



Power Electronic Systems
Laboratory

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IEEJ Journal of Industry Applications, Vol. 1, No. 1, pp. 2-14, July 2012

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T. Friedli
J. W. Kolar

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Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Milestones in Matrix Converter Research

Thomas Friedli^{*,**} Non-member, Johann W. Kolar^{***a)} Member

(Manuscript received Jan. 9, 2012, revised March 29, 2012)

The Matrix Converter (MC) evolved from the forced commutated cycloconverters and has been extensively investigated for more than thirty years. In this publication, the milestones in research on MCs in academia and industry are reviewed and presented chronologically and thematically ordered. The major contributions in the fundamental topic areas such as the development of the topology, topological extensions, commutation, modulation, loss calculation, control, or filtering and EMC are compiled and then expanded with examples of the latest activities in the corresponding field of research. In addition, an overview of the publicly reported research on MCs in industry is provided and the development of the commercialized MCs is briefly summarized. This review concludes with a brief comparison of the MC with the voltage source converter and a discussion of the current status of the MC technology and its future potential.

Keywords: matrix converter, ac-ac converter, review, overview

1. Introduction

In the academic community, research on the Matrix Converter (MC) and its extended topologies has been performed for more than three decades and is still very popular, given the number of papers published in this topic area every year. The MC seems to have become a “Power Electronic Evergreen” in the research area of ac-ac/ac-dc-ac converter topologies, which has fascinated and presumably in future will still fascinate several generations of researchers in academia.

One of the first reviews of the MC technology was presented in 2002 by Wheeler et al.⁽¹⁾, focusing on the single-stage MC and is dedicated to modulation, control, and the methods to solve the commutation problem of MCs. Later in 2003, Popov et al published an overview of the research on MCs performed in the former Soviet Union and Russia⁽²⁾. Since then, numerous papers have been published, leading to a considerable broadening of the knowledge on MCs.

The aim of this publication is to provide an unbiased review of the key steps in the development of the MC technology and to establish the state-of-the-art in research and industry of the single-stage MC, the two-stage MC, and the extended and reduced MC topologies opposed to (1) that considered only the single-stage MC. Sect. II is subdivided into different topic areas, summarizing the development of the MC topologies, commutation and modulation schemes, loss analysis methods, considered semiconductor technologies, control and stability, protection and operational

safety, filtering and EMC, application areas, and an overview of comparative studies of MCs with alternative converter topologies. Section III briefly summarizes the publicly reported activities in industry on MCs. Finally, in Sect. IV, a brief comparison of the MC and Voltage DC-Link Back-to-Back Converter (V-BBC) is presented. This paper concludes in Sect. V with a general discussion on the development of the MC technology and its future potential.

2. Development of the MC Technology

2.1 Basic Matrix Converter Topologies Forced commutated ac-ac converter topologies that can provide simultaneous amplitude and frequency transformation of multi-phase voltage-current systems without intermediate energy storage are referred to as Matrix Converters (MCs). MCs can generate sinusoidal input currents and output voltages, and the electrical output frequencies can be higher than the input frequency.

The three-phase to three-phase Half-Bridge MC topology, nowadays usually referred to as direct or Conventional Matrix Converter (CMC) [cf. Fig. 1(c)] performs the voltage and current conversion in one semiconductor stage by using an array of nine controlled bidirectional switches. Alternatively, the Indirect Matrix Converter (IMC) [cf. Fig. 1(e)] features a two-stage (indirect) power conversion with a bidirectional, unipolar current source input stage with six bidirectional switches and a two-level voltage source converter output stage.

Already in 1923, the Hazeltine Research Corporation filed a patent⁽³⁾ for a matrix-like electric power converter based on electro-mechanical switches. However, the modern (forced commutated) Full-Bridge MC [FBMC, cf. Fig. 1(b)] and Half-Bridge MC (HBMC) or CMC evolved from the forced commutated cycloconverters. Cycloconverters are direct ac-ac converters that can be basically categorized into Naturally Commutated Cycloconverters (NCCC) and artificially or Forced Commutated Cycloconverters (FCCC). NCCC are

a) Correspondence to: Johann W. Kolar. E-mail: kolar@lem.ee.ethz.ch

* Former researcher at the Power Electronic Systems Laboratory (PES), ETH Zurich
Zurich, 8092, Switzerland

