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186. Modular Multilevel Converters - An Emerging Trend in Advanced HVDC Systems

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Abstract

"Power Systems in today's world has the same importance as the back bone in human body. With the advent of modern power electronics converters, it is now possible to transfer bulk quantity of conventional and non-conventional energies to the load centers. Presence of renewable energy in far flung areas like deserts, and offshore etc., requires efficient, stable and long distance transmission system. High Voltage Direct Current (HVDC) systems these days have come up with the solution of minimal losses and high grid stability during this energy transfer. In this paper significance of HVDC systems based on modern power electronics converters is discussed. Various topologies related to the modular multilevel converters (MMCs) are examined. Such topologies are certainly able to convert ac power into dc power and vice versa along with fulfilling the grid regulations. The exploration of renewable energy resources like offshore and onshore wind power plants can also be possible by employing such MMCs based multi terminal direct current (MTDC) systems. In the end of paper, some major worldwide HVDC projects are listed to show their fast growth, adoption and power handling capability."

Keywords: *"HVDC Systems; Power Electronics Converters; Modular Multilevel Converters (MMC); MTDC"*

1. Introduction

Electrical energy is accepted as universal energy. Due to its easy conversion from various types of energies like chemical, potential, kinetic, solar etc. and then its re-conversion into these types of energies, it holds the status of universal energy. It is transferred from far located generating stations via high voltage AC and DC transmission lines to the populated areas. The high voltage direct current (HVDC) transmission has several benefits over its counterpart- the high voltage alternating current (HVAC) transmission. HVDC transmission possesses the advantages of long distance efficient power transmission, less number of conductors thus resulting in material saving and low width transmission corridor, negligible reactance, lesser corona losses and lightning strikes, provision of asynchronous back to back connections, high grid stability and use of cables.

The HVDC transmission can be classified into three main configurations: the mono polar connection, the bi-polar connection, and the homo polar connection. These connections are used with various types of convertors that are using power electronics switches and working as rectifiers/invertors. These power electronics systems are in continuous development phase and many advanced features are being incorporated in them by day to day research work [1-2].

Power electronics convertors are classified as line commutated convertors (LCC) and voltage source convertors (VSC). The VSC have gained great popularity in recent years because of their several advantages over LCC [3].

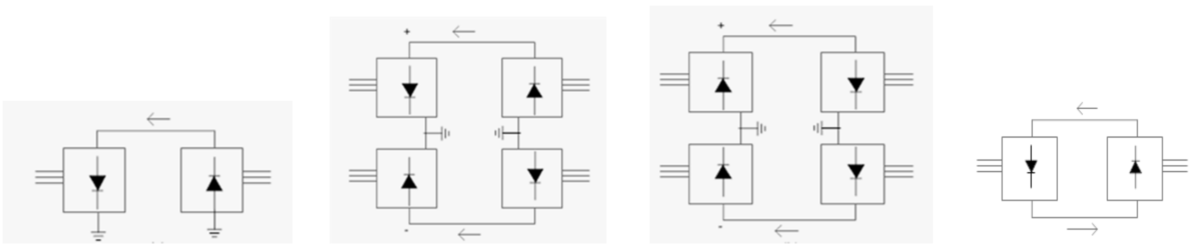
Various remote generating stations like wind farms and consumer loads can now be connected with the grid by using multi-terminal direct current (MTDC) transmission systems. This newly developed powerful aspect of HVDC systems is making them more adaptable for future interconnection of renewable resources like on shore and off shore wind farms, and various loads.

This paper presents a detailed description of HVDC transmission systems along with associated worldwide projects.

2. Configurations of HVDC Transmission Systems

HVDC transmission systems have following configurations:

2.1 Mono-polar Configuration



(a) (b) (c) (d)

Fig. 1. HVDC system configurations (a) Mono-polar (b) Bi-polar (c) Homo-polar (d) Back to back

In this configuration as shown in Fig. 1. (a), a single wire is placed to deliver dc power in between the convertors. The return path can be used via ground, sea or cable armoring. This method has advantage of great saving of conductor material but offers disadvantages of less reliability and corrosion of nearby metallic structures.

2.2 Bi-polar Configuration

As shown in Fig. 1. (b), this configuration involves two conductors having opposite polarities; use to transfer power between the convertor stations. Although it uses more conductor material, nevertheless, it will still provide half of the power via ground connection in case of breakage of any conductor [4].

