Multilevel High Power Converters for Reversible Power Flow between Utilities and Power Pool Transmission Corridor

A. F Nnachi, A.A Jimoh, *member IEEE* and D.V Nicolae, *member IEEE*

***Abstract*— Multilevel converters have emerged as the state of the art high power conversion for applications in reversible power flow. Electric power could be tapped from or injected to the grid regardless of the discrepancies in voltage levels, frequency, phase number and different modes of operation of the grid and the system. This paper presents an overview of different topologies of multilevel converters and modulation strategies with a verification of back-to-back neutral point converter for bi-directional power flow application.**

***Index Terms*—Multilevel Converter, Power Conversion, Power Systems, Power Semiconductor switches.**

I. INTRODUCTION

The modular nature of multilevel converters has made it suitable for high power applications. The emergence of high-power switching semiconductors such as insulated-gate bipolar transistors (IGBTs), has enabled Multilevel converters considered today as the most suitable power converters for high voltage capability and high power quality demanding applications. Voltage operation above classic semiconductor limits, lower common mode voltages, low harmonic distortion, low EMI, near sinusoidal outputs together with small *dv/dt*'s, are some of the characteristics that have made this power converters popular for industry and research [1-2].

Numerous topologies have been introduced and widely studied for conversion in both directions: from ac to dc voltage and dc to ac voltage, and most of the researches has been focused on high power AC-DC and DC-AC applications. However, some literatures discussed about multilevel DC-DC converters and the voltage choppers [2].

This paper presents an overview of different topologies of multilevel converters and modulation strategies with a verification of back-to-back Neutral point converter for bi-directional power flow. The specific application of interest here for bi-directional power flow is when a utility connected to either a transnational or intercontinental power pool has to inject excess power into the pool or tap deficit power from the pool.

Manuscript submitted March 5, 2007.

F. A. Nnachi, A.A. Jimoh (corresponding author: Telephone/Fax +27123824964, email: jimohaa@tut.ac.za), and D.V. Nioclae are with the Graduate School of Electrical and Electronic Engineering, Tshwane University of Technology, P.O.Box X680, Pretoria 0001, South Africa.

II. MULTILEVEL CONVERTER TOPOLOGIES

According to Richard [4] the oldest reference to multilevel power conversion is often stated to start with the paper presented by Nabae et al.[5] The waveforms of practical inverters are non-sinusoidal and contain certain harmonics and this may be acceptable for low and medium power applications but for high power applications, low distorted sinusoidal waveforms are required [14]. Hence certain challenges of multilevel converters on high power applications have evolved which are:

- Developing a topology that can achieve a sinusoidal output with low switching frequency (lower losses) of individual semiconductors.
- Appropriate series or shunt connection of these semiconductors to achieve higher current and voltage rating
- Elimination of transformer to increase efficiency and cost
- Modular and flexible design allowing easy expansion reconfiguration if possible automatic [6].

Generally multilevel topologies can be divided into two groups: *Topology-level multilevel converter and hybrid multilevel converter* [7].

III. TOPOLOGY-LEVEL MULTILEVEL CONVERTER

This replaces the two-level switch structure with a multilevel switch topology within an otherwise conventional converter [8]. These include:

- Diode-Clamped Multi-level converter
- Flying-Capacitor Multilevel converter
- Cascaded converters with separate DC sources
- Generalized multilevel converter

A. The Diode-Clamped Multilevel Converter

Diode-clamped multilevel converters DCMLC consists of m-1 capacitors in series on the DC bus to divide up the voltage into a set of voltage levels. This produces m levels on the phase output voltage.

The three-level diode-clamped inverter called *neutral point clamped* (NPC) was first introduced by A. Nabae, I. Takahashi and H. Akagi [5] in 1980 and published in 1981 and has received reasonable consensus for high power applications. It consists of two capacitor voltages in series and uses the central tap as the neutral so termed Neutral point clamped. With this nature of NPC three-level converter the voltage stress on its power switching devices is half that for the conventional two level inverter [9], [10].

According to [10] each phase leg of the three-level converter has two pairs of switching devices in series and the centre of each device pair is clamped to the neutral through clamping diodes as shown in figure 1. The wave form obtained from this three level converter is a quasi-square wave output [11].