** ABB Switzerland, R&D Traction Converters
Turgi, 5300, Switzerland

*** Head of the Power Electronic Systems Laboratory (PES), ETH Zurich
Zurich, 8092, Switzerland

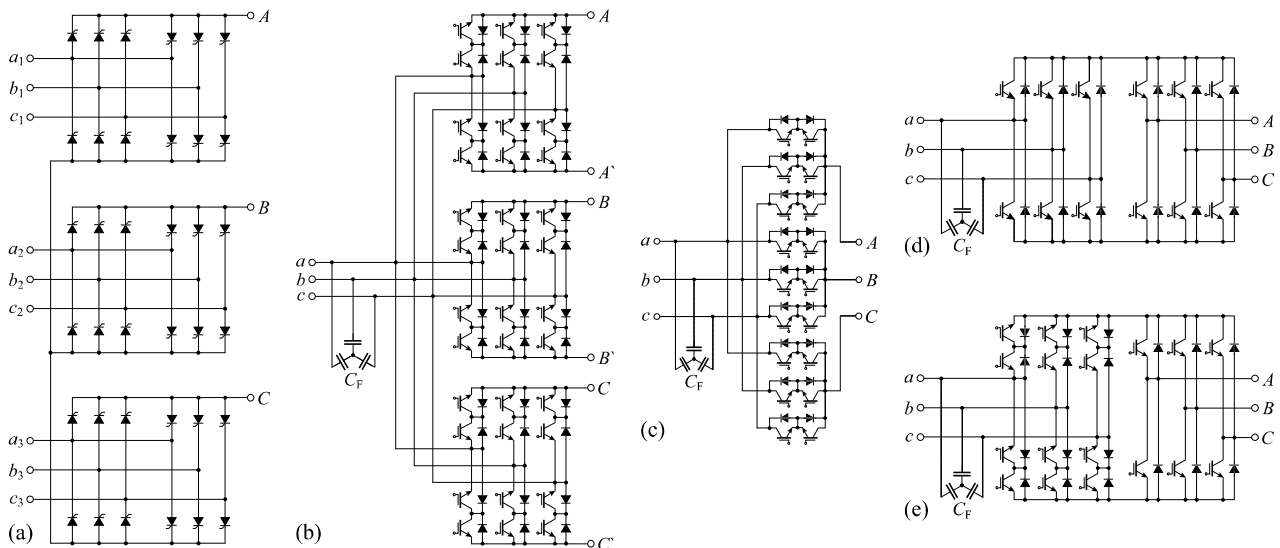


Fig. 1. Historical development of the fundamental MC topologies. (a) Circuit topology of the three-phase, star-connected cycloconverter, implemented with thyristors (transformers at the input terminals are not shown). Basic three-phase Matrix Converter topologies: (b) Single-stage Full-Bridge (direct) Matrix Converter (FBMC), (c) Half-Bridge Matrix Converter (HBMC) or Conventional (direct) Matrix Converter (CMC), (d) two-stage Fundamental Frequency Front-End Converter (F3EC), and (e) two-stage Indirect Matrix Converter (IMC)

based on discontinuous control-type switches such as thyristors or thyatrons [cf. e.g. Fig. 1(a)] that are turned off by ensuring that the voltage difference between the outgoing and the incoming switches is of the correct polarity. Thus, the turn-off is dependent on the momentary magnitudes of the input ac voltages to which the switches may be subjected. The amplitude and frequency of the output voltage is controlled by modulating the conducting intervals of the semiconductor switches (principle of the phase control⁽⁴⁾⁽⁵⁾). The maximum electrical output frequency of these NCCC is smaller than the electrical frequency of the source at their input. In contrast to the NCCC, in the FCCC, switching devices are used that can be actively turned off at any desired instant independently of the momentary magnitudes of the input ac voltages across the switches. Therefore, the FCCCs can generate electrical output frequencies that are higher than the electrical input frequency.

First documents describing the HBMC topology using Bipolar Junction Transistors (BJTs) have been found in a patent from Specialties Development Corporation by Blake *et al.*, filed in 1959⁽⁶⁾, and a patent from Westinghouse Electric Corporation by Jessee, filed in 1960⁽⁷⁾, for forced commutated frequency changers (correspond to FCCCs) for aircraft generator systems. Seven years later, in 1967, Westinghouse filed another patent authored by Gyugyi and Pelly⁽⁸⁾ for controlling the variable frequency converting switching units of FCCCs in order to control the output voltage.

The key component of MCs are the controllable bidirectional (four-quadrant) power switches⁽⁹⁾. The first FCCCs used thyristors with external commutation circuits to achieve the functionality of a bidirectional switch^{(5)(10)–(15)}. This led to bulky converters with unsatisfactory performance. Only the availability of power transistors (BJTs) for implementing the bidirectional switches made the FCCC^{(16)–(18)} and ultimately the MC more attractive for practical applications. Although the actual HBMC topology with BJTs was already described

in the late 1950' [e.g. in (6)], according to the current knowledge of the authors, Jones and Bose seem to be the first in 1976 who published experimental results of a three-phase to single-phase FCCC using BJTs⁽¹⁶⁾.

The actual development of the modern high-frequency modulated CMC topology started with the work of Venturini and Alesina in 1980^{(19)–(21)}. They described the power circuit of the CMC as a matrix of bidirectional switches and introduced the name "Matrix Converter". In 1983, Braun and Hasse proposed the use of space vectors in the description and control of MCs⁽²²⁾ (not for the modulation). In order to prove the MC concept for practical converter systems, numerous application specific research projects have been conducted, starting with the investigation of ac motor drives supplied by CMCs. Kastner and Rodriguez in 1985⁽²³⁾ and Neft and Schauder in 1988⁽²⁴⁾ experimentally confirmed that a CMC with nine four-quadrant switches can be effectively used for vector control of an induction machine.

First publications investigating the IMC topology appeared in 1989 by Holtz and Boelkens⁽²⁷⁾ and Shinohara *et al.*⁽²⁸⁾. However, for the following years, academic research mainly focused on the CMC topology. Around 2000, first experimental results of IMCs were presented such as by Zwimpfer and Stemmler in 2001⁽²⁹⁾.

An indirect MC topology, which is equivalent to a Voltage Source Back-to-Back Converter (V-BBC) without a dc-link capacitor, was suggested in 1986 by Ziogas⁽³⁰⁾ and analyzed in more detail in 1998 by Kim *et al.*⁽³¹⁾ [cf. Fig. 1(d)]. This converter topology cannot provide sinusoidal input currents and was named as the Fundamental Frequency Front-End Converter by Göpflich and Rebereh in 2003⁽³²⁾ [F3EC, cf. Fig. 10 in (33)]. A sinusoidal shape of the input currents can be obtained by implementation of a separate input stage for each input phase as proposed in 1998 by Mino *et al.* in (34).

The investigation of Isolated IMC (I-IMC) topologies

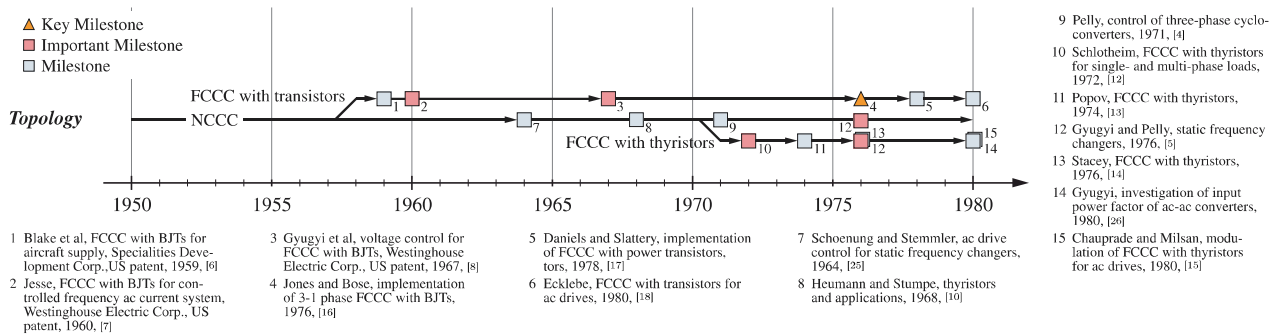


Fig. 2. Main steps in the historical development of the ancestors of the MC topology from 1950 to 1980. (NCCC: Naturally Commutated Cycloconverter; FCCC: Forced Commutated Cycloconverter)

began in 1990 by Kawabata *et al.*⁽³⁵⁾ for compact UPS converter systems based on the cycloconverter technology. In 2003, Cha and Enjeti proposed a novel topology of an I-MC for isolated direct ac-ac power conversion for a variable frequency input and a constant frequency output⁽³⁶⁾. Itoh *et al.* investigated in 2005 a modified version of this topology for UPS applications⁽³⁷⁾.

