

AN OVERVIEW OF IMPROVING POWER QUALITY IN CASCADE MULTILEVEL CONVERTERS BASED ON SINGLE-PHASE NON-REGENERATIVE POWER CELLS

[PAPER ID: ICITER- D 201]

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ABSTRACT:

In industrial applications Medium-voltage motor drives plays important role to extend the power rating of AC motor drives. Multilevel converters help to improve the power of AC motors. This survey provides information about new topology of family of modular multilevel converters: the modular double-cascade converter. The modularity of the converter is enabled by the application of multi winding medium frequency isolation transformers. Owing to the innovative transformer link, at a concept level the converter give more valuable properties: modularity, small footprint, high input and output power quality and wide variety of applications, among others. Further, the research demonstrates that the one of the disadvantage of topology is transformer link. An extensive simulation study on the new converter is performed which the focus on the development of control algorithms and the feasibility of the topology. In particular, the circuit and control concepts used in the grid interface, the coupling configurations load inverter, and the transformer link operation is thoroughly investigated. Experimental results provide proof-of-concept results on the operation principle of the converter. This work concludes a research collaboration project on multilevel converters between LUT and Vac on Plc.

KEYWORDS: Electromagnetic coupling, AC drive, medium-voltage drive, medium frequency transformer, multilevel converter, cascaded H-bridge.

INTRODUCTION:

In the field of high-power electric energy conversion, multilevel voltage source inverters (VSI) are an attractive alternative to conventional two-level VSIs and current source inverters (CSI). The two-level converter technology is considered established due to its vast application spectrum in medium to low power ranges. In the high-power range, however, medium and high voltages are used and the semiconductor

technologies are under development. This has given rise to the interest in multilevel converters, in which addition to a higher voltage quality, use mature low-voltage medium-power semiconductor technologies to achieve high-power ratings of the converter (Franquelo et al., 2008). The higher power demands of certain applications can be met by parallel connection of multiple two-level converters. An example of such an application is Wind power generators in the range of a few megawatts. The parallel connection of low-voltage two-level converters not only increases the power rating of the converter set, but also does not have an impact on the voltage rating. As powers increase higher voltages are used to reduce ohmic losses and current. From this demand, the need for multilevel converters arises (Rodríguez et al., 2002). Multilevel converters are employed in applications such as compressors, pumps, rolling mills, fans, mine hoists, conveyors, high-voltage direct current (HVDC) transmission, and many more. Because of their acceptance in the industry and intensive research carried out all across the world, the multilevel converters can be regarded as a mature technology. However, not all the potential of the multilevel converters has been implemented by the current technologies.

This holds true especially for the energy efficiency, reliability, and power density of the multilevel converters. Therefore, new multilevel converter topologies emerge quite frequently (Kouro et al., 2010). In the literature, three multilevel converter topologies are considered the classic and mature topologies (Franquelo et al., 2008; Kouro et al., 2010; Najafi and Yatim, 2012). These are a neutral-point-clamped inverter (NPC), a flying capacitor inverter (FC), and a cascaded H-bridge inverter (CHB) (Nabae et al., 1981; Meynard and Foch, 1993; Hammond, 1997).

These topologies have gained commercial interest in different applications. For instance, NPCs are used in high-power AC motor drives such as conveyors, pumps, and fans, whereas FCs are used in applications that require a high bandwidth (i.e., fast transient recovery) and a high switching frequency such as medium-voltage traction drives. CHBs have been successful in very high-

power applications and solutions requiring high power quality. Moreover, there are low-voltage applications of multilevel converters for instance in the solar power industry and in automotive applications.

LITERATURE SURVEY:

An every topology has a set of particular necessities of its own, which affect the design complexity and the control techniques that have to be used. NPC, for example, needs a control approach that balances the voltages of the series-connected DC link capacitors. This is also known as the neutral point (NP) control in the literature. A FC inverters, naturally balanced the voltages in the phase capacitors but typically, the required minimum ripple of the voltages of the phase capacitors sets the minimum limit for the switching frequency of the semiconductors. The CHB exhibits not only such balancing problems, but also requires hardware that provides isolated DC voltage sources for the series-connected modules. The classification of multilevel converters can be made according to the application spectrum or by the electrical circuit topology and the semiconductor technology. Figure 1 divides the topologies into categories according to the circuit topology and the semiconductor technology.

The MDC topology is introduced. Potential applications of the converter are presented, and its capability to change the voltage level is discussed. Simulation results are shown for a seven-level version of the converter operating in a 3.3 kV grid with an LR load. The first measurements of a three-level experimental system operating in a 400V grid and feeding a motor are reported [1].

Measurement results of the experimental system and the thorough analysis of the medium frequency transformer link are explained. The power of the experimental system is increased by a factor of three compared with 1, giving more insight into the dynamics of the converter topology [2].

