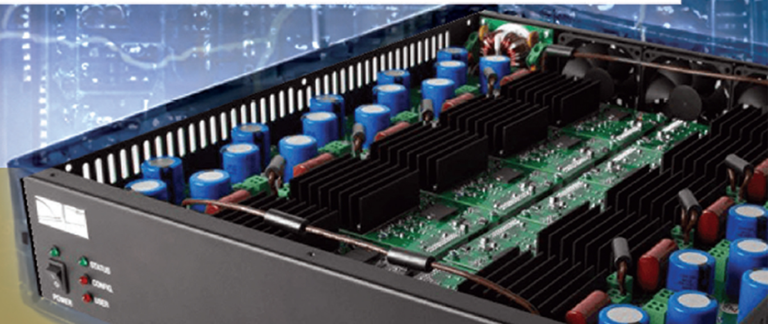
MULTI-LEVEL CONVERTERS



Edited By
Salman Ahmad,
Farhad Ilahi Bakhsh,
and P. Sanjeevikumar

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Contents

List of Contributors

Suresh Lakhimsetty, Department of Electrical Engineering, Sardar Vallabhbhai National Institute of Technology Surat, Surat, India. Email: suresh@eed.svnit.ac.in

Hareesh Myneni, Department of Electrical Engineering, National Institute of Technology Srinagar, Srinagar, India. Email: hari247.sol@gmail.com

Obbu Chandra Sekhar, Department of Electrical Engineering, National Institute of Technology Delhi, New Delhi, India. Email: obbuchandra@nitsri.net

Hasan Iqbal, Department of Electrical Engineering, Aligarh Muslim University, Aligarh, UP, India and Department of Electrical and Computer Engineering, Florida International University, Miami, FL, USA. Email:hiqba003@fiu.edu

Mohammad Tayyab, Department of Electrical Engineering, Aligarh Muslim University, Aligarh, UP, India and Electrical and Computer Engineering Department, Texas A & M University at Qatar, Doha, Qatar. Email: mtayyab1@myamu.ac.in

Arif Iqbal, Department of Electrical Engineering, Rajkiya Engineering College, Ambedkar Nagar (U.P.), India. E-mail: arif.iqbal.in@gmail.com

S. P. Singh, Indian Institute of Technology Roorkee, India. Email: spseefee@iitr.ac.in

Mohammad Ali, K.A. CARE Energy Research & Innovation Center, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia, Email: mohammad.ali@kfupm.edu.sa

Muhammad Khalid, Interdisciplinary Research Center for Renewable Energy & Power Systems, King Fahd University of Petroleum and Minerals, Dhahran, 31261, Saudi Arabia and Electrical Engineering Department, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia. Email: mkhalid@kfupm.edu.sa

Dhananjay Kumar, Dept. of Electrical Engineering, Government Engineering College, Siwan, Bihar, India. Email: dhananjayk00@gmail.com

Shailesh Kumar Gupta, Department of Electrical & Electronics Engineering, IIMT Engineering College, Meerut (U.P.), India. Email: geniousshailesh@gmail.com

Omveer Singh, Department of Electrical Engineering, Gautam Buddha University, Greater Noida (U.P.), India. Email: omveers@gmail.com

Akhlaque Ahmad Khan, Department of Electrical Engineering, Integral University, Lucknow, UP, India. Email: akhlaque@iul.ac.in

Ahmad Faiz Minai, Department of Electrical Engineering, Integral University, Lucknow, UP, India. Email: fzminai@gmail.com

Qamar Alam, Department of Electrical Engineering, Integral University, Lucknow, UP, India. Email: qamar@iul.ac.in

Farhad Ilahi Bakhsh, National Institute of Technology, Srinagar, India. Email: farhad@nitsri.ac.in

Kasinath Jena, Dept. of Electrical and Electronic Engineering, Arka Jain University, Jamshedpur, India. Email: kasi.jena@gmail.com

Jitendra Kumar Tandekar, Dept. of Electrical Engineering, Samrat Ashok Technological Institute Vidisha, India. Email: jitendra.tandekar@gmail.com

Niraj Kumar Dewangan, Department of Mechatronics Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka, India. Email: nirajdewangan11@gmail.com

Vishal Rathore, Department of Electrical and Electronics Engineering, Bhopal Institute of Technology and Science, Bhopal, India. Email: vishalrathore01@gmail.com

Haroon Rehman, Department of Electrical Engineering, Aligarh Muslim University, Aligarh, UP, India. Email: hiqba003@fiu.edu