In the early 1990', first Soft Switching MC (SSMC) topologies were described by Cho *et al.*⁽³⁸⁾⁽³⁹⁾. Later in 1996, researchers started to investigate the Auxiliary Resonant Commutated Pole MC (ARCP MC)^{(40)–(42)}.

Jones and Bose provided the basis for the three-phase to single-phase MC topology (3-1MC) with their investigation of the three-phase to single-phase FCCC in 1976⁽¹⁶⁾. Khan *et al.* proposed in 1986 a single-phase to three-phase topology⁽⁴³⁾. In 1997, Zuckerberger demonstrated the operating behavior of a single-phase to single-phase MC (1-1MC)⁽⁴⁴⁾.

The next major step with regard to the further development of MC topologies occurred in 2001 with the invention of the reduced switch IMC topologies known as Sparse Matrix Converters [SMC, Figs. 17 and 19 in (33)] by Kolar *et al.*^{(45)–(48)} and Wei and Lipo⁽⁴⁹⁾⁽⁵⁰⁾ followed by the first experimental results of a Very Sparse Matrix Converter in 2002⁽⁴⁷⁾. In 2003, Jussila *et al.*⁽⁵¹⁾ also demonstrated experimental results of an IMC.

The identified milestones in the research on MCs are visualized in the diagrams in Fig. 2 and Fig. 3 based on the current state of knowledge of the authors without, in any sense, claiming absolute completeness. The following classification is used: “key milestone”, “important milestone”, and “milestone” papers. The class of “key milestone” papers is reserved for contributions that describe the fundamental properties of the MC technology such as the topology, the commutation, and the modulation.

2.2 Extended and Reduced Matrix Converter Topologies Since the invention of the reduced switch IMC topologies in 2001, numerous topological extensions or combinations of the basic CMC and IMC topology have been suggested such as the Indirect Three-Level-Output-Stage Sparse Matrix Converter [SMC3, cf. Fig. 28(a) in (33)] by Kolar *et al.* in 2002⁽⁴⁶⁾⁽⁵²⁾ and the Indirect Three-Level MC topology with an additional bridge-leg across the link [cf. Fig. 28(b) in (33)] by Klumpner *et al.* in 2006⁽⁵³⁾ to reduce the output current harmonics. Erickson proposed in 2001 different Hybrid CMCs (HCMC)⁽⁵⁴⁾ to extend the output voltage range and

Klumpner in 2005⁽⁵⁵⁾ Hybrid IMCs (HIMC). Research on Capacitor Clamped multi-level MCs (CCMC) began in 2004 by Yang *et al.*⁽⁵⁶⁾. The Full-Bridge IMC (FBIMC) topology for supplying an open-winding ac machine with a limited common mode voltage was suggested by Mohapatra and Mohan in 2006⁽⁵⁷⁾.

Another means of extending the output voltage range is by a modular interconnection of multiple identical MCs [e.g. low-voltage three-phase to two-phase direct MCs, cf. Fig. 35 in (33)] by a common multi-pulse transformer, which was described by Yamamoto *et al.* in 2009⁽⁵⁸⁾ and Kang *et al.* in 2011⁽⁵⁹⁾. This class of MCs is in the following named as Modular Multi-pulse Transformer-interconnected MC (MMTMC).

The most recent extended MC topologies are the Z-Source MCs (ZSMC) proposed by Ge and Peng⁽⁶⁰⁾ and the three-phase single-input and dual-output unidirectional IMC (SIDO-UIMC) suggested by Liu and Blaabjerg *et al.* in 2011⁽⁶¹⁾.

The CMC topology can be simplified and restricted to unidirectional power flow, by omission of the reverse current path at the expense of reduced functionality. Possible circuit topologies were proposed by Ziegler *et al.* in 2004⁽⁶²⁾ and are referred to as S-A-X converters. The same concept was proposed in 2002 by Kolar *et al.*⁽⁴⁶⁾ for the Sparse Matrix Converters leading to the so-called Ultra Sparse Matrix Converter [USMC, cf. Fig. 19 in (33) (63)]. Later, in 2008, Kolar *et al.* proposed a unidirectional SMC topology⁽³³⁾⁽⁵²⁾ with a unidirectional three-level input stage as for the VIENNA Rectifier and a three-level output stage based on the three-level neutral-point clamped Voltage Source Converter (VSC) topology [USMC3, cf. Fig. 29 in (33)].

2.3 Commutation Schemes The simultaneous commutation of bidirectional switches used in MCs can be hardly achieved without short-circuiting the input voltages and/or interrupting the current path of the impressed load currents. This major issue was solved with the development of various multi-step commutation schemes first described by Burany⁽⁶⁴⁾ and Oyama *et al.*⁽⁶⁵⁾ in 1989 that enable a safe change of the switching state. The standard multi-step commutation requires four steps. The four-step commutation scheme can be reduced to a three-, two-, or even a one-step commutation scheme as suggested by Ziegler and Hoffmann in 1998 and 2001, respectively⁽⁶⁶⁾⁽⁶⁷⁾. In (65) (68)–(70), the switching sequence of the multi-step commutation is based on the sign of the voltage between the incoming and the outgoing input