In the first principle only the primary-side bridges and in the second principle also the secondary-side bridges of the transformer are switched. The third principle uses information from the load bridge controller and measurements to determine whether the corresponding transformer bridge should be switched or not [3].

The application of series resonant circuits to improve the energy efficiency of the medium frequency transformer link is introduced. The asymmetry of the transformer link is found to have a significant effect on the performance of the series resonance. A compensating circuitry is suggested to overcome the

asymmetry problem. The simulation results demonstrate the performance of the proposed method [4].

The design and implementation of the control of the active front end of the converter are presented. The grid filter and AFE controller design are performed for an example 3.3 kV motor application. The performance of the example design is assessed with simulation results [5].

An ant saturation control of the six-winding medium-frequency transformer is introduced. Additionally, the effects of the flux balance controller on the parallel windings on the primary and secondary side are discussed. A control algorithm that both controls the magnetic flux of the transformer and balances the loading of the parallel units is proposed. The algorithm has been granted a Finnish patent in 2013 [6].

STRUCTURE OF THE MDC:

Modular double-cascade converter is a relatively new topology, which belongs to the multilevel voltage source converter family. Vacon Plc owns the US patent, which discloses the invention. The structure and basic building blocks of the converter topology are presented in Figure 1 (Komulainen and Sarén, 2013). The basic building blocks of the MDC are

- **BELT** is a three-phase three-level unit, which comprises six identical sub modules and one medium-frequency six winding transformer. Connecting multiple belts in series or in parallel increases the voltage rating or current rating of the converter, respectively.
- **Filter** is installed in the grid interface of the MDC. The preferred structure is an LCL filter

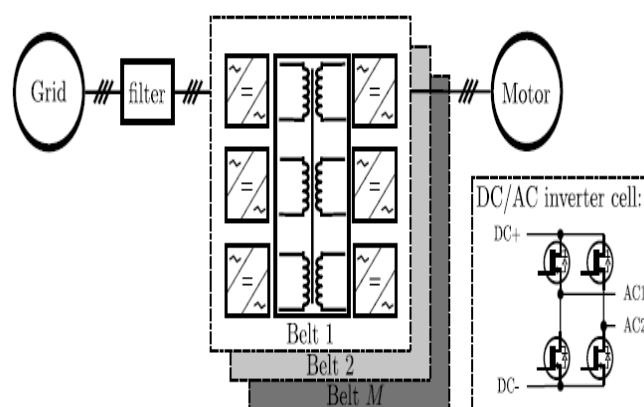


Figure 1. Simplified structure of a modular double-cascade converter. The grid and the load are both interfaced with a multilevel cascaded H-bridge inverter.

- **SUBMODULE** is an AC/AC unit, which comprises two DC/AC inverter cells connected back-to-back and an intermediate DC link capacitor. The first inverter cell is one piece of a cascaded H-bridge (CHB) connection. The second cell interfaces the medium-frequency transformer.

• **DC/AC INVERTER CELL** is a three-level single-phase unit, which comprises four low-voltage transistors. The type of the bridge cell is widely known as the H-bridge.

• **SIX-WINDING MEDIUM-FREQUENCY TRANSFORMER** is the true innovation of the MDC. The isolation of the sub modules required by the CHB setups is provided by the transformer.

PROPOSED OF THE WORK:

The different specific requirements of the three classic topologies lead to different applications for each of the topologies. Among the interests of a manufacturer of a multilevel converter is to have a product that has applications in all categories of medium-voltage drives. This means that the topology to be applied should be modular. The client who buys the inverter, on the other hand, may not care about the topology, but the client's interests are in the performance, lifetime costs, reliability of the converter, and the required footprint. As in any other industry and market, the driving force for a product development comes from the end-users, the customers. In the field of medium-voltage high-power electrical drives, the customer has some kind of a process that needs electrical energy to be converted into mechanical work, or vice versa. The processes in this category include heavy-duty hoists and conveyors, traction motors in trains, megawatt-size fans and pumps that move air or liquid, and wind mills and farms, among others. The installation of power electronic converters in these applications may be a part of a renovation of an old process, an installation of a completely new process line, or retrofitting an old process with converters to improve the system efficiency and controllability.

Partially reproduced from (Kouro et al., 2010) can be listed as

1. High efficiency (lower lifetime costs),
2. High reliability (no/few maintenance breaks),
3. Low investment costs,
4. Simple and adaptive user interface (communications to a higher-level control of the facility),
5. Low electromagnetic interference and acoustic noise,
6. Small footprint in certain applications (ships, trains, wind mills: smaller size of passive components such as transformers, du/dt, and harmonic filters), and
7. Low torque ripple (less mechanical stress on mechanical power transmission apparatuses: Gears, drive shaft, operating devices),
8. Personnel requirements (qualification and training)
9. Product lifetime service and maintenance.