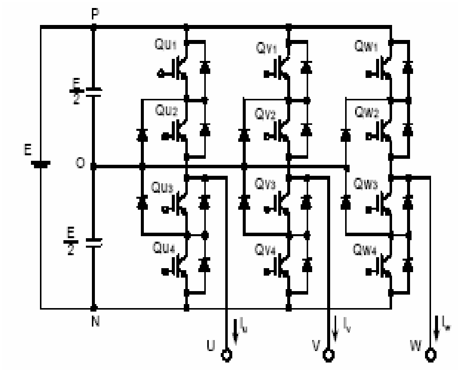


Figure 1 A Neutral Point Diode Clamped three-level Voltage Source Converter topology.

Features of neutral point clamped (NPC) three-level converter
1. Lower line-to-line and common-mode voltage steps
2. More frequent voltage step in one carrier cycle
3. Lower ripple component in the output current for the same carrier frequency

One major disadvantage of the NPC approach is the unequal load distribution among the switches and capacitors, especially for higher level converters [8].

Despite these many difficulties, the diode clamped converter, particularly in its three-level form, has received much attention and use. As a three level converter, it is relatively simple, and can remove the need for a transformer where one would otherwise exist.

More recently several higher level topologies, odd and even levels has been investigated, 4 level and 5 level converters were presented in [13]. With an even number of voltage levels, the neutral point is terminated hence the term multiple point clamped (MPC) is sometimes applied [8],[12],[13]..

B Multilevel Flying Capacitor Inverters

This involves series connection of capacitor clamped switching cells. When compared to diode clamped inverter, this topology has several unique and attractive features such as eliminating the need for added clamping diodes and having switching redundancy which can be used to balance the flying capacitors [12].

Basic Principle:

Each phase leg has an identical structure, and assuming the capacitors has the same voltage rating E, the series connection of the capacitors in fig.2 is to indicate the voltage level between the clamping points. All the phase leg share the same dc link $C_1 - C_4$. The phase voltage of an N-level converter has N levels including the reference level, and the line voltage has (2N – 1) levels whereas the dc bus needs (N – 1) capacitors. Moreover, it requires a total of (N – 1) x (N – 2) / 2 auxiliary capacitors per phase leg.

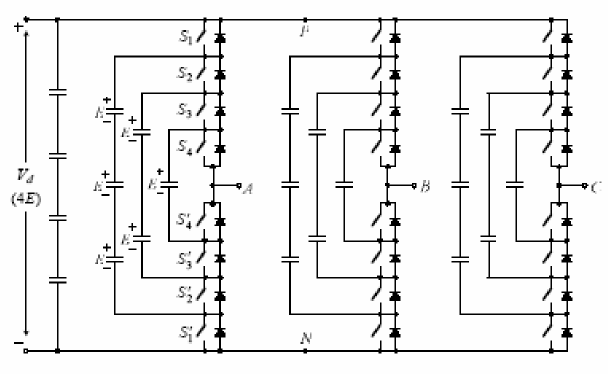


Figure 2 Five Level Flying capacitor Inverter

Voltage Synthesized in a five level capacitor-clamped converter has more flexibility than a diode-clamped converter.

From the fig.2 the voltage of the 5-level phase-leg a output with respect to the negative dc rail, V_{ao}, can be synthesized by different combination of the voltage levels with their corresponding switching states as fully explained in [10].

Features of Multilevel Flying Capacitor Inverters

Added clamping diodes are not needed, Low harmonic distortion, hence avoid the need of filters, their large amount of storage Capacitors can provide capabilities during power outages. They provide switch combination redundancy for balancing different voltage levels, both real and reactive power flow can be controlled [14], [15].

Drawbacks
- They require large number of storage capacitors [15].
- Inverter control can be complicated, and the switching frequency and switching losses are high for real power transmission. [14], [15]
- Complex pre-charging circuits [14], [15].

C. Cascaded Multilevel Converters (CMC) With Separate DC Sources.

Siriroj [7] stated that the basic concept of the CMC has existed for more than two decades but was not fully realized until two researchers, Lai and Peng, patented it and presented its various advantages in 1997. This new converter can avoid extra clamping diode or voltage balancing capacitors [10].