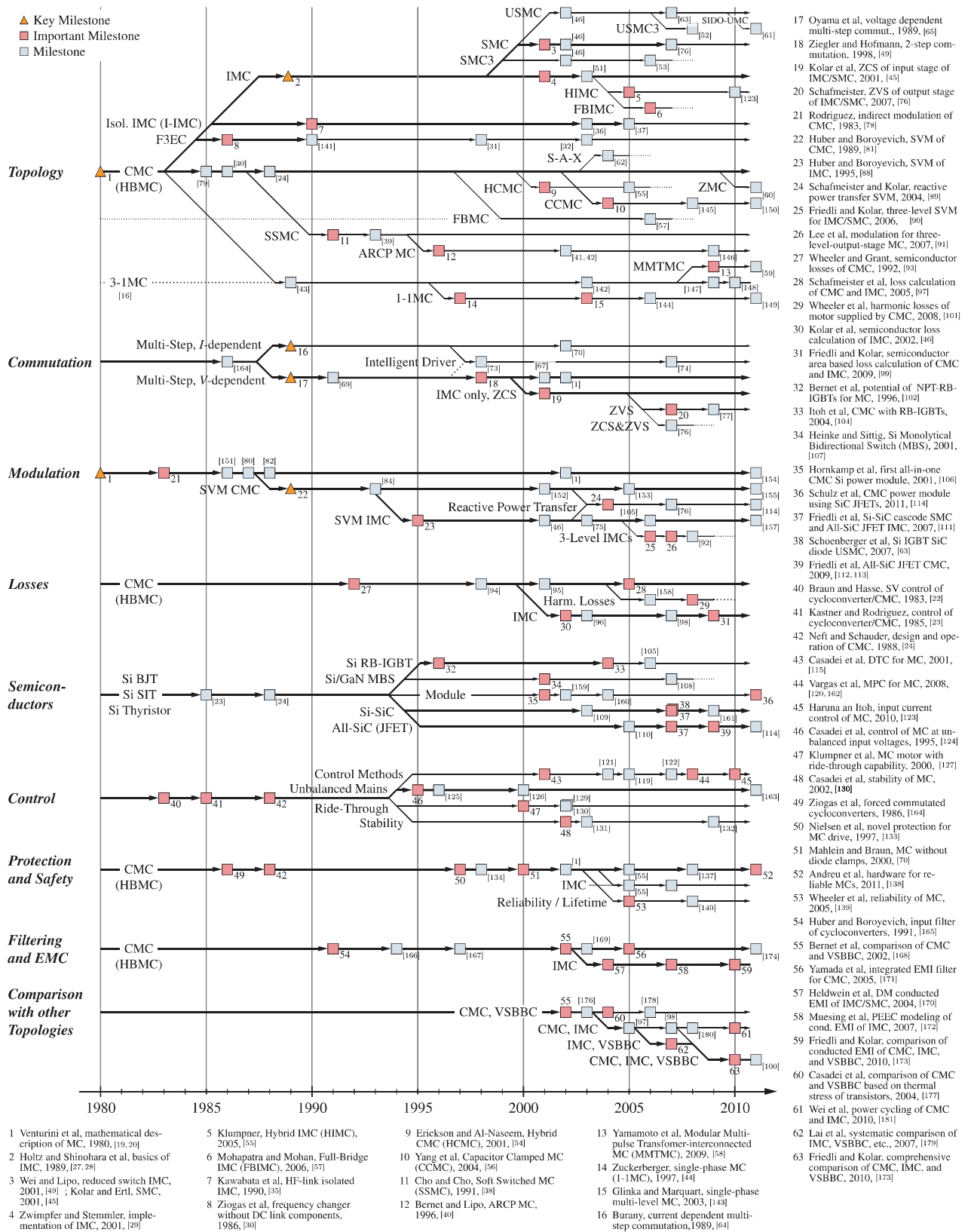


Fig. 3. Milestones in Matrix Converter Research from 1980 to 2011, considering nine key topic areas. (ARCP MC: Auxiliary Resonant Commutated Pole MC; CCMC: Capacitor Clamped MC; FBMC: Full-Bridge MC; FBIMC: Full-Bridge IMC; F3EC: Fundamental Frequency Front-End Converter; HBMC: Half-Bridge MC equivalent to CMC; HCCMC: Hybrid CMC; HIMC: Hybrid IMC; I-IMC: Isolated IMC; MMTMC: Modular Multi-pulse Transformer-interconnected MC; SMC3: Three-level SMC; SSMC: Soft Switched MC; USMC: Ultra Sparse MC; and ZMC: Z-Source MC)

lines. Safe commutation can be also achieved by detecting the sign (direction) of the output current⁽⁶⁴⁾⁽⁷⁰⁾⁽⁷¹⁾. The most effective method to prevent commutation failures is to detect both the polarity of the input voltages and the direction of the output currents, which is described in (72).

Intelligent gate driver circuits were presented by Empringham *et al* in 1998⁽⁷³⁾, in which the current direction is determined by measuring the voltage across the switching devices, to further increase commutation safety. An extension of this concept was proposed by Sun *et al* in 2007⁽⁷⁴⁾ for RB-IGBTs using the measured collector-emitter voltage and the output current to ensure safe commutation of the CMC.

The same commutation schemes known from the CMC are applicable to the IMC. Opposed to the CMC, significantly less complex commutation schemes can also be used for the IMC topology. In these simpler commutation schemes, the IMC is either operated at zero current commutation of the input stage, zero voltage commutation of the output stage, or a combination of both, for example to balance the switching losses between the input and output stage⁽⁷⁵⁾, which is described in detail in (33) (52) (76). The zero voltage commutation of the IMC is less known and was tested by Itoh *et al* in 2009⁽⁷⁷⁾.

2.4 Modulation Methods The modulation methods developed simultaneously with the circuit topology of the MC in the 1980', mainly triggered by the work of Venturini and Alesina⁽¹⁹⁾⁽²⁰⁾. One of their main contributions is the detailed mathematical analysis of the low-frequency operating behavior of the MC. Their modulation scheme is referred to as the "direct modulation method". A different representation of the modulation was introduced by Rodriguez in 1983 based on the concept of the "fictitious dc link"⁽⁷⁸⁾. This method is also known as the "indirect modulation method". Ziogas *et al* expanded in their work in 1985 the concept of the "fictitious dc link" and provided a detailed mathematical analysis⁽⁷⁹⁾. The so-called scalar modulation method proposed by Roy *et al* in 1987⁽⁸⁰⁾, where the switching signals are directly calculated from the measured input voltages and required output voltages, is representative for a number of modulation methods that were developed to facilitate the practical implementation of Venturini's method [cf. Sect. V in (1)].

Finally, in 1989, Huber and Boroyevich published the first paper⁽⁸¹⁾ in which the principles of space vector modulation are applied to describe the modulation of the CMC topology. For the following years, numerous Pulse Width Modulation (PWM) and Space Vector Modulation (SVM) methods were presented for the CMC^{(82)–(87)}.

