig. 10-a, Fig. 10-b and Fig. 10-c respectively. These space vector diagrams are valid for any two, three and five-level inverters despite their topologies. For example, Fig. 9-c can be used for a five-level NPC, FC or CHB. It is worth to mention that depending on the used topology, redundant switching states may vary.

Idea of SVM is based on activating three adjacent vectors to a reference vector at a sampling time. Switching times V_j, V_{j+1} and V_{j+2} which are the duty times of the pre-mentioned adjacent vectors, can be calculated using equation (1) which is based on the volt-second balancing principle [37].

$$V^* = \frac{(T_j V_j + T_{j+1} V_{j+1} + T_{j+2} V_{j+2})}{T} \tag{1}$$

In addition to aforementioned advantages, these features are also considered as the most important benefits of SVM:

- Proper utilization of DC bus voltage and capability to achieve maximum modulation index

- Lower current ripples compared to SPWM

- Relatively easier implementation using a Digital Signal Processor (DSP)

These features have made SVM a proper method for high-voltage high-power applications.

By increasing number of levels, number of redundant states increases subsequently. This leads to a better flexibility in selection of states in order to balance voltages. But in other hands makes it more complex. For example, switching and controlling of a five-level SVM based inverter is dramatically more complex than a three-level one. Thus some researchers have replaced hexagram of a five-level inverter with two hexagrams of a three-level inverter which are phase-shifted to achieve a simpler controlling method [19]. Besides the capability of this method in self-voltage-balancing is limited to the modulation index and the power factor of the AC-side [24].
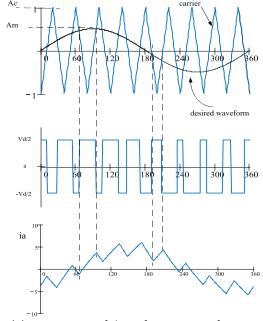

Figure 9: Principle of SPWM: (a) Comparison of the reference waveform with a carrier signal; (b) Gating signal; and (c) Output current waveform

High frequency techniques like SPWM and SVM cause more commutations per cycle that result in more switching losses. But overall quality of their outputs is better [36]. Selective Harmonic Elimination (SHE) [39, 40, 43], Space Vector Control (SVC) [34] and Direct Torque Control (DTC) [9] are some of the most popular low frequency switching techniques. Anyways each one of these techniques is dedicated to their special applications.

Common mode voltage is an important factor in EV's. Conventional two-level inverter produces a considerable common mode voltage which causes more stress on bearings of motors and higher dv/dt which results in higher current leakage. But multilevel inverters not only inherently produce lower common mode voltage but also reduce current leakages of EV's due to their lower dv/dt [55]. High frequency modulation techniques like SPWM and SVM are preferred to use in EV's and charging stations. In order to reduce common mode voltage in SPWM, some techniques like PD (phase disposition), POD (phase opposition disposition), APOD (Alternative phase opposition disposition) and PS (phase-shift) have been introduced in the literature [31, 32]. Studies have shown that in addition to all superiorities of SVM over SPWM, its more efficient in reduction of common mode voltage [30].
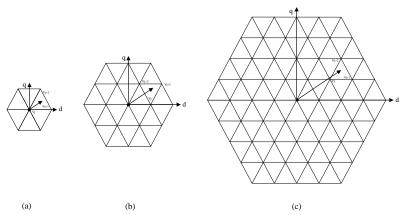

(a) (b) (c)

Figure 10: Reference voltage vector and its adjacent vectors in (a) two-level; (b) Three level; and (c) Five-level space vector modulation

Conclusion

Almost four decades have been passed since first introduction of multilevel inverters. Their important role in industry and academia is well known. A comprehensive view of MLI's and their applications especially in renewable energies, electric vehicles and charging stations has been presented in this paper. Main advantages of multilevel inverters over conventional two-level inverter are as follows: 1-smoother waveform with lower THD, 2-lower common mode voltage, 3-less distorted input current and 4-lower switching frequency and therefor lower switching loss. Multilevel inverters have also some drawbacks like more number of components which results in lower reliability, higher cost and more complex controller. However, with recent developments in semiconductors and emerging GaN and SiC devices, drawbacks of using MLI's can be neglected over their numerous advantages. Although all the achievements in this area couldn't fit in such paper, best efforts have been made to describe the most important principles of MLI's mostly in the field of electric transportation.

References

[1]   K. Al-Haddad, Y. Ounejjar, and L.-A. Gregoire, "Multilevel electric power converter," ed: Google Patents, 2009.
[2]   R. H. Baker, "Switching circuit," ed: US Patent 4,210,826, 1980.
[3]   R. H. Baker and L. H. Bannister, "Electric power converter," ed: U.S.Patent 3,867,643, 1975.
[4]   T. Brückner, S. Bernet, and H. Güldner, "The active NPC converter and its loss-balancing control," Industrial Electronics, IEEE Transactions on, vol. 52, pp. 855-868, 2005.