Adil Sarwar, Department of Electrical Engineering, Aligarh Muslim University, Aligarh, UP, India. Email: hiqba003@fiu.edu

Md Reyaz Hussan, Department of Electrical Engineering, Aligarh Muslim University, Aligarh, UP, India. Email: hiqba003@fiu.edu

Akhlaque Ahmad Khan, Department of Electrical Engineering, Integral University, Lucknow, UP, India. Email: akhlaque@iul.ac.in,

Ahmad Faiz Minai, Department of Electrical Engineering, Integral University, Lucknow, UP, India. Email: fzminai@gmail.com

Mohammed Aslam Husain, Department of Electrical Engineering, REC, Ambedkar Nagar, UP, India. Email: mahusain87@gmail.com

Mohammad Naseem, Department of Electrical Engineering, Integral University, Lucknow, UP, India. Email: mnansar@gmail.com

Aishwarya V., Department of Electrical & Electronics Engineering, APJ Abdul Kalam Technological University, Trivandrum, India. Email: aishwarya@tistcochin.edu.in

Zahid Afzal Thoker, Department of Electrical Engineering, National Institute of Technology, Srinagar, India. Email: thokerzahid_10phd17@nitsri.ac.in

Shameem Ahmad Lone, Department of Electrical Engineering, National Institute of Technology, Srinagar, India. Email: sadial_14@yahoo.com

Amit Ojha, Dept. Electrical Engineering, Maulana Azad National Institute of Technology, Bhopal (M.P.), India. Email: ojha.amit@gmail.com

Shailendra Jain, Dept. Electrical Engineering, Maulana Azad National Institute of Technology, Bhopal (M.P.), India. Email: sjain68@gmail.com

Zahoor Ahmad Ganie, Department of Electrical Engineering, Islamic University of Science and Technology, Kashmir, India. Email: zahoor.rifi@gmail.com

Abdul Hamid Bhat, Department of Electrical Engineering, National Institute of Technology Srinagar, India. Email: bhatdee@nitsri.net

Salman Ahmad, Department of Electrical Engineering, Islamic University of Science and Technology, Kashmir, India. Email: salmanahmad19@gmail.com

Javeed Bashir, Department of Electrical Engineering, Islamic University of Science and Technology, Kashmir, India and Indian Institute of Technology Roorkee, India. Email: javeedbashir001@gmail.com

Ahmed Sharique Anees, Department of Electrical Engineering, Islamic University of Science and Technology, Kashmir, India. Email: shariq.anees@islamicuniversity.edu.in

Faizan Fayaz Bhat, Department of Electrical Engineering, National Institute of Technology Srinagar, Hazratbal, Srinagar (J&K), India. Email: bfaizan999@gmail.com

Zahid Ahmad Tantry, Department of Electrical Engineering, National Institute of Technology Srinagar, Hazratbal, Srinagar (J&K), India. Email: zahidtantry969@gmail.com

Md Ibrahim, Department of Electrical Engineering, Integral University, Lucknow, India. Email: ibrahimalig3893@gmail.com

Tajamal Hayat Parray, Department of Electrical Engineering, National Institute of Technology, Hazratbal, Srinagar, Jammu and Kashmir, India. Email: tajamulhayat05@gmail.com

Mohammad Ali Abido, K.A.CARE Energy Research & Innovation Center at King Fahd University of Petroleum & Minerals (KFUPM), Saudi Arabia and Interdisciplinary Research Center for Sustainable Energy Systems, KFUPM, Dhahran, Saudi Arabia.

Preface

Multilevel converters have gained much attention in recent years for medium/high-voltage and high-power industrial and residential applications. The main advantages of a multilevel converter over two-level converters include less voltage stress on power semiconductors, low dv/dt, low common voltage, reduced electromagnetic interference, and low total harmonics distortion among others. Better output power quality is ensured with the increasing number of levels in the synthesized output voltage waveform. Several multilevel topologies have been reported in the literature, such as neutral point clamped (NPC), flying capacitor (FC), cascaded H-bridge (CHB), hybrid cascaded H-bridge, asymmetrical cascaded H-bridge, flying capacitor, modular multilevel converter (MMC), active neutral point clamped converter (ANPC), and packed U-cell-type converter, and various topologies based on reduced device count and reduced number of sources have also been proposed in the literature.