Since the IMC is functionally equivalent to the CMC, the modulation methods, originally developed for the CMC, are also applicable to the IMC apart from the methods based on rotating space vectors [cf. Table I in (33)]. Two of the most important findings for the modulation of the IMC are the space vector representation of the IMC modulation by Huber in 1995⁽⁸⁸⁾ and the reactive power transfer modulation schemes suggested by Schafmeister in 2004⁽⁸⁹⁾ that can be also applied to the CMC.

In 2006, Klumpner *et al* proposed a modulation for a three-level SMC⁽⁵³⁾ with an additional bridge-leg compared to the three-level modulation described in (48) (90) for MCs in general. Lee *et al* presented in 2007 a modulation method for the

Three-Level-Output-Stage IMC⁽⁹¹⁾, which was further investigated by Loh *et al* in 2008⁽⁹²⁾.

2.5 Loss Analysis Simulation based as well as analytical calculation based methods, using approximated loss data, were suggested for calculating the semiconductor losses of the CMC, for example by Wheeler and Grant in 1992⁽⁹³⁾ or Sunter and Altun in 1998⁽⁹⁴⁾. Bland *et al* presented in 2001 a comparison of the calculated and measured losses of a CMC⁽⁹⁵⁾.

A systematic method for an analytically closed calculation of semiconductor losses for the IMC and SMC topologies was first presented by Kolar *et al* in 2002⁽⁴⁶⁾ and extended by Schafmeister in 2003 to the Very Sparse MC⁽⁹⁶⁾ and later in 2005 to the CMC topology for comparison⁽⁹⁷⁾. In 2007, Jusila and Tuusa presented a comparison of the semiconductor losses of the CMC and IMC⁽⁹⁸⁾. Finally, Friedli and Kolar suggested in 2009 to consider the required semiconductor chip area for a given junction temperature (variation) and characteristic operating points for calculating and comparing the semiconductor losses of the CMC and IMC⁽⁹⁹⁾⁽¹⁰⁰⁾.

An interesting study was published by Wheeler *et al* in 2008, investigating the harmonic losses of induction machines due to operation from MCs⁽¹⁰¹⁾.

2.6 Power Semiconductor Devices The semiconductor technology has always played a key role in the development of the MC. In 1996, Bernet *et al* compared a CMC in which the required bidirectional switches are implemented by conventional common collector configurations of IGBTs and anti-parallel connected Reverse Blocking NPT IGBTs (RB-IGBTs)⁽¹⁰²⁾. Odaka *et al* from Fuji Electric described in 2004 one of the first theoretical and experimental loss analysis for a CMC⁽¹⁰³⁾, using RB-IGBTs. Control concepts and protection circuits for a practical CMC motor drive system using RB-IGBTs were proposed by Itoh *et al* also in 2004⁽¹⁰⁴⁾. Friedli *et al* analyzed in 2006 an IMC using RB-IGBTs from IXYS in the input stage and demonstrated the converter performance⁽¹⁰⁵⁾. Hornkamp *et al* presented in 2001 the first MC power module EconoMAC⁽¹⁰⁶⁾, manufactured by Euppec. In 2001, Heinke and Sittig⁽¹⁰⁷⁾ suggested a Monolytical Bidirectional Switch (MBS) to facilitate the implementation of the bidirectional switches of MCs. This device concept was reconsidered in 2007 by Morita *et al* from Matsushita-Panasonic for a GaN-based MBS for MCs using normally-off gate injection transistors⁽¹⁰⁸⁾.

The performance and potential of the SiC switch technology for MCs was investigated by a semiconductor loss analysis of Schafmeister *et al* in 2003⁽¹⁰⁹⁾ and Domes *et al* in 2005⁽¹¹⁰⁾. In 2007, Friedli *et al* investigated and experimentally verified the feasibility and operating behavior of a high-switching-frequency SiC Sparse Matrix Converter using a cascode configurations of a low-voltage Si MOSFET and a 1200 V normally-on SiC JFET and an All-SiC JFET IMC⁽¹¹¹⁾ and later, in 2009, an All-SiC JFET CMC⁽¹¹²⁾⁽¹¹³⁾. Schulz and Wheeler *et al* presented in 2011 also a SiC JFET hardware demonstrator of a CMC, applying a SiC JFET prototype power module from Infineon⁽¹¹⁴⁾.

2.7 Control and Stability Most of the control schemes, known from VSCs, were applied and analyzed for MCs: Direct Torque Control (DTC) by Casadei and Blaabjerg in 2001⁽¹¹⁵⁾, sensorless control for example by Snary and

Eskola in 2004⁽¹¹⁶⁾⁽¹¹⁷⁾, sliding mode control by Hamouda in 2004⁽¹¹⁸⁾, dead beat control for example by Lee⁽¹¹⁹⁾ in 2005, and Model Predictive Control (MPC) by Vargas *et al* beginning in 2008⁽¹²⁰⁾.

Klumpner *et al* demonstrated in 2004 the control of an IMC with a single voltage sensor in the intermediary circuit⁽¹²¹⁾. A rather special control scheme is the regeneration control by Imayavaramban *et al* in 2007⁽¹²²⁾, avoiding energy feedback into the mains as is currently required for More Electric Aircraft (MEA) applications. In 2010, Haruna and Itoh proposed a control scheme for MCs that enables to control the converter input currents at the cost of output current control quality⁽¹²³⁾.

Operation at unbalanced input voltages is more critical compared to voltage dc-link converter systems due to the absence of an intermediate energy storage. First publications that proposed control methods to improve the operating behavior at abnormal input conditions were published by Casadei *et al* in 1995⁽¹²⁴⁾, Nielsen *et al* in 1996⁽¹²⁵⁾, and Blaabjerg *et al* in 2000⁽¹²⁶⁾.

The basic concept to enable ride-through capability and safe converter shut-down during mains failures is to decelerate the drive during power outages, receiving energy from the inertia of the load to supply the control electronics of the converter as is known from variable-speed drives with a voltage dc-link. Klumpner *et al* proposed in 2000 such a ride-through strategy for a CMC with a standard protection circuit with 12 diodes⁽¹²⁷⁾. Cha and Enjeti suggested in 2002 a different ride-through concept for the CMC based on a special ride-through module⁽¹²⁸⁾ that requires a capacitor and three additional power transistors with anti-parallel diodes. In the same year, Wiechmann *et al* presented an extended ride-through strategy⁽¹²⁹⁾ that increases the modulation index up to dynamic over-modulation and only if necessary reduces the motor speed.