2.3 Homo-polar Configuration

This configuration shown in Fig. 1. (c), uses two conductors for transferring power between convertor stations. It has same advantages as in bi-polar connection besides same polarity of the conductors, hence causing less corrosion in nearby metallic structures and less corona loss.

2.4 Back to Back Configuration

The great advantage of HVDC systems has been seen in connecting two different AC grids operating at different frequencies, as shown in Fig. 1. (d). No need of synchronization is necessary while power can be transferred from any side to other side with greater stability margin. Even a few meters connecting wires are sufficient to install this back to back intertie.

3. Types of HVDC Convertors

HVDC systems comprises of two major types viz., the Line commutates converter, also known as current source converter (CSC), and the more advanced voltage source converter (VSC) [3,5].

3.1 The Line Commutated Convertors (LCC)

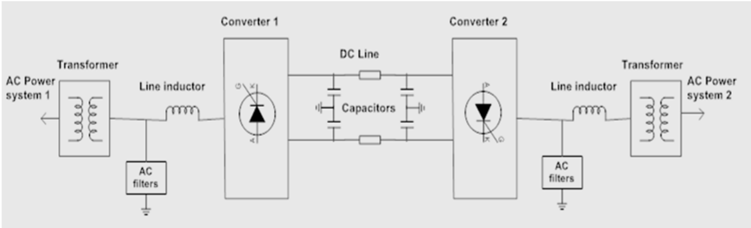


Fig. 2. Schematic of HVDC LCC system

The line commutated convertor (LCC), also known as current source convertor (CSC), uses thyristor as switching device operating at line frequency. This convertor requires natural commutation or line commutation therefore need of a strong synchronous power source is needed to operate this convertor satisfactorily. Although black start capability is not available with these types of convertors, nevertheless they are the most popular HVDC convertors used these days [6]. They can deal power as high as 10000 MW range with +- 1100 kV with a length of 2600 km as in the case of a Zhundong –Sichuan scheme located in China [7].

3.2 The Voltage Source Convertors (VSC)

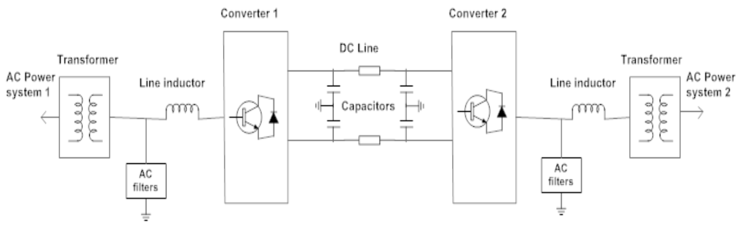


Fig. 3. Schematic of HVDC VSC system

The voltage source convertors (VSC) is based on IGBT technology, requires no separate synchronous power source and has the black start capability [8]. Instead of inverting the DC voltage polarity in both convertor stations as in LCC HVDC systems they have to change the direction of current flow. The famous high frequency based PWM is used as switching technique in these convertors making them comparatively less efficient and poor power quality producers. VSC has high degree of controllability of active and reactive power flow in both directions [9]. These powers can be given by Eq. (1) and Eq. (2).

$$P = \frac{Vac\,Vconv\ \sin\delta}{X} \quad (1)$$

$$Q = \frac{Vconv\,(Vconv - Vac\ \sin\delta)}{X} \quad (2)$$

Where Vconv is the converter voltage, Vac is the ac grid voltage, δ is the angle between Vconv and Vac, and X is the series reactance of the line inductor.
Various topologies have been developed to enhance the characteristics of these convertors. Some of them are listed below:

3.2.1 The 2- Level Convertor

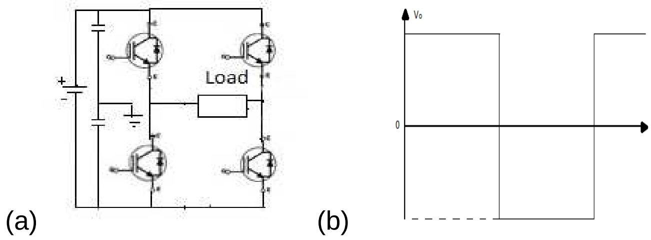


Fig. 4. Schematic of a 2-level converter (a) Basic topology (b) Load voltage waveform

The 2-level VSC convertor produces a square wave output having lot of harmonics and power losses. The positive and negative terminals of the DC source are connected to the load by periodically switching on and off the switching devices so that the AC output voltage is obtained. Freewheeling diodes are also required to transfer the stored energy in the load inductances back to the DC source.