The multilevel converters have been commercialized in many standard and customized products such as mixers, blowers, pumps, compressors, conveyors, fans, crushers, rolling mills, extruders, grinding machines, solar photovoltaic systems, wind power conversion, traction and ship propulsion, electric vehicles, variable speed drives, static compensators (STATCOMS), high-voltage direct-current (HVDC) transmission, and hydro pump storage, to name a few. However, the multilevel converter, although a proven and enabling technology, still presents numerous challenges in topologies, modulation, and control and need-based applications. Since multilevel converters offer a wide range of possibilities, research and development in the area of multilevel converter topologies, modulation, and control and in various applications are still growing in depth and width. To further improve multilevel converters' energy efficiency, reliability, power density, and cost, many research groups across the world are working to broaden the application areas of multilevel converters and to make them more attractive and competitive compared to classic topologies. Multilevel converters represent a very important topic in modern power electronics, and many research groups are working on topologies, modulation techniques, and control strategies to improve the global behavior of the system.

This book, "*Multilevel Converters*", intended to provide a deep insight about multilevel converters' operation, modulation, and control strategies and the various applications of multilevel converters such as in variable speed drives, renewable energy generation, and power systems. The book will serve as a reference for academic researchers, university students, and practicing engineers who are working in the area of multilevel converters. This book contains 17 chapters on multilevel converter topologies, modulation, control, and applications and organized as detailed below.

Chapter 1 discusses the invention and applications of multilevel converters, which were created to overcome voltage limitations in semiconductor devices. The chapter's main objective is to comprehensively study multilevel inverters, including their advantages, drawbacks, and recent applications. The study begins with an examination of dual two-level inverter systems, highlighting their benefits, challenges, techniques for issue resolution, and various applications.

Chapter 2 highlights the historical development of multilevel inverters. It mentions the evolution of MLI configurations, including newer models with fewer switches that produce more voltage levels. The chapter emphasizes the industrial uses of MLI in on-grid renewable energy systems and discusses important MLI configurations such as flying capacitor MLI (FC-MLI), neutral point clamped (NPC) or diode clamped MLI (DC-MLI), and cascaded H-bridge MLI (CHB-MLI). Finally, it notes the attractiveness of multilevel technology for photovoltaic (PV) applications and provides an overview and classification of MLI topologies relevant to PV systems.

Chapter 3 provides a detailed explanation of both conventional and new multilevel converter topologies. It also covers various pulse width modulation techniques and discusses their applications in motor drives. To support the theoretical concepts, the chapter includes simulation and hardware results to validate the discussed findings.

Chapter 4 introduces a novel inverter modulation technique to generate 11 voltage levels at the inverter output. This modulation optimizes capacitor charging and discharging, reducing inrush current peaks significantly, improving reliability, and extending the inverter's lifespan, making it well-suited for solar PV applications even in challenging weather conditions. This innovative approach also reduces stress on switch voltage and current. To validate the effectiveness of this enhanced technology, comprehensive experiments are conducted using hardware-in-the-loop setups and simulation environments as well as rigorous testing in a laboratory prototype.

Chapter 5 discusses a four-level open-end winding induction motor (OEW-IM) drive controlled by a single inverter through space vector pulse width modulation (SVPWM). It employs two two-level voltage source inverters (VSIs) connected to each side of the OEW-IM. To achieve four-level inversion, the DC-link voltages of the dual-inverter system are maintained at a 2:1 ratio. The four-level OEW-IM drive faces two main challenges: 1) circulating zero sequence currents in the OEW-IM phase windings and 2) preventing overcharging of the lower DC-link voltage capacitor by the higher DC-link voltage capacitor. The latter issue is mitigated by providing independent DC power supplies to the dual-inverter system. The former challenge is addressed through a novel SVPWM scheme, which promises improved performance compared to existing SVPWM methods.

Chapter 6 discusses the use of field-oriented control (FOC) in induction motor drives, which is widely adopted for high-performance applications. FOC enhances motor drive performance by independently controlling the torque and field flux components, making the motor operation similar to a separately excited DC motor. This chapter specifically introduces a diode-clamped multi-level inverter for the closed-loop control of an induction motor drive using FOC. It covers the operation of the induction motor in both motoring and regenerating modes, powered by a diode-clamped three-phase three-level inverter circuit. The entire drive system is developed and analyzed using MATLAB/Simulink.

Chapter 7 focuses on the development of innovative topological designs for multilevel inverters that offer several key advantages, including a low component count, high voltage gain, cost-effectiveness, and minimized voltage stress on power switches. The study introduced five-level single-cell multilevel inverter (SCMLI) topologies designed to efficiently generate multilevel voltage waveforms, particularly suitable for medium- and high-power applications. Experimental testing has been conducted to validate the practical feasibility of each proposed topology. The results highlight several significant advantages, including reduced voltage stress, high voltage gain, the ability to operate at various power factors, reduced switching components, and high overall efficiency. The suggested topologies underwent both simulation in the MATLAB/Simulink environment and practical experimentation using the dSPACE-1104 controller, further reinforcing their viability and potential for practical implementation in real-world applications.