It consists of a series of H-bridge (single-phase, full-bridge) inverter units, and each bridge inverter can generate three level outputs: $+V_{dc}$, 0 , and $–V_{dc}$.

The phase output voltage is synthesized by the sum of *N* H-bridge inverter outputs.

For example, in the fig. 3 is a phase leg of a nine-level cascaded inverter with four separate DC sources, the phase output $V_{an} = V_1 + V_2 + V_3 + V_4$ with each having 3-levels. The resulting output ac voltage swings from $-4V_{dc}$ to $+4V_{dc}$ with nine levels and the staircase form is nearly sinusoidal, even without filtering.

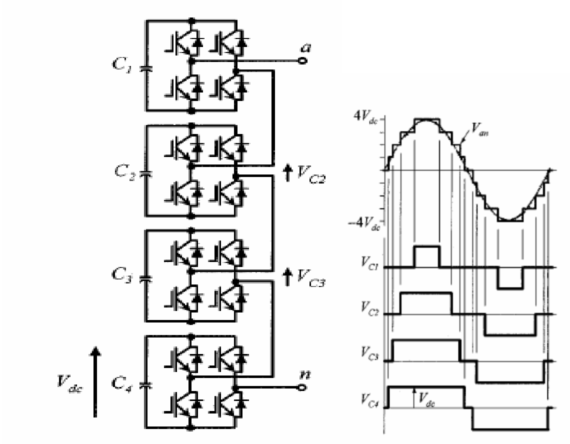


Figure 3. Nine level cascaded inverter circuit topology and its associated waveform [11].

With the phase current, i_a, leading or lagging the phase voltage v_{an} by 90^o, the average charge to each dc capacitor is equal to zero over one cycle. Therefore all series dc capacitor voltages can be balanced [10].

A three phase converter can be constructed by connecting three of the above single phase in star or Delta form.

These topology finds its application in FACTs/UPFC Applications, Active power filter, Sag Compensation, Static Var Compensation (improve power factor) and interface with distributed Generation Resources such as photovoltaic, Fuel cells, wind turbines and energy storage [27].

D. Generalized Multilevel Converter

The existing multilevel inverters such as diode-clamped and capacitor-clamped multilevel inverters can be derived from the generalized inverter topology. Moreover, the generalized multilevel inverter topology provides a true multilevel structure that can balance each DC voltage level automatically without any assistance from other circuits, thus in principle providing a complete and true multilevel topology that embraces the existing multilevel inverters. From this generalized multilevel inverter topology, several new multilevel inverter structures can be derived.

Three structures of generalized multilevel inverter topology are *P2, P3D and P3C* and are made elaborate in [3]. A Generalized P2 multilevel inverter as shown in fig.4 is a horizontal pyramid of two-level phase legs hence called P2 multilevel inverter. Any level can be cut from this generalized structure.

IV. HYBRID MULTILEVEL CONVERTERS

Hybrid multilevel converters are fundamentally a combination of two topologies in the first category, or one of the first categories with additional magnetic circuits [17].

They can be sub-divided into two: Multi-pulse based on two-level and three-level converters and mixed-level hybrid cell converters [7].

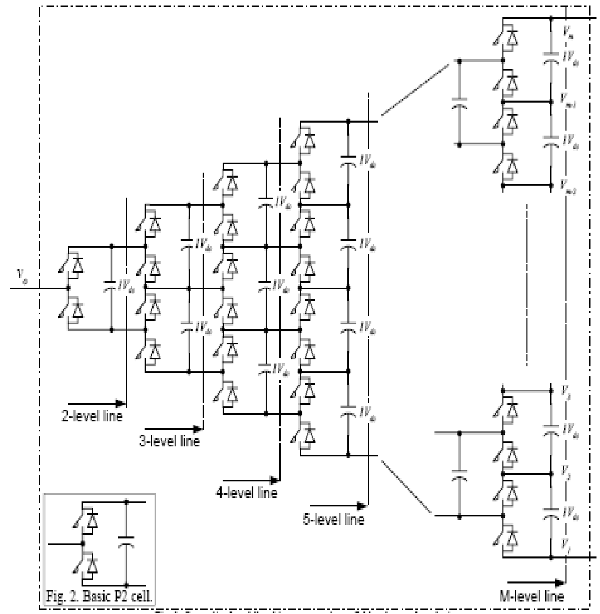


Figure 4. Generalized multilevel inverter topology. (M-level, one phase leg).The operating principles are fully explained in [3].