Manufacturers provide solutions to meet the customers' needs. Different customers may have different requirements for instance in terms of voltage, power, and footprint specifications which pose challenges for the manufacturer: In order to meet the specific requirements of multiple customers, many types of converters should be manufactured.

In order to have a product that is scalable in power, the underlying circuit topology should be modular. In modular topologies, a sufficient number of low-voltage power modules are connected in series or in parallel according to the voltage or current rating of the application. At the initiative of Vacon Plc in 2009, LUT and Vacon started a research program, the topic of which was a new modular multilevel converter invented by MrRisto Komulainen and DrHannu Sarén from Vacon. The topology is based on the classic cascaded H-bridge topology featuring one CHB for the grid connection and another for the load connection. The power module isolation is provided by medium-frequency transformers instead of a line frequency transformer. First, the functionality of the topology in medium-voltage drives was validated by simulations. The study then continued into the inspection of more specific technical challenges, and finally, a prototype was built to verify some of the simulation-based results. According to the Construction, this topology was named a modular double-cascade converter (MDC).

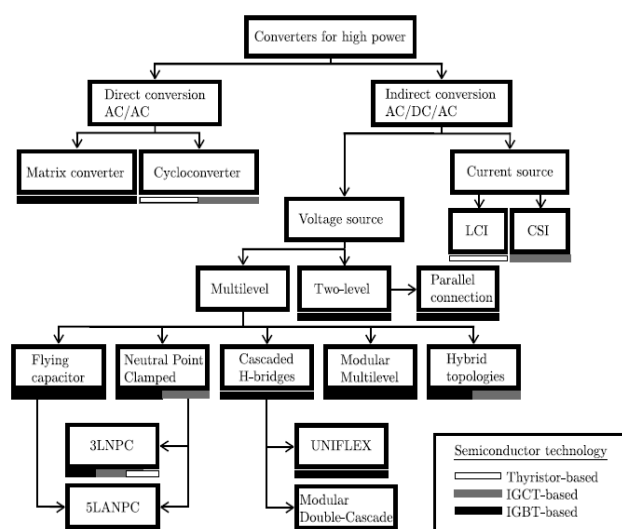


Figure 2. Classification of high-power converters according to the circuit topology and the semiconductor technology

HIGH-POWER MULTILEVEL CONVERTER TOPOLOGIES:

The amount of academic research effort put into the multilevel converter technology increases annually, and at the same time, the industry has shown a wide interest in the technology. Certain multilevel converter topologies are reviewed in this section. The topologies chosen for the review are five-level active-neutral-point-

clamped inverter (5LANPC), the cascaded H-bridge inverter, and the UNIFLEX-PM.

The 5LANPC is chosen for the review because it is an extension of the classic NPC and FC topologies having five levels in the line-to-neutral voltage. The topology has been commercialized by ABB as the ACS2000 product. The classic NPC and FC are omitted from the review because numerous other contributions already provide detailed analyses on them. Inoue and Akagi (2006) invented a topology for new-generation MV motor drives, which is based on the cascaded H-bridge topology. The converter topology was then adapted to the UNIFLEX-PM project (Universal and Flexible Power Management). UNIFLEX-PM was a EU-funded research program, which took place in the University of Nottingham, UK. Application of the converter was mainly focused on the interconnection of supply networks using the said circuit topology. This converter has a lot in common with and its invention precedes that of the MDC. Therefore, the UNIFLEX-PM system cannot be left unmentioned in the scope of this work. The cascaded H-bridge inverter and the UNIFLEX converter are therefore selected for review here. The modular multilevel converter is a viable solution for high-voltage direct current (HVDC) applications, but its usability in motor drives is compromised by the poor operation at low output frequencies.

Although applications of the M2C have recently been reported for motor drives for example in (Spichartz et al., 2013), Modularity has at least two different meanings in the literature. First, the physical construction of a converter can be modular, which means that different operational segments (e.g. rectifier, inverter, control) are separate components. This kind of modularity is advantageous, for instance, if one part gets damaged and has to be replaced quickly. Second, the modularity is a property of a multilevel converter that defines its applicability in a wide power and voltage range. The CHB, for instance, is a modular technology since by adding more similar cells in the cascade connection, the voltage and power ratings of the converter can be increased. NPCs and FCs are not modular since the addition of voltage levels changes the circuit design and adds complexity. The latter definition of modularity is a property that a manufacturer of a multilevel converter appreciates since the same design can be used in a wider application spectrum leading to the need for only one design and potentially lower manufacturing costs.

STATE-OF-THE-ART OF HIGH-POWER CONVERTERS:

The number of multilevel converter topologies is immense, and new topologies emerge quite frequently.