The switched-capacitor multilevel converters (SCMLCs) are gaining popularity for the integration of solar photovoltaic (SPV) systems into the grid. The current emphasis is on minimizing the number of components in SCMLCs, leading to cost savings and the creation of smaller converters. SCMLCs are particularly suitable for grid integration of low-voltage sources like SPV and fuel cells due to their ability to provide significant voltage boosting. In this context, Chapter 8 discusses a 13-level SCMLC topology for the grid-connected operation of SPV systems. This topology achieves threefold voltage boosting while utilizing a reduced component count, making it a promising solution for efficiently integrating SPV systems into the grid.

Chapter 9 discusses the multilevel inverters useful for solar photovoltaic (SPV) systems and provides a concise overview. The selection of suitable maximum power point tracking (MPPT) strategies for grid-connected SPV/hybrid systems with multilevel inverter has also been discussed in detail.

Chapter 10 discusses electric-drive-reconstructed onboard converter (EDROC), which can function in either the grid-to-vehicle (G2V) or the vehicle-to-grid (V2G) mode. It gives an extensive examination of the global implementation of power converters for electric vehicle systems and contemporary solutions for electric vehicle (EV) charging infrastructure.

In Chapter 11, the packed U-cell (PUC) inverter is highlighted as an innovative technology that achieves a seven-level voltage output using only six active switches, one isolated DC source, and a second capacitor source. However, maintaining a precise voltage ratio between the two capacitor sources is crucial. The chapter delves into the modulation and control of the PUC topology, focusing on its application in solar photovoltaic systems.

Chapter 12 proposes a reduced switch count-based multilevel converter for application in unified power quality conditioner (UPQC) in distribution power systems. The independent control of real and reactive power exchanged between the UPQC and the power networks using multilevel converters is investigated in this chapter in detail.

Chapter 13 illustrates the process of computing power losses, assessing efficiency, and conducting a harmonic analysis of a three-phase infinite-level inverter (TILI). The TILI boasts of exceptional DC-link voltage utilization with a factor of 1.23, reduced input voltage demands, minimized switching power losses, decreased voltage stress, enhanced working efficiency, and improved output power quality.

Chapter 14 discusses the modeling, analysis, and control of a doubly fed induction generator (DFIG) using direct torque control space vector pulse width modulation (DTC-SVPWM) which is employed in wind energy conversion systems, featuring a partially rated converter and facilitating a direct grid connection. The analysis covers aspects such as the quality of stator current, dynamic response, and steady-state response.

Chapter 15 discusses a novel robust sliding mode control strategy for the static var compensator (SVC) for reactive power support to reduce the mismatch in the system reactive power. To improve the performance of a sliding mode controller (SMC) and eliminate the chattering problem, a sliding mode observer (SMO) is constructed to estimate the SVC parameters effectively. The Lyapunov stability analysis is conducted to guarantee the stability of the controller. Simulink/MATLAB is used to validate the efficacy of the proposed controller through simulation studies.

For modular multilevel converter (MMC)-based applications, it is crucial to ensure trouble-free operation for 2 to 3 years. Various types of electrical failures, such as open circuits, short circuits, DC-bus short circuits, and single line-to-ground faults, can potentially disrupt the MMC's operation, leading to a voltage drop within the system. Therefore, the development of a robust fault-tolerant strategy is imperative. A fault-tolerant plan typically comprises three distinct phases: pre-fault preparation, fault isolation and localization, and post-fault restoration and control. Chapter 16 primarily focuses on the post-fault control procedures aimed at swiftly and reliably restoring voltage levels to their pre-fault conditions.

Finally, Chapter 17 explores the application of cascaded H-bridge multilevel inverter (CHB-MLI)-based active filter systems and demonstrates their dynamic performance under transient and steady-state conditions. Specifically, a nine-level CHB-MLI-based SAPF system is simulated using MATLAB/Simulink, showcasing its effectiveness in addressing power quality issues arising from non-linear loads.

This book serves as a valuable reference for individuals interested in the area of multilevel converter topologies, modulation, control, and practical application. Both researchers and practicing engineers will find this book highly adaptable and enriching for their work. Covering a wide range of subject areas and providing a wealth of information from fundamental to advanced levels, this single volume stands as a comprehensive guide for anyone engaged in this field.