A. Multi-pulse based on two-level and three-level converters

This relies on Series or parallel connection of the outputs of a number of conventional two-level converters to generate a resultant multilevel output waveform [8]. Some examples are: Transformer/inductor summed Multiple Bridge Converter, Parallel phase inverter, mixed-level hybrid cell converters that are created through parallel and series (cascade) connection of the fundamental topologies and have been seen to have immense advantages [7], [12].

V. MULTILEVEL CONVERTER MODULATION AND CONTROL METHODS

Many Multilevel topologies have evolved and presented by series of researchers with their corresponding modulation schemes being developed. These modulation techniques can be classified as *a.* Multiple carrier Pulse Width Modulation (PWM), ***b.*** Space Vector Modulation (SVM), c. Selective Harmonic Elimination, *d.* Space Vector Control, *e.* Mixed frequency modulations [1].

***A.** Multiple Carrier Pulse Width Modulation (PWM).*

This classic carrier-based sinusoidal PWM uses a *phase shifting or level shifted* techniques to reduce the harmonic in the load hence, are very popular in industrial applications.

The level shifted (LS) are: (*i*) Phase Disposition (PD), (*ii)* Phase Opposition Disposition (POD), (*iii)* Alternative Phase Opposition Disposition (APOD). They are well known for three-level NPC converter and can be applied also to Flying Capacitors but the distinction between POD and PD is only relevant to for the three phase motor converter because the output voltage of a single-phase line converter is in both cases identical.

iv. Phase Shifted (PS) carrier PWM [1], [11], [18].

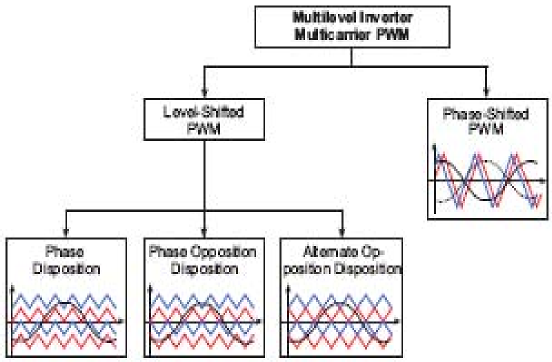


Figure 5 Classification of Multiple PWM [1].

B Space Vector Modulation (SVM):

This modulation is based on vector selection in the d-q stationary reference frame [12]. In NPC converters, not all switch states are usable as some do not guarantee a continuous path for load current to flow. Should the modulator produce these states, they must be re-mapped to the equivalent valid state. For this reason, space vector modulators with this knowledge of allowed states are usually used. Further, of these allowed states, different switch states slew the voltages on the capacitors in different directions. This fact should be used to control the capacitor voltages [8]. This SVM has been extended for the multilevel inverters [1] and are being made suitable for high power application due to the following attractive features: good utilization of dc-link voltage, low current ripple, and relatively easy hardware implementation by a digital signal processor (DSP) [11].

C. Selective Harmonic Elimination (SHE)

Selective Harmonic Elimination (SHE) is an off-line (pre-calculated) non carrier based PWM technique which was proposed in an early paper by Patel and Hoft [8].

Theoretically, Selective Harmonic Elimination PWM-based method provides the highest quality output among all the PWM methods and together with Selective Harmonic Minimization. [8], [28].

D Space Vector Control

This recently introduced unique voltage source modulation is fundamentally different than sine-triangle or SVM [12], because it works with low switching frequencies and does not generate the mean value of the desired load voltage in every switching interval [11]. The premise of this scheme is that the inverter can be switched to nearest the commanded voltage vector and held there until the next cycle of the DSP as a result computing switching times and schedule timing in the Programmable logic device is not needed. Although this method is simple to implement, it is most useful on inverters with a relatively high number of voltage vectors and can produce a lower THD than the SVM method [12].