The classic topologies and a few new topologies have been commercialized by several manufacturers, and the application spectrum of these converters is wide. A state-of-the-art analysis of multilevel inverters published by Rodríguez et al. (2002) listed the NPC, FC, and CHB as the three basic topologies that were already commercialized for medium-voltage (MV) applications. The publication discusses the usage of multilevel converters in applications such as: multilevel rectifiers that replace phase-shift transformers and multipulse diode rectifiers, DC/DC converters, non regenerative and regenerative motor drives, and power systems that require power flow control or harmonic compensation units.

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Table 1. Topologies comparison

Topology comparison,			
Topology	Voltage	Current	Power range
LCI	nearly sinusoidal + commutation spikes	quasi-square wave	tens of MW (typ.), up to 100MW
CSI	nearly sinusoidal	three-level PWM	<10 MW (typ.), >10 MW with parallel connection
CCV	piecewise rep- resentation of three-phase input	nearly sinusoidal +clamping to 0 A at zero-crossing	<10 MW (typ.), up to 70 MVA
5LANPC	five-level PWM	nearly sinusoidal	< 10 MW
CHB	N-level PWM	nearly sinusoidal	< 10 MW (typical)

COMPARISONS:

Medium-voltage high-power converters found in the industry at present comprise multilevel voltage source converters, current source converters, and converters with direct conversion. From the current source family, the PWM-CSI and LCI drives were presented. The major difference between these two is the switching components: while the LCI uses thyristors without a self-extinguishing capability, the CSI uses GTOs and can therefore employ PWM to synthesize the output current. With this capability, the PWM-CSI can be applied to induction motor drives unlike the LCI, which is only suitable for synchronous motors with a leading power factor. Both current source topologies are robust and reliable solutions found in industrial applications. The cycloconverter (CCV) was selected for review from the direct-conversion family. Unlike the current source topologies, the CCV provides nearly sinusoidal output current to the load. The output voltage is synthesized by successively connecting one of the input phase-voltages to the output thereby imposing a fundamental limitation on the topology: the output frequency is restricted to below approximately one-eighth of the input frequency.

The three topologies selected from the voltage source family were the five-level active-neutral-point clamped inverter, the cascaded H-bridges, and the UNIFLEX-PM. In these topologies, the voltage in the capacitive voltage sources is synthesized to the output by switching the transistors with selected modulation methods. The 5LANPC and the CHB are direct competitors to the MDC, which is why they were chosen for review. The UNIFLEX PM converter, on the other hand, has a lot in common with the MDC. Its invention

precedes that of the MDC, and it was therefore also included in the review.

The main properties of the six topologies considered in this chapter are summarized in Tables 2. In the first table, the input and output waveforms and the converter power ranges are presented. The second table presents the advantages and applications of each topology, and the third table compares the switching frequencies, modulation techniques, and topology specific limitations. Out of the reviewed topologies, the LCI and CCV reach the highest power levels, even up to 100MW. The power range that is of interest in this dissertation is 1–10MW. Each of the studied topologies have applications in this power range. All of the topologies can be used in 4Q applications. The current source topologies are robust mainly because of the low component count and reach a very high efficiency. However, their dynamic performances are not at the same level with the voltage source topologies. The limitation on the dynamic performance is mainly caused by the high-value inductance in the DC link. The current of the motor is adjusted by controlling the current through the DC link inductor. In the voltage source topologies, the DC link energy storage is a capacitor, which acts as a low impedance source when it comes to rapid changes in the output current. The switching frequencies of the LCI and CCV are the lowest owing to the fact that they employ thyristors without a self-extinguishing capability. The CSI uses GTOs and can thus reach a switching frequency of a few hundred hertz in the specified power range. In the voltage source topologies, the main switching component is the IGBT. Therefore, switching frequencies in the kHz range are obtained.

CONCLUSION:

Multilevel converters have gained a strong foothold in medium-voltage motor drives in the industry over the past couple of decades. New power circuit topologies emerge frequently as research is conducted by the industry and academia. The development of new topologies is motivated by energy saving, striving for modular topologies, and intellectual property issues. This dissertation work is a part of a university-industry collaboration research project. The industry partner's new innovative topology with the objectives presented above was in the focus of the project. The topology is known as the modular double-cascade converter (MDC), and it features two sets of cascaded H-bridge (CHB) inverters: one for the grid connection and the other for the load.

The feasibility of the converter was studied by two approaches. In the first approach, the MDC was compared with parallel topologies. These other

topologies were introduced in the literature review of the dissertation. The topologies were compared with regard to the component count and technical features with the focus on a special application in mining industry. It was discovered that the concept-level topology comparison is not sufficient to determine the most suitable topology for the application.

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