We extend our heartfelt gratitude to all the contributors of this book for their invaluable contributions in crafting exceptional literature for the research community. Their dedication and expertise have resulted in the creation of high-quality content that will undoubtedly benefit and enhance research in this field.

We also wish to express our appreciation to our colleagues and friends for their insightful contributions and helpful discussions throughout the production of this edited book.

Salman Ahmad
Department of Electrical Engineering, Islamic University of Science and Technology, Awantipora J&K, India
Farhad Ilahi Bakhsh
Department of Electrical Engineering, National Institute of Technology, Srinagar J&K, India
P. Sanjeevikumar
Department of Electrical Engineering, IT and Cybernetics, University of South-Eastern Norway, Porsgrunn, Norway

1

Analysis of Dual Two-Level Converters for Multilevel Performance

Shailesh Kumar Gupta[1*] and Omveer Singh[2]

[1]Department of Electrical & Electronics Engineering, IIMT Engineering College, Meerut (U.P.), India
[2]Department of Electrical Engineering, Gautam Buddha University, Greater Noida (U.P.), India

Abstract
Multilevel converters were invented to circumvent the voltage restriction of semiconductor devices. The coupling of AC and DC high voltage systems was its first use. Multilevel converters are mostly used to connect many devices in series while clamping the voltages between their pins. The clamping method is determined by the variations between multiple converter architectures. Recently, the use of multilevel inverter technology has become a highly significant alternative for controlling high-power, medium-voltage energy. The goal of this paper is to study this multilevel inverter from the ground up. A review of multilevel converters will cover their benefits, drawbacks, and applications in recent years. The examination of dual two-level inverter systems is then followed by a discussion of the benefits of dual inverter systems as well as issue identification, techniques, and applications. Then, the multilevel performance of dual two-level converters is investigated in the MATLAB/SIMULINK environment. Finally, conclusion and future scope are discussed.

***Keywords*:** Multilevel inverters, dual inverter, space vector pulse width modulation, artificial nural network based pulse width modulation, harmonic spectrum, simulation

1.1 Introduction

By the end of the 1990s, industry has started to require more powerful machinery, which can now produce megawatts of power. The medium-voltage

**Corresponding author*: drskggbu@gmail.com

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network is typically coupled to controlled ac drives in the megawatt range. Currently, connecting a solitary semiconductor switch directly to medium-voltage grids is challenging. For these reasons, working with greater voltage levels has been made possible by a new family of multilevel inverters (MLIs) [1–3]. In order to create a stepped voltage waveform for larger power levels, a multilevel inverter is a power electronic circuit that combines a number of low-rated power semiconductor switches with a number of different DC sources. Batteries, fuel cells, capacitors, and solar PV panels are just a few of the energy sources that can be used to power numerous DC input sources. Semiconductors and capacitor voltage sources are used in multilevel inverters, whose output produces voltages with stepped waveforms. The power semiconductors must endure only low voltages, whereas the commutation of the switches allows the addition of capacitor voltages, which touch high voltage at the output. When compared to the negative pole of the capacitor, the output voltage of a two-level (2-L) inverter has two values (levels), a three-level (3-L) inverter has three levels, and so on.

When the three-level inverter was first introduced in [4], the name “multilevel” was coined. By raising the inverter’s level count, the output voltages have more steps, creating a waveform resembling a staircase with less harmonic distortion. A large number of levels, however, complicates control and creates issues with voltage imbalance. MLIs have three alternative topologies that have been suggested: diode-clamped MLIs [4], flying capacitor MLIs [1, 5, 6], and cascaded H-bridge MLIs [1, 7, 8]. MLIs have the ability to draw input current with very low distortion, generate smaller common-mode (CM) voltage, and generate output voltages with exceptionally low distortion and lower dv/dt, all of which reduce the stress on the motor bearings. Furthermore, it is possible to eliminate CM voltages [8] and operate with a reduced switching frequency by applying sophisticated modulation techniques.

In diode-clamped converters, the clamping is done by the diode batteries, in cascade H-bridge topologies, the clamping is done by the batteries, and so on. The former use of a multilevel converter in high voltage applications to connect the DC side to the AC grid is still used on HVDC transmission lines. In addition, low-voltage applications for which multilevel is appropriate have been discovered. The output waveforms of multilevel converters are better than those of standard converters. This feature is extremely beneficial in meeting energy quality standards. Even in drive applications, multilevel converters are now a good choice. Sophisticated control algorithms can take advantage of the system’s large number of levels to improve performance.

Furthermore, a 3-L inverter also produces space vectors that are similar to those generated by a double 2-L inverter, where every sector is split