3.2.2 The Multi Level Convertor (MLC)

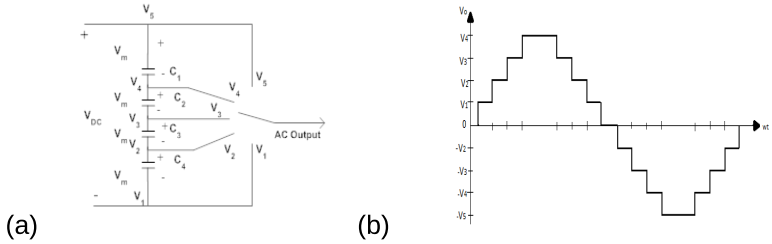


Fig. 5. Schematic of MLC (a) Basic switching scheme (b) 5-level AC Output waveform

To overcome the problems present in two level convertors, an improved topology called Multi-level convertors (MLC) have been introduced. The MLC has the features of synthesizing an AC output waveform generated with the help of multiple input dc sources. In this manner both positive and negative levels are combined to construct a stepped AC waveform close to sine wave having lesser harmonics. MLC can be operated at switching frequency either at power frequency (thus reducing switching losses to a great extent), or at high frequency (several kHz) to minimize harmonic content. Moreover, low dv/dt stress is also an added advantage of this type of convertors. Therefore, commercial HVDC converters are based on multilevel technology. Following section gives an overview of multilevel topologies [10-14].

4. Multi-Level Convertors Topologies

MLC has many topologies including basic and derived topologies but three basic types are as below:

4.1 The Neutral Point Clamped Convertor (NPC)

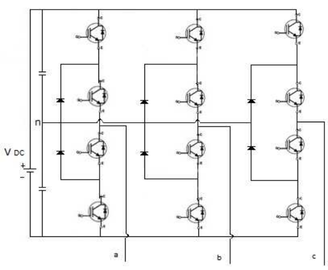


Fig. 6. Schematic of 3-phase 3 level NPC

The neutral point clamped converter (NPC), also named as diode clamped converter, is the modification of the conventional VSC and was initially proposed as a three level convertor. This topology is shown in Fig. 6, the three phase three level NPC convertor has three legs consisting of three upper and three lower arms. The midpoint of the armed switches is connected with a common neutral point through clamping diodes enabling the introduction of a zero voltage level. By this configuration the switches have to with stand half of the dc linked voltage. The NPC convertor can be extended to more than three levels. This topology has the drawback of capacitor voltage unbalancing and distortion of output AC waveform. This scheme is not yet suitable for high number of voltage levels. [15]

4.2 The Flying Capacitor (FC) Converters

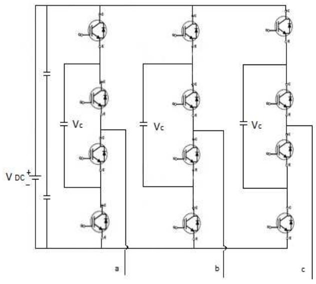


Fig. 7. Schematic of a 3-phase, 3 level FC converter

As illustrated in Fig. 7. each leg capacitor is charged up to various voltage levels and thus by switching on and off the devices, different voltage output levels can be achieved [16]. It has an inherent problem the initial charging of the capacitors but afterwards the capacitors store the energy and provide this energy in times of voltage outages and sags. Although this topology can be extended to a large number of cells, the addition of capacitors introduces increased complexity, need of control, and cost.

4.3 The Cascaded H-Bridge (CHB) Converters

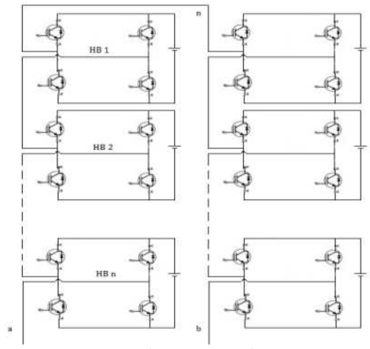


Fig. 8. Schematic of two legs of a 3-phase CHB

The cascaded converter (either half bridge or full bridge) has inherently no problems such as voltage balancing and capacitor initialization like in NPC or FC converters. Clamping diodes and flying capacitors are not needed in this type of converters, rather series connected bridge switches known as cells, are required. The output phase voltage is the resultant of voltages generated by the series connected cells present in a particular leg of the converter [16].

