TITLE

Capacitor Voltage Control in NPC and Hybrid Multilevel Converters: Where are we now?

NAME AND AFFILIATION OF THE AUTHORS

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SCOPE AND BENEFITS

The controllability of capacitor voltages in multilevel converters is essential to enable their use in practice. This includes the voltage balancing of the dc-link capacitors and the flying capacitor (FC) voltage control. When the number of voltage levels of neutral-point-clamped (NPC) converters is four or higher, the capacitor voltage control becomes particularly challenging. To address this issue, various new hybrid multilevel topologies and new modulation and control strategies have been proposed with many recent developments. In particular, the virtual vector/zero modulation, combined with optimal zero-sequence injection, has shown superior capability to balance the dc-link capacitor voltages through software, without the need of additional hardware. This enables conventional NPC converters with four or higher number of levels to operate independently as a single rectifier or inverter (or with a passive front end) over the full power factor and modulation index range. This tutorial will answer questions such as: How can we derive various multilevel topologies? How do we enable their capacitor voltage balance through modulation and control? This tutorial will cover both the basic and advanced multilevel converter topologies, their control, and their applications. It is suitable for researchers interested in multilevel converters at various levels.

CONTENTS

Schedule is as follows:

Monday, 7 September 2020 - Tutorial day (Location: INSA Lyon, LyonTech-la Doua , 20, avenue Albert Einstein – 69621 Villeurbanne CEDEX.France)

13:00 - 14:00	Registration for afternoon tutorials
14:00 - 14:40	Derivation of multilevel topologies integrating dc-link and flying capacitors
14:40 - 15:30	Existing capacitor voltage control methods

15:30 - 16:00 Discussion and coffee break

16.00 - 17:10 Virtual vector modulation for NPC multilevel converters

17.10 - 17:40 Application examples and discussion

Contents:

1. Derivation of multilevel topologies integrating dc-link and flying capacitors

This part of the tutorial will provide an overview of existing multilevel converter topologies and answer the questions such as 'where the new topologies come from, whether there are fundamental common building blocks in multilevel converters, whether there is a generic multilevel converter from which all or most multilevel converters can be derived or there is a common way to form various multilevel converters'. This part will present a systematic approach to derive basic and hybrid multilevel dc-ac converter topologies involving dc-link and flying capacitors. It will then point out the issue of dc-link capacitor voltage balancing and flying capacitor voltage control, especially in converters with more than three dc-link voltage levels. A rule to judge whether a topology has intrinsic voltage balancing capability at various modulation indexes and power factors will be introduced.

2. Existing capacitor voltage control methods

This section will comprehensively review the existing capacitor voltage control methods, detailing their strengths and limitations. This includes the methods based on phase-leg redundant switching-states, the nearest-three-vector space vector modulation, the conventional level-shifted carrier-based modulation with zero-sequence injection, defining an objective function for capacitor voltage control, using back-to-back structures, increasing output voltage jump levels (i.e. not limited to jumping between adjacent levels) and increasing switching actions for capacitor voltage balancing. In particular, the fast multilevel space vector modulation based on a line (120 degree) coordinate system will be analyzed in detail. The equivalence between multilevel space vector modulation and multilevel carrier based modulation with zero-sequence voltage injection will be explained and how to select the optimal zero-sequence voltage will be presented. A three-level T-type converter will be used as an example to show the capacitor voltage ripple under various modulation indexes and power factors. A virtual zero modulation method will be introduced to attenuate the voltage ripple to zero under zero-power-factor, which conventional methods cannot achieve.

3. Virtual vector modulation for NPC multilevel converters

This section will explain the virtual vector modulation for balancing the dc-link capacitor voltages of NPC dc-ac converters. It will start introducing the concept of virtual vector in the typical case of a three-level three-phase dc-ac converter and its application to derive modulation strategies that guarantee capacitor voltage balance in every switching cycle. Then, the carrier-based implementation of these strategies will be presented, providing a computationally efficient way of bringing them to practice and a simple way to illustrate their features. Finally, the need of a closed-loop control tied to these modulation strategies will be justified, and an efficient configuration of this closed-loop control will be presented.

It will be proven that NPC dc-ac converters with any number of dc-link levels and any number of ac phases can be operated with dc-link capacitor voltage balance over the full operating range (i.e., for any modulation index and for any load power factor) without the need of additional hardware by using the virtual vector modulation. In addition, it will be also discussed how we can extend these operating strategies to multilevel NPC dc-dc converters with and without galvanic isolation.

The tradeoff between voltage balancing capability, switching loss, and harmonic distortion will be analyzed and alternatives to the virtual vector modulation strategy previously presented will be discussed.

4. Application examples and discussion

Application examples will be given regarding the previously discussed advanced topologies and control strategies.

A permanent-magnet synchronous motor drive based on a four-level three-phase NPC dc-ac converter will be presented, with a closed-loop control fully-embedded into an FPGA. The FPGA controller comprises a virtual-vector-based modulator, a dc-link voltage balancing closed-loop control, and a field-oriented control. Experimental results under different operating conditions will be presented to demonstrate the good performance of this type of motor drive under all operating conditions, including accelerations, decelerations, and speed reversal transients.