[5]   D. Carlton and W. G. Dunford, "Multi-level, uni-directional AC-DC converters, a cost effective alternative to bi-directional converters," in Power Electronics Specialists Conference, 2001. PESC. 2001 IEEE 32nd Annual, 2001, pp. 1911-1916 vol. 4.

[6]   S. Daher, Analysis, design and implementation of a high efficiency multilevel converter for renewable energy systems: Kassel University Press, 2006.

[7]   S. Daher, J. Schmid, and F. L. Antunes, "Multilevel inverter topologies for stand-alone PV systems," Industrial Electronics, IEEE Transactions on, vol. 55, pp. 2703-2712, 2008.

[8]   S. Debnath, J. Qin, B. Bahrani, M. Saeedifard, and P. Barbosa, "Operation, control, and applications of the modular multilevel converter: A review," 2014.

[9]   M. Depenbrock, "Direct self-control (DSC) of inverter-fed induction machine," Power Electronics, IEEE Transactions on, vol. 3, pp. 420-429, 1988.

[10] J. Dixon and L. Moran, "High-level multistep inverter optimization using a minimum number of power transistors," Power Electronics, IEEE Transactions on, vol. 21, pp. 330-337, 2006.

[11] D. C. Erb, O. C. Onar, and A. Khaligh, "Bi-directional charging topologies for plug-in hybrid electric vehicles," in Applied Power Electronics Conference and Exposition (APEC), 2010 Twenty-Fifth Annual IEEE, 2010, pp. 2066-2072.

[12] L. G. Franquelo, J. Rodriguez, J. I. Leon, S. Kouro, R. Portillo, and M. A. Prats, "The age of multilevel converters arrives," Industrial Electronics Magazine, IEEE, vol. 2, pp. 28-39, 2008.

[13] V. Guennegues, B. Gollentz, F. Meibody-Tabar, S. Rael, and L. Leclere, "A converter topology for high speed motor drive applications," in Power Electronics and Applications, 2009. EPE'09. 13th European Conference on, 2009, pp. 1-8.

[14] K. Gupta, A. Ranjan, P. Bhatnagar, L. Sahu, and S. Jain, "MULTILEVEL INVERTER TOPOLOGIES WITH REDUCED DEVICE COUNT: A REVIEW," Power Electronics, IEEE Transactions on, vol. PP, pp. 1-1, 2015.

[15] D. G. Holmes and B. P. McGrath, "Opportunities for harmonic cancellation with carrier-based PWM for a two-level and multilevel cascaded inverters," Industry Applications, IEEE Transactions on, vol. 37, pp. 574-582, 2001.

[16] Z. Jing, Y. Han, H. Xiangning, T. Cheng, C. Jun, and R. Zhao, "Multilevel Circuit Topologies Based on the Switched-Capacitor Converter and Diode-Clamped Converter," Power Electronics, IEEE Transactions on, vol. 26, pp. 2127-2136, 2011.

[17] S. Kouro, M. Malinowski, K. Gopakumar, J. Pou, L. G. Franquelo, B. Wu, et al., "Recent advances and industrial applications of multilevel converters," Industrial Electronics, IEEE Transactions on, vol. 57, pp. 2553-2580, 2010.

[18] J.-P. Lavieville, P. Carrere, and T. Meynard, "Electronic circuit for converting electrical energy, and a power supply installation making use thereof," ed: Google Patents, 1997.

[19] L. Li, D. Czarkowski, L. Yaguang, and P. Pillay, "Multilevel space vector PWM technique based on phase-shift harmonic suppression," in Applied Power Electronics Conference and Exposition, 2000. APEC 2000. Fifteenth Annual IEEE, 2000, pp. 535-541 vol.1.

[20] Y. Liu, A. Q. Huang, W. Song, S. Bhattacharya, and G. Tan, "Small-signal model-based control strategy for balancing individual DC capacitor voltages in cascade multilevel inverter-based STATCOM," Industrial Electronics, IEEE Transactions on, vol. 56, pp. 2259-2269, 2009.

[21] J. Mahdavi, A. Agah, A. M. Ranjbar, and H. A. Toliyat, "Extension of PWM space vector technique for multilevel current-controlled voltage source inverters," in Industrial Electronics Society, 1999. IECON '99 Proceedings. The 25th Annual Conference of the IEEE, 1999, pp. 583-588 vol.2.

[22] M. Manjrekar and G. Venkataramanan, "Advanced topologies and modulation strategies for multilevel inverters," in Power Electronics Specialists Conference, 1996. PESC '96 Record., 27th Annual IEEE, 1996, pp. 1013-1018 vol.2.

