Milestones in Matrix Converter Research

Thomas Friedli  Non-member  (ETH Zurich, Switzerland, friedli@lem.ee.ethz.ch)
Johann W. Kolar  Member  (ETH Zurich, Switzerland, kolar@lem.ee.ethz.ch)

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

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 chrono-
logically and thematically ordered. The major contributions in the fundamental topic areas such as the development of the topology, topo-
logical 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 comparison of the MC with the Voltage DC-Link Back-to-Back Converter (V-BBC) and a discussion of the current status of the MC technology and its future potential.

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 commu-
tation by Burany and Oyama et al in 1989 [64,65] to solve the com-
mutation problem of the bidirectional switches, and finally the space vector representation of the modulation by Huber and Boroyevich in [80] to enable a consistent mathematical description of the con-
verter system from the source to the load. With these fundamental features, the MC (CMC) is operational and can be used as a direct ac-ac converter with variable voltage and frequency transformation capability.

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 topol-
ogy and is implemented with RB-IGBTs. One year later in 2006, Fuji Electric announced also a new MC product, the Frenic-MX, which, however, is currently not anymore part of Fuji’s product port-
folio. Meanwhile, Yaskawa extended their matrix converter product line with a medium voltage MC series.

Despite intensive research for the last three decades, MCs have until now only achieved low market penetration with Yaskawa Electric as the only drive manufacturer currently of-
fering MCs as commercial products. The reason for the low usage of the MC technology in industry is mainly due 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 voltage source converters, the restricted reactive power compensa-
tion capability, or the limited operation at unbalanced input volt-
ages.

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 in-
put, the control of the output currents (load), 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 figu-
rative 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 con-
verter stages with intermediate energy storage as for the V-BBC.
Sensorless Control of IPMSM: Past, Present, and Future

Seung-Ki Sul  Member (Seoul National University, sulsk@plaza.snu.ac.kr)
Sungmin Kim  Non-member (Seoul National University, ksmin@eepel.snu.ac.kr)

Keywords: IPMSM, sensorless control

Since the early 1980s, with the development of high-performance rare-earth permanent magnets, the Interior Permanent Magnet Synchronous Motor (IPMSM) has evolved. It was first used in high-performance servo drive and has recently been used in general-purpose industrial drives. From the 1990s, because of the soaring cost of electricity, the IPMSM has been considered as a candidate that could replace the induction motor. The induction machine has many merits, for example, it is mechanically robust, has low cost, is technically mature, and can be designed to have different speeds, torques, and shapes. However, because of the magnetizing current, its efficiency is poorer than that of a permanent-magnet-based motor, especially at a low load factor. Even though the control of the IPMSM is complex because of the reluctance torque associated with the saliency of the magnetic structure of the rotor, the IPMSM has been used in many industrial applications. In some applications, a general-purpose IPMSM has been used as the Surface-Mounted Permanent Magnet Synchronous Machine, where the d-axis current is set to be zero, for easier implementation of the control algorithm at the cost of the reluctance torque. Even under such a simple operating principle, the torque density of IPMSM is considerably higher than that of the general-purpose induction motor. The torque density per unit volume is 30% higher and the torque density per unit weight is 25% higher in the power range of several tens of kilowatt, for operation in near 1800 r/min. Further, the efficiency of the IPMSM is 7% higher than that of the high-efficiency premium induction motor and 10% higher than that of the standard general-purpose induction motor. Hence, recently, IPMSMs with ratings exceeding 500 hp have been used to replace the induction machine in general industrial applications such as hoist operation. However, in making the replacement, the position sensor of the IPMSM has been of concern. Even though the IPMSM is mechanically robust and has a small size, the position sensor increases the axial length in making the replacement, the position sensor of the IPMSM has been used in many industrial applications. In some applications, the saliency of the magnetic structure of the rotor, the IPMSM has been technically mature, and can be designed to have different rotor positions to the stator.

The rotor position of the IPMSM can be estimated from the inductance variation according to the rotor position, as shown in Fig. 1. From the inductance variation, rotor position information is determined from the rotor position because of the saliency of the IPMSM characteristics: the spatial inductance distribution can be exploited. The rotor position of the IPMSM can be estimated from the back EMF voltage from the permanent magnet flux linkage using a state or observer or state filters.

$$\hat{v}_s = -\omega_L \sin \hat{\theta}_r \approx v_{ds} - R_s i_{ds} + \omega_L i_{qs} \sin \hat{\theta}_r \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad 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Fig. 1. Magnitude of current ripple according to the injected voltage signal at different rotor position to the stator.
Extended Summary

Concurrent Designs of Surface Permanent Magnet Machines for Self-Sensing Position Estimation and Power-Conversion

Shih-Chin Yang Non-member (Texas Instruments Incorporated, USA)
Robert D. Lorenz Non-member (The University of Wisconsin-Madison, USA)

Keywords: self-sensing machine, sensorless control

This paper presents the design approaches of surface permanent magnet (SPM) machines for saliency-tracking self-sensing position estimation with consideration of power-conversion capabilities. Three SPM machine design issues are discussed from the perspectives of position estimation. These are (1) design of rotor iron teeth to create an asymmetric rotor, (2) modification of stator tooth bridge height to have leakage flux saturation-induced saliency and (3) eddy-current loss reflected asymmetric resistance caused by the high-frequency signal injection. Simulations with finite element analysis are mainly used in this study to obtain an insight of the magnetic behaviors in SPM machines. It is shown that machine design tradeoffs between self-sensing position estimation and power-conversion performance can be made.