E. Mixed Frequency Hybrid Modulation (HM)

These have been designed specially for asymmetric and hybrid topologies [1].

VI. STATE OF THE ART HIGH-POWER SEMICONDUCTOR SWITCHING DEVICES

In the field of power electronic, semiconductor devices are used in energy control and conversion circuits and the power function (switching or protection) is achieved through use of data and signal processing circuits separated from the discrete power device. [20].

Some ideal requirements of power devices for use in converters are:

1. Adequate blocking voltage.
2. High turn off current and surge current capabilities.
3. Adequate isolation voltage withstands.
4. Reverse conducting and active switch in one module.
5. Low conduction and switching losses.
6. Suitable for parallel and series operation
7. Fast switching; tolerance to *dV/dt* and *dI/dt*.
8. Good thermal performance
9. Ease of protection and control
10. Fail-safe' failure mode [20].

More and more powerful converters implies an increase of the current and the voltage of power electronics switches, and the major contenders in the device arena are integrated-gate-commutated thyristor (IGCT), IGBT, emitter turn-off (ETO) thyristor [11] and GTO. Moreover, new components controllable in open and closed states (GTO and IGBT) have led to the conception of new and fast converters for high power applications [21], [22].

According to Bernet et al [23], these High- Voltage IGBTs (HV-IGBTs) which are available as 3.3kV, 4.5kV and 6.5kV as well Integrated Gate Commutated Thyristors (IGCTs) with blocking voltages of 4.5kV, 5.5kV and 6kV are generally used as power semiconductors in new products and systems.

VII. BACK-TO-BACK MULTILEVEL CONVERTER APPLICATION IN POWER SYSTEM INTEGRATION

With the advancement in high voltage capability IGBTs, Multilevel converters present many advantages in high-power applications. For instance, in power system integration several isolated systems are integrated into a larger one and necessary intermediate integration steps are the harmonization of technical standards such as voltage levels, frequency, reliability standards over the region [26]. Fig. 7 shows a proposed scheme to achieve this. Here this back-to-back multilevel converter is capable of coupling electricity of different networks, which are either of different frequency, or of the same nominal frequency but no fixed phase relationship, or of different frequency, phase number and modes of operation [28]. This scheme is presently being researched at our laboratory and will be reported in future work.

VIII. BACK-TO-BACK MULTILEVEL CONVERTER APPLICATION IN REVERSIBLE POWER FLOW

The idea of transnational or intercontinental power pool is an obvious option to the solution of electricity power supply for some regions. In a power pool, several utilities are linked together through HVAC or HVDC transmission corridors that transverse the continent or intercontinental regions. A utility so connected to a pool often wants the opportunity to inject excess power into the pool or tap deficit power from the pool.

To achieve this, a modular back-to-back multilevel converter can be used to connect different large AC systems to HVAC transmission corridor. Here AC power is rectified and high voltage DC power is converted back to AC using back-to-back multilevel converter.

Taking as an example in the Southern African Power Pool (SAPP), a project is being contemplated to link the national electricity networks of various nations in the Southern African sub-region along the western axis from the Democratic republic of Congo (DRC) down through to Cape Town in South Africa. Supposing the national electricity network of each nation is to be connected to the ensuing transmission corridor. To enable bidirectional power flow (injection and tapping) the scheme of Fig. 8 is proposed for two of such connections of national network to the corridor. The link is assumed to be an HVAC transmission corridor, while the national electricity networks (say Eskom, South Africa, or BPC of Botswana, or any other) are indicated as utility 1 and utility 2. The back-to-back multilevel converter not only allows bidirectional power flow, but also avoids the transfer of technical disturbances from utilities to the corridor and vice versa.

IX. SIMULATION RESULT

As shown in figure 8, a modular back-to-back multilevel converter linking the utility 1 and the transmission corridor is modeled and simulated in simulink environment. This comprises AC/DC connected back-to-back with DC/AC three-level converter and both being controlled by level shifted PWM with 2 KHz carrier frequency as shown in fig 9.

An hypothetical utility of say 220KV, 50Hz is connected to the 760KV 60Hz transmission corridor via the back-to-back converter. The converter allows power to be transmitted from the 50Hz system to the 60Hz transmission corridor and vice versa.