[23] M. D. Manjrekar, P. K. Steimer, and T. A. Lipo, "Hybrid multilevel power conversion system: a competitive solution for high-power applications," Industry Applications, IEEE Transactions on, vol. 36, pp. 834-841, 2000.

[24] M. Mazuela, I. Baraia, S. Alvarez, I. Atutxa, and D. Madariaga, "Comprehensive analysis of voltage balancing techniques for 5L-NPC converters," in Power Electronics and Applications (EPE), 2013 15th European Conference on, 2013, pp. 1-10.

[25] B. P. McGrath, D. G. Holmes, and T. A. Lipo, "Optimised space vector switching sequences for multilevel inverters," in Applied Power Electronics Conference and Exposition, 2001. APEC 2001. Sixteenth Annual IEEE, 2001, pp. 1123-1129 vol.2.

[26] T. Meynard and H. Foch, "Multi-level conversion: high voltage choppers and voltage-source inverters," in Power Electronics Specialists Conference, 1992. PESC'92 Record., 23rd Annual IEEE, 1992, pp. 397-403.

[27] A. Nabae, L. kahashi, and H. Akagi, "A New Neutral Point Clamped PWM Inverter," in IAS Annual Meeting, 1980, pp. 761-766.

[28] M. Odavic, V. Biagini, M. Sumner, P. Zanchetta, and M. Degano, "Low carrier–fundamental frequency ratio PWM for multilevel active shunt power filters for aerospace applications," Industry Applications, IEEE Transactions on, vol. 49, pp. 159-167, 2013.

[29] M. A. Parker, L. Ran, and S. J. Finney, "Distributed control of a fault-tolerant modular multilevel inverter for direct-drive wind turbine grid interfacing," Industrial Electronics, IEEE Transactions on, vol. 60, pp. 509-522, 2013.

[30] B. Raja and S. Raghu, "Comparative Analysis of Different PWM Techniques to Reduce the Common Mode Voltage in Three-Level Neutral-Point-Clamped Inverters for Variable Speed Induction Drives," International Journal of Power Electronics and Drive Systems (IJPEDS), vol. 3, pp. 105-116, 2013.

[31] M. M. Renge and H. M. Suryawanshi, "Five-Level Diode Clamped Inverter to EliminateCommon Mode Voltage and Reduce inMedium Voltage Rating Induction Motor Drives," Power Electronics, IEEE Transactions on, vol. 23, pp. 1598-1607, 2008.

[32] M. M. Renge and H. M. Suryawanshi, "Multilevel inverter to reduce common mode voltage in AC motor drives using SPWM technique," Journal of Power Electronics, vol. 11, pp. 21-27, 2011.

[33] J. Rodríguez, S. Bernet, B. Wu, J. O. Pontt, and S. Kouro, "Multilevel voltage-source-converter topologies for industrial medium-voltage drives," Industrial Electronics, IEEE Transactions on, vol. 54, pp. 2930-2945, 2007.

[34] J. Rodriguez, P. Correa, and L. Moran, "A vector control technique for medium voltage multilevel inverters," in Applied Power Electronics Conference and Exposition, 2001. APEC 2001. Sixteenth Annual IEEE, 2001, pp. 173-178 vol.1.

[35] J. Rodriguez, L. G. Franquelo, S. Kouro, J. I. Leon, R. C. Portillo, M. A. M. Prats, et al., "Multilevel converters: An enabling technology for high-power applications," Proceedings of the IEEE, vol. 97, pp. 1786-1817, 2009.

[36] J. Rodriguez, J.-S. Lai, and F. Z. Peng, "Multilevel inverters: a survey of topologies, controls, and applications," Industrial Electronics, IEEE Transactions on, vol. 49, pp. 724-738, 2002.

[37] M. Saeedifard, R. Iravani, and J. Pou, "Analysis and control of DC-capacitor-voltage-drift phenomenon of a passive front-end five-level converter," Industrial Electronics, IEEE Transactions on, vol. 54, pp. 3255-3266, 2007.

[38] P. Samuel, R. Gupta, and D. Chandra, "Grid interface of wind power with large split-winding alternator using cascaded multilevel inverter," Energy Conversion, IEEE Transactions on, vol. 26, pp. 299-309, 2011.

[39] M. Sharifzade, H. Vahedi, A. Sheikholeslami, H. Ghoreishy, and K. AI-Haddad, "Selective harmonic elimination modulation technique applied on four-leg NPC," in Industrial Electronics (ISIE), 2014 IEEE 23rd International Symposium on, 2014, pp. 2167-2172.