It will be also shown how a virtual-vector modulation together with a suitable state-of-charge balancing control maximize the capacity utilization of a battery bank in an electric vehicle power train configured by a multilevel multiphase NPC dc-ac converter fed by multiple battery packs connected in series, without the need of introducing a battery management system among battery packs. The full battery bank capacity can be employed, even under different initial state-of-charge values or different battery nominal capacities. The state-of-charge (SoC) balancing among battery packs is accomplished through the multilevel converter operation in a lossless manner, by simply distributing the dc-to-ac power flow among the batteries according to their state-of-charge. Experimental results under different operating conditions will be presented to demonstrate the good performance of the aforementioned system.

Finally, a multilevel multiphase NPC dc-ac conversion system fed by multiple series-connected photovoltaic arrays with independent voltage control of each solar array will be presented. The controller is again based on a virtual-vector-based modulator together with a suitable photovoltaic array voltage balancing control. Compared to a conventional two-level conversion system, this system configuration allows extracting the maximum power from the photovoltaic arrays, even under partial shading or mismatching of the photovoltaic arrays. It also allows reducing the devices voltage rating (with the subsequent benefits in device-performance characteristics), reducing the output-voltage distortion, and increasing the system efficiency. Experimental results under different operating conditions will be presented to demonstrate the good performance of the aforementioned system.

WHO SHOULD ATTEND

We would like to encourage anyone who is interested in multilevel converters from both academia and industry to attend this tutorial. The contents will suit audience with various backgrounds, and you will find something new in our tutorial. There will be plenty of opportunities for discussion and answering your questions in multilevel converters.

Technical Level: This tutorial is suitable for both beginners and experienced researchers who are interested in multilevel converters, topologies, control and applications.

ABOUT THE INSTRUCTORS

Xibo Yuan (S'09-M'11-SM'15) received the B.S. degree from China University of Mining and Technology, Xuzhou, China, and the Ph.D. degree from Tsinghua University, Beijing, China, in 2005 and 2010, respectively, both in electrical engineering.

He has been a Professor since 2017 in the Electrical Energy Management Group, Department of Electrical and Electronic Engineering, University of Bristol, Bristol, U.K, where he became a Lecturer, Senior Lecturer and Reader in 2011, 2015 and 2016, respectively. He also holds the Royal Academy of Engineering/Safran Chair in Advanced Aircraft Power Generation Systems. He is an executive committee member of the UK National Centre for Power Electronics and the IET Power Electronics, Machines and Drives (PEMD) network. He was a Visiting Scholar at the Center for Power Electronics Systems, Virginia Tech, Blacksburg, VA, USA, and the Institute of Energy Technology, Aalborg University, Denmark. He was a Postdoctoral Research Associate in the Electrical Machines and Drives Research Group, University of Sheffield, Sheffield, U.K.

His research interests include power electronics and motor drives, multilevel converters, wind power generation, application of wide-bandgap devices and electric vehicles. Professor Yuan is an Associate Editor of IEEE Transactions on Industry Applications and IEEE Journal of Emerging and Selected Topics in Power Electronics. He is a Fellow of IET and received The Isao Takahashi Power Electronics Award in 2018.

He has proposed several new multilevel converter topologies, simplified modulation and control methods, and fault detection and protection for multilevel converters. Working with industry partners, he has successfully delivered several multilevel converter prototypes for wind power generation and more electric aircraft systems, which have been further turned into products by industry.

Sergio Busquets-Monge (S'99-M'06-SM'11) was born in Barcelona, Spain. He received the M.S. degree in electrical engineering and the Ph.D. degree in electronic engineering from the Universitat Politècnica de Catalunya (UPC), Barcelona, in 1999 and 2006, respectively, and the M.S. degree in electrical engineering from Virginia Polytechnic Institute and State University (VPI&SU), Blacksburg, VA, USA, in 2001.

From 2001 to 2002, he was with Crown Audio, Inc. Since 2007, he has been an Associate Professor with the Electronic Engineering Department, UPC. In 2009, he was a Visiting Scholar at the Center for Power Electronics Systems, VPI&SU, VA, USA, and the Institute of Energy Technology, Aalborg University, Denmark.

His current research interests include standardized/modular power converter design based on neutral-point-clamped (NPC) topologies and electric vehicles.

His contributions to the field of Power/Industrial Electronics have mainly focused on power converter design optimization and multilevel conversion. Within the area of multilevel conversion, he has proposed novel topologies, modulations, and controls of NPC converters. In particular, through the introduction of novel modulations and controls, he has demonstrated that NPC converters with an arbitrary number of levels can be operated with dc-link capacitor voltage balance in every switching cycle over the full operating range in all types of power conversion configurations (dc-dc, dc-ac, ac-dc, and ac-ac).