4.4 Modular Multi Level Convertors (MMC)

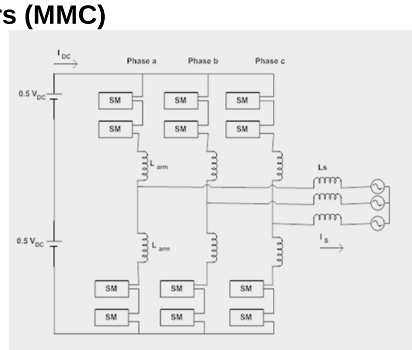
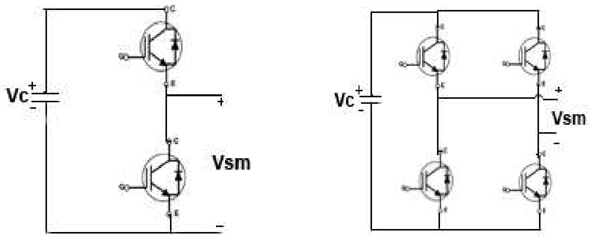


Fig. 9. Schematic of a MMC

The MMC topology was proposed in 2002 by R. Marquardt and is one of the most emerging technologies in current

VSC HVDC systems. It is using a number of series connected cells also known as sub modules (SM). The SM is made up of a half bridge consisting of two Power switches with anti parallel diodes and a DC capacitor as shown in Fig. 10. By turning on specific SM switches, insertion or bypassing the SM into the converter arm can be possible while the uninterrupted current flow is achieved by the connection of the anti parallel diodes [17-18].
Table-1 and 2 below illustrate states of the switches along with status of sub module SM. The switches are to be operated in complimentary manner preventing short circuit of the SM source capacitor. Following a specific switching pattern, a staircase output voltage waveform can be achieved at the output.



(a) (b)

Fig. 10. Schematic of (a) half bridge SM (b) full bridge SM

Table 1. Half bridge SM switching states

Upper switch state	Lower switch state	SM terminal voltage with current polarity	DC capacitor status
1	0	Vc (+)	Charging
0	1	0 (+)	By passed
1	0	Vc (-)	Discharging
0	1	0 (-)	By passed
1	1	-	Short circuit
0	0	-	Open circuit

Table 2. Full bridge SM switching states

Upper left switch state	Upper right switch state	Lower left switch state	Lower right switch state	SM terminal voltage with current polarity	DC capacitor status
1	0	1	0	Vc (+)	Charging
0	1	0	1	0 (+)	By passed
1	0	1	0	Vc (-)	Discharging
0	1	0	1	0 (-)	By passed
1	1	1	1	-	Short circuit
0	0	0	0	-	Open circuit

Fig. 11, below is showing a schematic of HVDC MMC system. Here need for AC side filters and transformers are reduced. Other advantages of MMC based HVDC systems are their modularity, improved quality of output waveform, redundancy based reliability and increased efficiency [19-21].