A further control related topic has been the analysis of methods to investigate control stability of MCs, which was addressed by Casadei *et al* in 2002⁽¹³⁰⁾, by Liu *et al* in 2003⁽¹³¹⁾ or later in 2009 by Wang and Sheppard for a PMSM drive⁽¹³²⁾.

2.8 Protection and Operational Safety The lack of a dc-link energy storage element affects the operational safety of MCs in case of failures as for example over-voltages cannot be limited by a dc-link capacitor as in VSCs, and no intrinsic return path for the load current is provided.

Nielsen *et al* proposed in 1997 a protection concept for the CMC that requires only six additional diodes⁽¹³³⁾ opposed to 12 diodes as for the standard protection circuit. Schuster presented in 1998 a protection concept for MCs without reactive clamp elements for a motor drive system using varistors only⁽¹³⁴⁾. An extended protection concept was proposed by Mahlein and Braun in 2000 based on varistors and suppressor diodes⁽¹³⁵⁾ that allows the removal of the standard diode clamp circuit. Various techniques to reduce the complexity of the protection circuits in CMCs and IMCs were suggested and investigated by Klumpner in 2005 including a protection concept for the IMC topology with only six diodes in the clamp circuit using standard half-bridge inverter modules⁽¹³⁶⁾. In 2008, Andreu *et al* started to investigate start-up, ride-through, and protection concepts of the CMC focusing on the actual hardware implementation and experimental

verification⁽¹³⁷⁾ and provided in (138) a detailed description of the hardware.

Schönberger *et al* presented in 2007 an active clamp circuit for the (unidirectional) Ultra Sparse Matrix Converter and demonstrated the performance of the converter and the clamp in operation for a PMSM drive⁽⁶³⁾.

First academic reliability studies on MCs have been presented by Wheeler *et al* in 2005⁽¹³⁹⁾. Wei *et al* started to investigate in 2008 the power cycling capability of MCs for 1200 V IGBT and diode power modules⁽¹⁴⁰⁾.

2.9 Input Filters and EMC Although MCs are sometimes presented as an “all-silicon solution” due to the absence of intermediate energy storage elements, they also require passive components for the implementation of the input filter (not shown in Fig. 1).

Huber and Boroyevich presented in 1991 the design of input filters for FCCCs⁽¹⁶⁵⁾. Wheeler *et al* investigated in 1994 the relative cost of two different input filter topologies for MCs⁽¹⁶⁶⁾ and suggested in 1997 an optimized input filter design for MCs using a one-stage *LC* input filter with harmonic diversion⁽¹⁶⁷⁾. In 2002, Bernet *et al* computed the total conducted noise of a CMC and compared it with the results for a corresponding VSC⁽¹⁶⁸⁾. One year later, Cha and Enjeti suggested a novel modulation method for MCs to reduce the generated common mode voltage⁽¹⁶⁹⁾. Yamada *et al* from Yaskawa Electric presented in 2005 the first study of a CMC with an integrated differential and common mode input and output filter⁽¹⁷¹⁾.

A systematic modeling of the differential mode noise of an IMC/SMC including an experimental verification was first presented by Heldwein *et al* in 2004⁽¹⁷⁰⁾. In 2007, Müsing *et al* demonstrated the prediction of conducted differential and common mode noise for an IMC by using the Partial Element Equivalent Circuit (PEEC) method to account for the parasitics of the printed circuit board⁽¹⁷²⁾.

Finally, in 2010, Friedli and Kolar compared the differential and common mode noise generated by a CMC, IMC, and a V-BBC and the impact on the volume of the passive components of the EMC input filter for a motor drive⁽¹⁷³⁾.

2.10 Application Areas The MC has primarily been considered for bidirectional variable frequency ac drives for low- and later also for medium voltage applications. The drive system integration capability of MCs was demonstrated in 2000 by Klumpner *et al* by attaching a CMC directly to a motor, leading to the so-called Matrix Converter Motor (MCM)⁽¹²⁷⁾.

MCs have been widely analyzed for aircraft applications⁽¹⁸²⁾⁽¹⁸³⁾ motivated by their potential for a light weight and compact implementation and are still considered as an alternative converter concept for this application area. More recent investigations suggested the MC also for wind generation systems⁽¹⁸⁴⁾, deep-sea robots⁽¹¹⁶⁾, contact-less energy transmission⁽¹⁸⁵⁾, or ac utility power units⁽¹⁸⁶⁾. The three-phase to single-phase MC has been recently proposed for distributed energy generator systems⁽¹⁴⁷⁾, whereas the single-phase MC topology is being mainly investigated as an active front-end for single-phase ac traction applications⁽¹⁴⁹⁾.

2.11 Comparisons with Other Topologies Most comparative studies focus on a performance comparison based on semiconductor loss calculations or measurements

and typically involve two different converter topologies.

Bernet *et al* presented in 2002 a comparison of the semiconductor losses and the design including a computation of the conducted noise (EMC) between the CMC and V-BBC⁽¹⁶⁸⁾. In the same year, Zhou *et al* from Rockwell Automation investigated the critical operating points and their impact on the semiconductor design of CMCs from a drive manufacturer's perspective⁽¹⁷⁵⁾ and nicely summarized the key properties of the CMC in respect of the industrially widely applied V-BBC. One year later, Bland *et al* compared the semiconductor losses of the CMC and the VSC⁽¹⁷⁶⁾. Casadei *et al* proposed in 2004 a comparison between the CMC and V-BBC based on the thermal stress of the switches⁽¹⁷⁷⁾.

The first analytical semiconductor loss comparison between the CMC and the Very Sparse Matrix Converter was presented by Schafmeister *et al* in 2005⁽⁹⁷⁾. Round *et al* described in 2006 a comparison of the semiconductor losses and the implementation effort including the passive component values between the Very Sparse Matrix Converter and the V-BBC using the same semiconductors in both topologies⁽¹⁷⁸⁾. In 2007, Jussila and Tuusa published another semiconductor loss comparison between the CMC and IMC⁽⁹⁸⁾, followed by an investigation of the relation between the load and supply current distortion for both the CMC and IMC⁽¹⁸⁷⁾.