[40] M. Sharifzadeh, H. Vahedi, A. Sheikholeslami, P.-A. Labbé, and K. Al-Haddad, "Hybrid SHM-SHE Modulation Technique for Four-Leg NPC Inverter with DC Capacitors Self-Voltage-Balancing," IEEE Trans. Ind. Electron., vol. 62, pp. 4890-4899, 2015.

[41] S. S. Shekhawat, P. J. Dhyanchand, and P. Thollot, "Bi-directional switch for neutral point clamped PWM inverter," ed: Google Patents, 1987.

[42] B. Singh, B. N. Singh, A. Chandra, K. Al-Haddad, A. Pandey, and D. P. Kothari, "A review of single-phase improved power quality AC-DC converters," Industrial Electronics, IEEE Transactions on, vol. 50, pp. 962-981, 2003.

[43] S. Sirisukprasert, L. Jih-Sheng, and L. Tian-Hua, "Optimum harmonic reduction with a wide range of modulation indexes for multilevel converters," in Industry Applications Conference, 2000. Conference Record of the 2000 IEEE, 2000, pp. 2094-2099 vol.4.

[44] L. M. Tolbert, P. Fang Zheng, and T. G. Habetler, "Multilevel converters for large electric drives," Industry Applications, IEEE Transactions on, vol. 35, pp. 36-44, 1999.

[45] L. M. Tolbert and T. G. Habetler, "Novel multilevel inverter carrier-based PWM method," Industry Applications, IEEE Transactions on, vol. 35, pp. 1098-1107, 1999.

[46] L. M. Tolbert and F. Z. Peng, "Multilevel converters for large electric drives," in Applied Power Electronics Conference and Exposition, 1998. APEC '98. Conference Proceedings 1998., Thirteenth Annual, 1998, pp. 530-536 vol.2.

[47] H. Vahedi and K. Al-Haddad, "Half-bridge based multilevel inverter generating higher voltage and power," in Electrical Power & Energy Conference (EPEC), 2013 IEEE, 2013, pp. 1-6.

[48] H. Vahedi and K. Al-Haddad, "Single-Phase Single-Switch Vienna Rectifier as Electric Vehicle PFC Battery Charger," in VPPC 2015-Vehicular Power and Propulsion Conference, Canada, 2015, pp. 750-755.

[49] H. Vahedi, K. Al-Haddad, and H. Y. Kanaan, "A new voltage balancing controller applied on 7-level PUC inverter," in Industrial Electronics Society, IECON 2014-40th Annual Conference of the IEEE, 2014, pp. 5082-5087.

[50] H. Vahedi, K. Al-Haddad, P.-A. Labbe, and S. Rahmani, "Cascaded multilevel inverter with multicarrier pwm technique and voltage balancing feature," in Industrial Electronics (ISIE), 2014 IEEE 23rd International Symposium on, 2014, pp. 2155-2160.

[51] H. Vahedi, K. Al-Haddad, Y. Ounejjar, and K. Addoweesh, "Crossover Switches Cell (CSC): A new multilevel inverter topology with maximum voltage levels and minimum DC sources," in Industrial Electronics Society, IECON 2013-39th Annual Conference of the IEEE, 2013, pp. 54-59.

[52] H. Vahedi, A. Chandra, and K. Al-Haddad, "Five-Level Reduced-Switch-Count Boost PFC Rectifier with Multicarrier PWM," in ECCE 2015-Energy Conversion Congress & Exposition, Canada, 2015, pp. 2253-2258.

[53] H. Vahedi, P.-A. Labbe, H. Y. Kanaan, H. F. Blanchette, and K. Al-Haddad, "A new five-level buck-boost active rectifier," in Industrial Technology (ICIT), 2015 IEEE International Conference on, 2015, pp. 2559-2564.

[54] H. Vahedi, S. Rahmani, and K. Al-Haddad, "Pinned mid-points multilevel inverter (PMP): three-phase topology with high voltage levels and one bidirectional switch," in Industrial Electronics Society, IECON 2013-39th Annual Conference of the IEEE, 2013, pp. 102-107.

[55] A. Verma, P. Thakura, K. Jana, and G. Buja, "Cascaded multilevel inverter for hybrid electric vehicles," in Power Electronics (IICPE), 2010 India International Conference on, 2011, pp. 1-6.

[56] C.-M. Young, N.-Y. Chu, L.-R. Chen, Y.-C. Hsiao, and C.-Z. Li, "A single-phase multilevel inverter with battery balancing," Industrial Electronics, IEEE Transactions on, vol. 60, pp. 1972-1978, 2013.

[57] D. Yu, S. Lukic, B. Jacobson, and A. Huang, "Review of high power isolated bi-directional DC-DC converters for PHEV/EV DC charging infrastructure," in Energy Conversion Congress and Exposition (ECCE), 2011 IEEE, 2011, pp. 553-560.