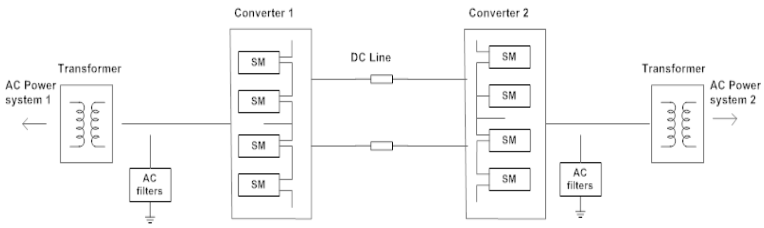


Fig. 11. Schematic of a HVDC MMC system

5. MTDC Systems and Integration of Renewable Power (like Wind, Solar)

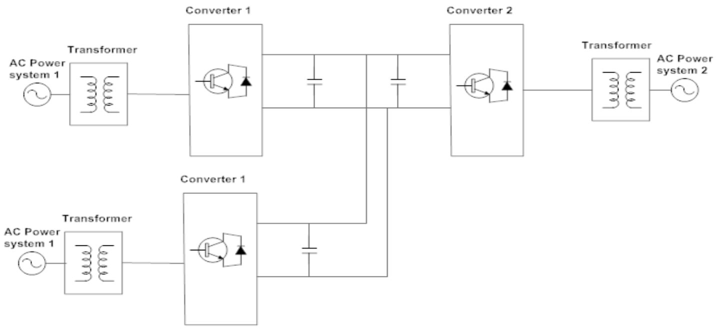


Fig. 12. Schematic of a MTDC system

In past years, HVDC systems had no provision for tapings in between the converter stations i.e. they are characterized with point to point configuration in contrast with HVAC systems which are offering tapings with respect to multiple source and multiple load connections. Due to tremendous research work in recent years a new concept of multi-terminal direct current (MTDC) systems is introduced, as shown in Fig.12, in which multiple generating sources as well as multiple loads can be connected via HVDC systems. Renewable resources like onshore and offshore wind farms and solar power parks can now be integrated into existing HVDC grid. Multiple bulk loads can also be connected via these MTDC systems. This powerful feature of multiple interconnections makes the HVDC systems more reliable for adoption in the near future [15].

6. Global HVDC Projects

Table 3. below is showing a short list of global HVDC projects with relevant details [7].

Table 3. Some Worldwide HVDC Projects

Country	Project Name	Year	Type of Converter	Specifications
China	Zhundong – Sichuan	2015(Planned)	LCC	10000 MW, +-1100 kV, 2600 km
China	Gansu-Hunan	2015(Planned)	LCC	8000 MW, +-800 kV, 2490 km
China	Northern Hami-Chongqing	2015(Planned)	LCC	8000 MW, +-800 kV, 2223 km
China	Southern Hami-Zhengzhou	2015 (Ongoing)	LCC	8000 MW, +-800 kV, 2200 km
China	Zoushan multi-terminal	2014 (Ongoing)	VSC	1000 MW, +-200 kV, 141 km Subsea cable
China	Xiamen Island Infeed	2014 (Planned)	VSC	1000 MW, +-320 kV, 10 km Subsea cable
Norway	Skagerrak 4	2014	VSC	700 MW, +-500 kV, 244 km
France	Inelfe	2013	VSC	1000 MW, ±320 kV, 65 km
Brazil	Rio – Madeira	2013	LCC	3300 MW, +-600 kV, 2375 km
Brazil	Rio – Madeira	2012	LCC	800 MW, 100 kV, back to back
UK	EWIC	2012	VSC	500 MW, +-200 kV, 261 km
China	Jinping-Sunan	2012 (Commissioned)	LCC	7200 MW, +-800 kV, 2090 km
China	Xiangjiaba-Shanghai	2010 (Commissioned)	LCC	6400 MW, +-800 kV, 1980 km
In between UK & Netherlands	UK - Netherlands	2011	LCC	1000 MW, +-400 kV, 260 km
USA	Transbay	2010	VSC	400 MW, +-200 kV,85 km
Namibia	Caprivi link	2010	VSC	350 MW, +-350 kV, 951 km

From the given table, it is evident that the advancement and adoption of HVDC systems all over the world are tremendously increasing day by day.

7. Conclusion

HVDC systems have gained great popularity in recent years due to their certain benefits in contrary with HVAC systems. Transfer of bulk power over longer distances is more feasible and economical when HVDC systems are under consideration. A great many research, improvement and development work is on going with respect to HVDC converters connections and topologies. Two main converter topologies are LCC and VSC in which LCC is more confirmed for its well established technology, efficiency and fault handling capability. Research is carried out in VSC based MMC systems which have the advantages of lesser harmonics, increased efficiency, reduced footprint because of reduction of AC side filters and bulky DC link capacitors, flexible control of active and reactive powers, use of multi-terminals, and integration of renewable power via cables with existing grid. Due to all these benefits, the MMC based HVDC systems have proven to be the most suitable topology for future HVDC applications.