The filters on each side of the converter help to reduce current and voltage perturbations, and to generate reactive power so that the system will not be unnecessarily loaded with reactive current for the converter. It has been supposed that the neutral point of converters is ideally balanced.

Figure 10 and 11 shows the output voltage waveform of power injection to the corridor from the utility and power tapping by the utility with their respective DC-link voltages.

IX. CONCLUSION

With the advancement in high voltage capability IGBTs, Multilevel converters present many advantages in high-power applications such as capacitor voltage balance in DC-link, minimization of harmonic distortion, decrease of switching losses, etc. This paper presents a brief summary of multilevel converters, different modulation techniques and state of the art of switching devices and its application in reversible power flow.

In a power pool, several utilities are linked together through HVAC or HVDC transmission corridors that transverse the continent or intercontinental regions. A utility so connected to a pool often wants the opportunity to inject excess power into the pool or tap deficit power from the pool. Sequel to this, a modular back-to-back diode-clamped multilevel converter connecting such utility to the transmission corridor for bi-directional power flow is simulated. On-going further work not included in this paper includes calculation and modeling of DC bus capacitor based on different levels of the converter, regulation of DC-link voltage etc.

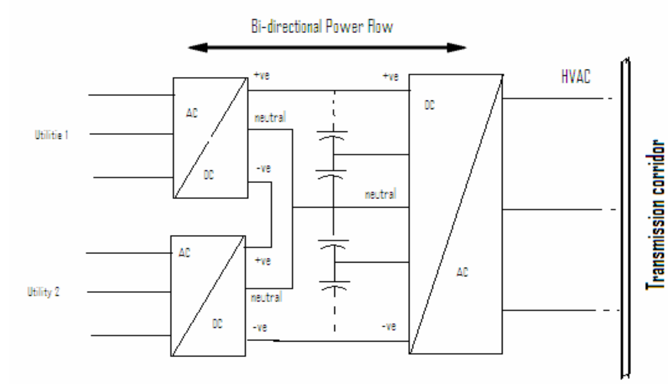


Figure 7 Utilities integrated together through back-to-back Multilevel converter to the transmission corridor.

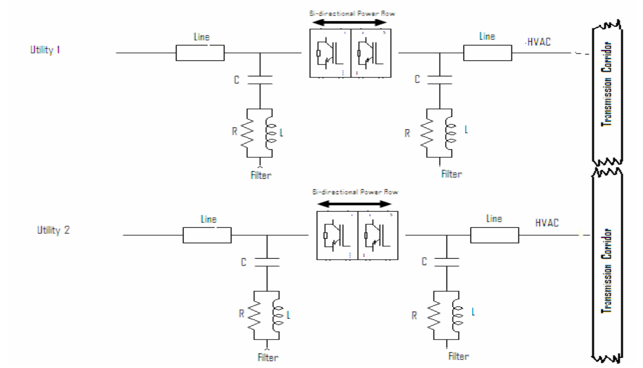


Figure 8 One line diagram of Utilities connected separately to Transmission corridor through back-to-back multilevel converters