Contrary to most of the other comparisons of topologies, a systematic evaluation was presented by Lai *et al* in 2007 comparing four converter topologies for aircraft applications among other the IMC and V-BBC⁽¹⁷⁹⁾. With the proposed method, the individual topologies are analyzed using weight as a comparison metric.

In 2010, Friedli and Kolar presented a comprehensive comparison between the CMC, IMC, and V-BBC⁽¹⁷³⁾ determining the required semiconductor chip area for a given operating point in the torque-speed plane under predefined thermal constraints, the resultant semiconductor losses, the volume and losses of the passive components including the EMC input filter, and the cooling system.

An important contribution was also published by Wei *et al* end of 2010 with their comparison of the IGBT power cycling capabilities of the CMC and IMC⁽¹⁸¹⁾.

2.12 Key Contributions The key contributions in the development of the MC can be summarized as follows: the investigation of the basic MC concept by Venturini in 1980⁽¹⁹⁾, the development of the multi-step commutation by Burany and Oyama *et al* in 1989⁽⁶⁴⁾⁽⁶⁵⁾ to solve the commutation problem of the bidirectional switches, and finally the space vector representation of the modulation by Huber and Boroyevich in (81) to enable a consistent mathematical description of the converter system from the source to the load.

With these basic features, the MC is operational and can be used as a direct ac-ac converter with variable voltage and frequency transformation capability.

3. Matrix Converters in Industry

The world's first commercial MC was presented by the Japanese drive manufacturer Yaskawa in 2005 with the product name "Varispeed AC". This converter series is based on the CMC topology and is implemented with 1200 V RB-IGBTs produced by Fuji Electric. According to Yaskawa,

Table 1. Overview of publicly reported research on MCs in industry

Company	MC Topology	Year	Publication
ABB & Daimler Benz	CMC	1997	(188)
ABB	CMC	2002	(168)
	CMC	2008	(189)
Alstom	CMC	2003	(190)
	PP-MC ^a	2009	(191)
Bosch	S-A-X ^b	2004	(62)
Danfoss	CMC	2002	(127)
Eupec & Siemens	CMC	2001	(106)
Fuji Electric	CMC	2004	(104)
	I-IMC	2005	(37)
Hitachi Electric	CMC	2006	(192)
Hyundai Heavy Industries	CMC	2011	(193)
Meidensha	CMC	2007	(86)
Mitsubishi Electric	I-IMC	1990	(35)
	CMC	2004	(194)
Rockwell Automation	CMC	2002	(175)
	CMC, IMC	2010	(181)
SamsungSDI	CMC	2006	(195)
Schneider-Toshiba	CMC, IMC	2010	(196)(197)
Siemens	CMC	2002	(198)
Smith Aerospace	CMC	2004	(199)
Toyo Electric	CMC	2007	(200)
Westinghouse	CMC	1988	(24)
Yaskawa	CMC	2002	(201)
	ARCP MC	2009	(146)
	MMTMC ^c	2009	(58)

^aPoly-Phase MC; ^bUnidirectional (direct) MC;

^cModular Multi-pulse Transformer-interconnected MC.

typical applications for their MC result from two main advantages of this product: power regeneration functionality and low total harmonic distortion.

One year later in 2006, Fuji Electric, another Japanese company, announced also a new MC product, the Frenic-MX. Similar to Yaskawa, Fuji also selected the CMC topology. Since the product launch, Fuji has not been heavily advertising their MC, and currently, it is not anymore part of Fuji's product portfolio.

Meanwhile, Yaskawa extended their matrix converter product line with the FSDrive-MX1S medium voltage MC series for input voltages of 3.3 kV and 6.6 kV with a maximum output power of 2.5 MW and 5 MW. The increased blocking voltage capability is achieved through a modular interconnection of multiple three-phase CMCs, leading to a poly-phase matrix converter, which is connected to the three-phase medium voltage mains and optionally also to the load with multi-pulse transformers (MMTMC)⁽⁵⁸⁾.

An overview of publicly reported research on MCs in industry is provided in Table 1.

4. Comparison of the MC and V-BBC

Finally, the main properties of the CMC, IMC, and V-BBC are shown in Fig. 4 using eight characteristic performance indicators. The converter topologies are designed and comparatively evaluated according to the methodology and the models presented in (100) for a 15 kVA, 3×400 V converter system for a PMSM drive based on the 1200 V Si IGBT4 Trench and Fieldstop technology (Infineon) for a switching frequency of 8 kHz. A load torque characteristic of fan, compressor, or pump applications is assumed, i.e. the torque and thus the converter output current is proportional to the square of the power.

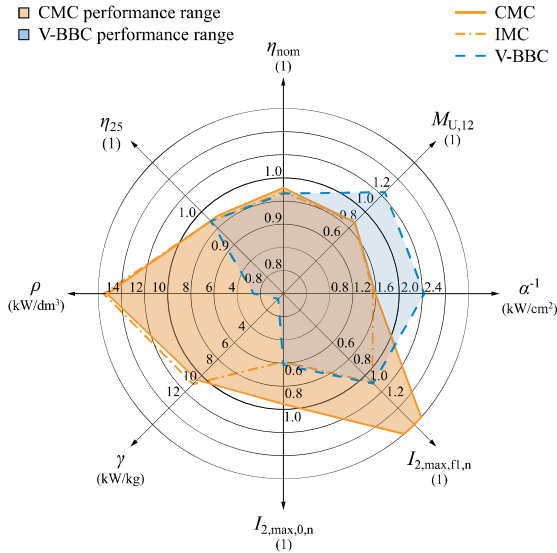


Fig. 4. Comparison of the CMC, IMC, and V-BBC with eight performance indicators for $T_{J,max} \leq 140^\circ\text{C}$, $\Delta T_{J,max} \leq 10\text{ K}$, $T_S = 95^\circ\text{C}$, and $f_{sw} = 8\text{ kHz}$.

The following performance indicators are defined for this comparison:

Voltage transfer ratio (for sinusoidal modulation)

$$M_{U,12} = \frac{U_{2,max}}{U_1} \dots\dots\dots (1)$$

The dc-link voltage of the V-BBC is assumed with $U_{DC} = 700\text{ V}$. U_1 and U_2 denote the rms value of the input and output line voltages.