8. References

[1.] S. Shah, R. Hassan, and S. Jian, "HVDC transmission system architectures and control - A review," in Control and Modeling for Power Electronics, 2013 IEEE 14th Workshop on, 2013, pp. 1-8.
[2.] N. M. Kirby, "HVDC system solutions," in Transmission and Distribution Conference and Exposition T&D, IEEE PES, 2012, pp. 1-3.
[3.] M. P. Bahrman, "HVDC transmission overview," in Transmission and Distribution Conference and Exposition, 2008; IEEE/PES, 2008, pp. 1-7.
[4.] M. H. Okba, M. H. Saied, M. Z. Mostafa, and T. M. Abdel-Moneim, "High voltage direct current transmission - A review, part I," in Energytech, 2012 IEEE, 2012, pp. 1-7.
[5.] H. K. Müller, S. S. Torbaghan, M. Gibescu, M. M. Roggenkamp, and M. A. M. M. van der Meijden, "The need for a common standard for voltage levels of HVDC VSC technology," Energy Policy, vol. 63, pp. 244-251, 12// 2013.
[6.] H. Jingbo, L. Mingjie, Y. Jun, C. Qing, X. Tao, and Y. Zhao, "Research on dynamic characteristics and countermeasures of AC-DC hybrid power system with large scale HVDC transmission," in Power System Technology (POWERCON), 2014 International Conference on, 2014, pp. 799-805.
[7.] Anonymous, "HVDC Project Listing," Prepared for HVDC and Flexible AC transmission subcommittee of the IEEE Transmission and Distribution Committee, March 2012.
[8.] Y. Jiang-Hafner, H. Duchen, M. Karlsson, L. Ronstrom, and B. Abrahamsson, "HVDC with voltage source converters-a powerful standby black start facility," in Transmission and Distribution Conference and Exposition, 2008; D. IEEE/PES, 2008, pp. 1-9.
[9.] J. Luo, J. Yao, D. Wu, C. Wen, S. Yang, and J. Liu, "Application research on VSC-HVDC in urban power network," in Power Engineering and Automation Conference (PEAM), 2011 IEEE, 2011, pp. 115-119.
[10.] E. Najafi and A. H. M. Yatim, "Design and implementation of a new multilevel inverter topology," Industrial Electronics, IEEE Transactions on, vol. 59, pp. 4148-4154, 2012.
[11.] Y. Zhang, G. P. Adam, T. C. Lim, S. J. Finney, and B. W. Williams, "Analysis of modular multilevel converter capacitor voltage balancing based on phase voltage redundant states," Iet Power Electronics, vol. 5, pp. 726-738, 2012.
[12.] M. Glinka and R. Marquardt, "A new AC/AC multilevel converter family," Industrial Electronics, IEEE Transactions on, vol. 52, pp. 662-669, 2005.
[13.] A. Lesnicar and R. Marquardt, "An innovative modular multilevel converter topology suitable for a wide power range," in Power Tech Conference Proceedings, 2003, p. 6.
[14.] M H. Rashid, “Power Electronics Devices, Circuits and Applications”, Pearson Education, 4th Ed. 2014
[15.] E. Kontos, R. T. Pinto, S. Rodrigues, and P. Bauer, "Impact of HVDC Transmission System Topology on Multiterminal DC Network Faults," Power Delivery, IEEE Transactions on, vol. 30, pp. 844-852, 2015.
[16.] Artjoms Timofejevs and Daniel Gamboa, “Control of MMC in HVDC Applications”, Master Thesis, Department of Energy Technology, Denmark, 2013
[17.] C. C. Davidson and D. Trainer, "Innovative concepts for hybrid multilevel converters for HVDC power transmission," in AC and DC Power Transmission. 9th IET International Conference on, 2010, pp. 1-5.
[18.] R. Marquardt, "Modular Multilevel Converter: An universal concept for HVDC-Networks and extended DC-Bus-applications," in Power Electronics Conference (IPEC), 2010 International, 2010, pp. 502-507.
[19.] H. Abu-Rub, J. Holtz, J. Rodriguez, and G. Baoming, "Medium-voltage multilevel converters—State of the art, challenges, and requirements in industrial applications," Industrial Electronics, IEEE Transactions on, vol. 57, pp. 2581-2596, 2010.
[20.] G. P. Adam, S. J. Finney, A. M. Massoud, and B. W. Williams, "Capacitor balance issues of the diode-clamped multilevel inverter operated in a quasi-two-state mode," Ieee Transactions on Industrial Electronics, vol. 55, pp. 3088-3099, Aug 2008.
[21.] E. Najafi and A. H. M. Yatim, "Design and implementation of a new multilevel inverter topology," Industrial Electronics, IEEE Transactions on, vol. 59, pp. 4148-4154, 2012.