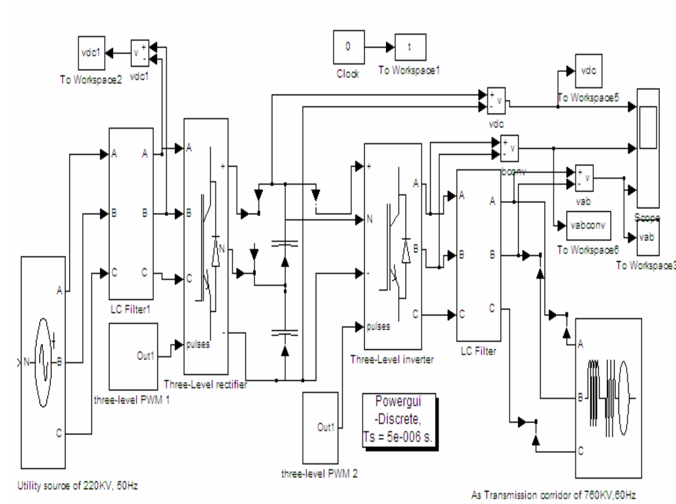
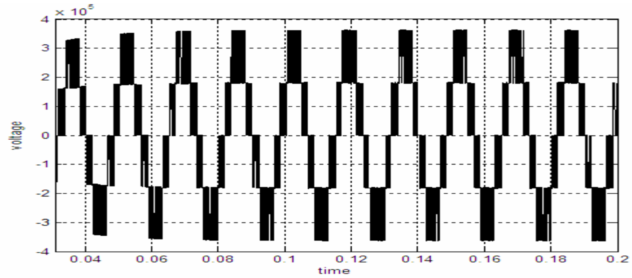
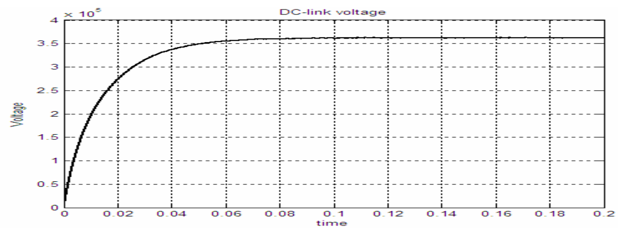


Figure 9 Simulation Model of Back-to-back three-level converter

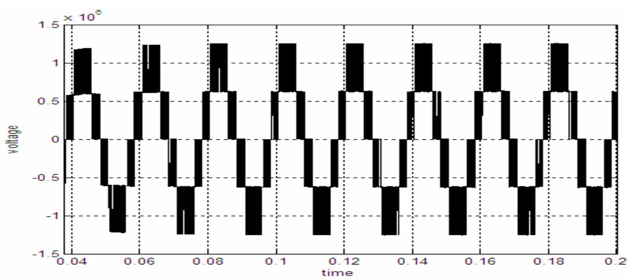


(a)

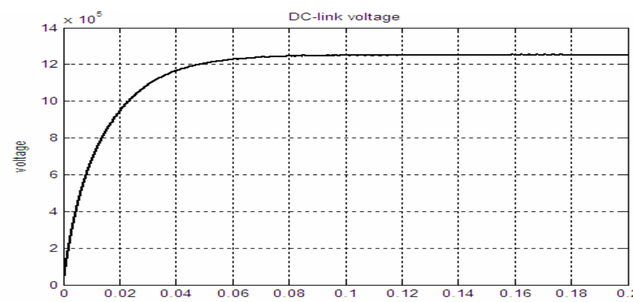


(b)

Figure 10 (a).Output line voltage (b) DC-link voltage (during power injection from utility supply of 220KV, 50Hz to the Corridor).



(a)



(b)

Figure 11 (a). Output line voltage (b) DC-link voltage (during power tapping by the utility from 760KV, 60Hz transmission corridor.

REFERENCES

.

[1] S. Kouro, J. Rodr´ıguez, J. Pontt and M. Angulo. 2005."Multilevel Inverter Modulation with DC-Link Disturbance Compensation." E-mail samir.kouro@ieee.org pp 708 – 714. 2005 IEEE

[2] F. Zhang, F. Z. Peng and Z. Qian, "Study of the Multilevel Converters in DC-DC Applications," 35th Annual IEEE Power Electronics Specialists Conference, Aachen Germany, 2004. pp.1702 – 1706.

[3] F. Z. Peng, "A Generalized Multilevel Inverter Topology with Self Voltage Balancing". 2000. Oak Ridge National Laboratory.

[4] L. Richard, "Multilevel Power Electronic Converter for Electrical Motor drives," Ph D thesis, Norwegian University of science and Technology, 2005.

[5] A. Nabai, I. Takahashi and H. Akagi, "A new neutral-point clamped PWM Inverter," IEEE trans. Ind. Application, vol. 1A – 17, pp. 518 – 523, Sept./Oct.1981.

[6] J. Géza, "Power Electronics: An Unavoidable Interface Between energy Sources and Electric Loads". McGill University Montreal, Canada Oct. 2001

[7] S. Siriroj, "The Modeling and Control of a Cascaded-Multilevel Converter-Based STATCOM," Ph D thesis, Virginia Polytechnic Institute and State University Blacksburg, Virginia United State of America 2004.