Nominal efficiency

$$\eta_{nom} = \frac{P_{2,nom}}{P_{2,nom} + P_{loss,nom}} \dots\dots\dots (2)$$

at a modulation index for the MCs of $M_{12} = 0.9$ and a modulation index for the output stage of the V-BBC of $M_2 = U_2 \sqrt{6}/U_{DC} = 0.9$.

Efficiency at 25% of the nominal output power for motor operation

$$\eta_{25} = \frac{P_{2,25}}{P_{2,25} + P_{loss,25}} \quad I_{2,25} = \frac{1}{2} \cdot I_{2,nom} \dots\dots\dots (3)$$

at half of the nominal output current $I_{2,25}$, a modulation index for the MCs of $M_{12} = 0.45$, and a modulation index for the output stage of the V-BBC of $M_2 = 0.45$.

Power density and power-to-mass ratio

$$\rho = \frac{P_{2,nom}}{V_{tot}} \quad \gamma = \frac{P_{2,nom}}{m_{tot}} \dots\dots\dots (4)$$

V_{tot} and m_{tot} equal to the total boxed volume and mass of the passive components, the cooling system, the semiconductor module, the gate drivers, and the auxiliary hardware [cf. Fig. 24 in (100)].

Nominal output power per total Si chip area

$$\alpha^{-1} = \frac{P_{2,nom}}{A_{chip,tot}} \dots\dots\dots (5)$$

Maximum output current when the output frequency equals the input frequency and when it equals to zero

$$I_{2,max,f_i,n} = \frac{I_{2,max}}{I_{2,nom}} \Big|_{f_2=f_i} \quad f_i = \{f_1, 0\} \dots\dots\dots (6)$$

such that the maximum junction temperature does not exceed $T_{J,max} = 140^\circ\text{C}$ at a sink temperature $T_S = 95^\circ\text{C}$ (beneath the power module), leading to a limitation of the maximum junction temperature variation of $\Delta T_{J,max} = 45\text{ K}$.

The area spanned by the polygon curves in Fig. 4 can be considered as a relative measure for comparison. The better the converter performance is the larger is the area. As can be seen in the diagram, the only significant advantages of the MC compared with the V-BBC at a switching frequency of 8 kHz are the higher achievable power density and power-to-mass ratio, which is mainly due to the absence of the boost inductors at the input of the MC [cf. also (100)].

5. Conclusions

MCs have been frequently presented as a future converter concept for ac variable-speed drives over the past decades. However, despite intensive research for the last thirty years, MCs have until now only achieved low market penetration. In view of the numerous scientific contributions on MCs published since the 1980' but with Yaskawa Electric as the only drive manufacturer currently offering MCs as commercial products, the MC is one of the academically most investigated but industrially least applied converter topology.

The reason for the low usage of the MC technology in industry cannot be ascribed to a lack of academic research promoting the matrix converter but to the intrinsic, physical limitations given by the MC concept, such as the maximum input-to-output voltage transfer ratio of 86% (for sinusoidal modulation), the more complex commutation compared to VSCs, the restricted reactive power compensation capability, or the limited operation at unbalanced input voltages. These fundamental obstacles have remained the same also after thirty years of intense research and have prevented the MC to become a serious challenger of the VSC. The considerable improvement of the capacitor technology regarding volume, weight, and lifetime since the beginning of the MC era in 1980 has devitalized former arguments in favor of the MC such as that with the absence of a dc-link capacitor the converter lifetime can be considerably increased. With regard to the past development of the MC technology, it is unlikely that the MC will ever replace the VSC. It is currently expected that the low-voltage MC concept remains restricted to niche applications.

Nevertheless, a major future task of academic activity on MCs is seen in maintaining and expanding the knowledge of a compact and light-weight converter system as a benchmark for evaluating state-of-the-art or future three-phase converter concepts and in the education of power electronic engineers⁽¹¹²⁾⁽²⁰²⁾. MC comprise all challenges of modern pulse width modulated voltage or current source converters in a single converter system [cf. Sects. I and II in (202)]. In addition, the MCs is a demonstrative example of a converter concept in which multiple functions such as the generation of sinusoidal input currents and output voltages, the power factor correction at the input, the control of the output cur-

rents, etc. are integrated into one semiconductor stage at the expense of a higher complexity and restrictions in the operating behavior. Thus, the MC shows in a figurative way the trade-off between functional integration by reduction of converter stages and elimination of intermediate energy storage and functional modularization through application of multiple converter stages with intermediate energy storage as for the V-BBC.

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Thomas Friedli (Non-member) received his M.Sc. degree in electrical engineering and information technology (with distinction) and his Ph.D. from the Swiss Federal Institute of Technology (ETH) Zurich, in 2005 and 2010, respectively. From 2006 to 2011, he was with the Power Electronic Systems Laboratory, ETH Zurich, Switzerland where he performed research on current source and matrix converter topologies using silicon carbide power semiconductors, active three-phase PFC rectifiers, and conducted electro-magnetic interference. Since 2012, he has been with ABB Switzerland Ltd as an R&D engineer for power electronics and medium voltage drives for traction converter systems. His current research interests are in the areas of high-efficiency power electronic systems and their control, three-phase power converters, electro-magnetic interference, and applications of wide band-gap power devices. Dr. Friedli received the 1st Prize Paper Award of the IEEE IAS IPCC in 2008 and the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS Prize Paper Award in 2009.

Johann W. Kolar (Member) received his M.Sc. and Ph.D. degree (summa cum laude/promotio sub auspiciis praesidentis rei publicae) from the University of Technology Vienna, Austria. Since 1984 he has been working as an independent international consultant in close collaboration with the University of Technology Vienna, in the fields of power electronics, industrial electronics and high performance drives. He has proposed numerous novel PWM converter topologies, and modulation and control concepts, for example, the VIENNA Rectifier, the Swiss Rectifier, and the Three-Phase AC-AC Sparse Matrix Converter. Dr. Kolar has published over 400 papers in international journals and conference proceedings and has filed more than 80 patents. He was appointed Professor and Head of the Power Electronic Systems Laboratory at the Swiss Federal Institute of Technology (ETH) Zurich on Feb. 1, 2001.