[8] R. W Geoffrey, "Modulation and Control of Multilevel converters". PhD Thesis, University of Queensland, QUEENSLAND, 1999.

[9] H. Krug, T. Kume and M. Swamy "Neutral-Point Clamped Three-Level General Purpose Inverter- Features, Benefits and Applications,"35th Annual IEEE Power Electronics Specialists Conference Aachen, Germany, 2004. pp. 323 – 328

[10] J. S. Lai, and F. Z. Peng , "Multilevel converters – a new breed of power converters," IEEE Transactions on Industry Applications, Vol. 32, No. 3, May/June 1996, pp. 509 – 517.

[11] J. R. Rodriguez, J. W. Dixon, J. R. Espinoza, J. Pontt, and P. Lezana, "PWM regenerative rectifiers: state of the art" Feb. 2005 Volume: 52, Issue: 1

[12] K. Corzine, 2005 "Operation and design of Multilevel converters," University of Missouri-Rolla.

[13] W. Bin, "High-Power Converters and AC Drives", Wiley - IEEE Press, 2006

[14] M. Rashiid, "Power Electronics, circuit devices and applications," 2004 Second Edition.

[15] S. B. Burlington "Distributed Energy Resources Integration Research Program," Power Electronics Research Assessment; Prepared By: Navigant Consulting, Inc., MA Contract No. 500-02-019 Prepared For: California Energy Commission Public Interest Energy Research Program. December 2005 Source: http://www.eere.energy.gov/de/pdfs/der_conf_01/jm_foster.pdf

[16] Rech C., Pinheiro J. R. 2004. Line Current Harmonics Reduction in Hybrid Multilevel Converters Using Phase-Shifting Transformers, 2004 35th Annual IEEE Power Electronics Specialists Conference, Aachen Germany, pp. 2565 – 2571.

[17] S. Dieckerhoff, S. Bernet and Dietmar "Power Loss-Oriented Evaluation of High Voltage IGBTs and Multilevel Converters in Transformerless Traction Applications. IEEE Transaction on power electyronics, vol. 20, No. 6; 2005, pp 1328 – 1336.

[18] L. Klingbeil, W. Kalkner, C. Heinrich "Fast acting solid-state circuit breaker using state-of-the-art power electronic devices". EPE 2001 – Graz, pp 1 – 5.

[19] M. Kazmierkowski "High Power Converters and AC Drives" Industrial Electronics Newsletter. 2006.

[20] A. Talha, E. M. Berkouk, B. Francois, M. Boucherit "Modeling and control of a power electronic Cascade for the Multi DC Bus supply of a seven level NPC Voltage source inverter," EPE-PEMC 2006, Portoroz, Slovenia. Pp 200 – 205.

[21] D. Krug, S. Bernet and S. Dieckerhoff , 2003, "Comparison of State-of-the-Art Voltage Source Converter Topologies for Medium Voltage Applications" pp. 168 – 175.

[22] Kollensperger P., Bloh J. V. Schroder S. De Doncker R. W. 2004. A GCT-Driver Optimized for soft-switching High-Power Inverters with short circuit protection. 35th Annual IEEE power electronics specialists conference, Aachen, Germany. Pp 105 – 111.

[23] Engineering News at NC State. 1998 pp. 1-3. http:www.engr.ncsu.edu/news/innerviews/iv.arc.1998.spring.html

[24] R. Bayerer, 1998, "IGBT module technology: state of the art and future evolutions", EUPEC GmbH + Co. KG, D-59581 Warstein, Germany

[25] L. Li, D. Czarkowski, Y. Liu, and P. Pillay, "Multilevel Selective Harmonic Elimination PWM Technique in Series-Connected Voltage Inverters" IEEE Transactions on Industry Applications, Vol. 36, No. 1, January/February 2000

[26] V. Francois, T. Laurent, "Achieving the integration of regional electric power systems," 19th world Energy Congress, Sydney, Australia September 5-9, 2004.

[27] L. M. Tolbert., "High Power Electronics for a sustainable 21st Century". University of Tennessee. December 1, 2000. Page 1-26

[28] Wikipedia http://en.wikipedia.org/wiki/High-voltage_direct_current

Copyright Information