In the case of a self-sensing SPM machine design with the rotor iron teeth, the saliency whereby \( L_q > L_d \) (q-axis inductance) is achieved. The designed saliency is sufficient for position estimation. However, reduced torque output and increased torque ripple are the design tradeoffs.

In the case of a SPM machine design with modified stator tooth bridge height, the reverse saliency whereby \( L_d > L_q \) is resulted. This designed saliency ratio increases as load increases, which is suitable for position estimation. In addition, the minor impact on the power conversion is another important advantage for this saliency design.

In the case of a SPM design using loss-reflected asymmetric resistance, this type of saliency can appear in standard SPM machines when a high-frequency voltage is superimposed. However, the strong load dependency on the distribution of high-frequency eddy-current in the stator is the primary limitation.

By comparing the performance of these three saliency design methods, it can be concluded that the SPM machine with the modified stator tooth bridge height is a suitable saliency-design option because of its reverse saliency property and the minor impact on power conversion.

Goh Teck Chiang  Student Member  (Nagaoka University of Technology, tcgoh@stn.nagaokaut.ac.jp)  
Jun-ichi Itoh  Member  (Nagaoka University of Technology, itoh@vos.nagaokaut.ac.jp)

Keywords: AC/AC conversion, DC/AC conversion, induction motor, modulation techniques

This paper describes the performance and loss analysis of a three-port AC/DC/AC three-phase power converter based on the Japanese 10-15 mode vehicle driving pattern. The structure of the proposed circuit consists primarily of an indirect matrix converter (IMC) and a boost converter connected to the neutral point of the induction motor.

The authors previously proposed an AC/DC/AC circuit that is applicable to a HEV system; the circuit is shown in Fig. 1. The proposed circuit has an advantage owing to its size; which two passive components, the electrolytic capacitors and the boost reactor, have been removed from the converter. The boost converter connects the batteries to the neutral point of motor, and it utilizes the leakage inductance of the motor. In addition, the authors demonstrated that the proposed circuit could operate under PWM or single pulse modulation, which makes it suitable for HEV applications.

However, when the proposed circuit is implemented with single pulse modulation, the neutral point voltage becomes a square wave voltage with frequency that is three times the output frequency and an amplitude that is 1/6 of the DC link voltage. The voltage fluctuation affects the battery current because of the direct connection between the boost converter and motor.

In this paper, the discussion on the performance of the proposed circuit is divided into two parts. The first part shows that the proposed circuit can be operated under single pulse modulation. The application of feedforward compensation to the boost converter during single pulse modulation is proposed for the purpose of suppressing the battery ripple, which can be suppressed by approximately 72% (Fig. 2). The analysis data also show that the proposed converter can achieve high efficiency that is approximately equivalent to that of the PWM drive.

The second part discusses the overall performance of the proposed circuit for the Japanese 10-15 mode vehicle driving pattern. Converter losses under different conditions and circumstances are studied, and on the basis of the results, the optimal point of the power control for the converter is discussed. Three different operating modes are presented, and the proposed circuit is analyzed for two different modulations under the Japanese 10-15 mode driving pattern. All the simulation results and analysis data are presented in the paper. The data show that in order to achieve the highest efficiency, the proposed circuit should operate under specific conditions. For instance, Fig. 3 shows the efficiency that the proposed converter could achieve in cycle 1 of the Japanese 10-15 mode driving pattern, where the power management is divided into three modes. Mode III (HEV mode) can achieve the highest efficiency while operating under PWM for low speed drives, and the battery power should be designed to be approximately 30% of the output power.

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Fig. 1. Proposed circuit diagram

Fig. 2. Experimental results comparison between PWM and single pulse modulation

Fig. 3. Efficiency analysis in cycle 1 of the Japanese 10-15 mode driving pattern. (PWM, P_{out} = 30% of P_{in} in Mode II, and P_{out} = 30% of P_{in} in Mode III)
Extended Summary

Smart Grid Development in Taiwan

Chia-Chi Chu  Non-member  (National Tsing Hua University, Taiwan, cchu@ee.nthu.edu.tw)
Faa-Jeng Lin  Non-member  (National Central University, Taiwan, linfj@ee.ncu.edu.tw)
Po-Tai Cheng  Member  (National Tsing Hua University, Taiwan, ptcheng@ieee.org)

Keywords: renewable energy, smart grid, advanced metering infrastructure

1. Introduction

Ever since the first coal-fire electric generator was installed in 1888, Taiwan’s power grid has continued to grow to meet the needs of its people. In 1904, the first hydroelectric power station was commissioned in suburb of Taipei. Several small-scale, privately-owned electric companies flourished since then, before they were all consolidated and became Taiwan Power Corporation (台灣電力公司) in July 31, 1919, a corporation co-owned by the Taiwan Governor-General Office, the executive power during the colonial years, and several civilian organizations. Its generation capacity reached 320 MW in 1944. After the end of the World War II, it was re-organized in 1946 and became Taiwan Power Company (TPC, 台灣電力公司), a state-owned monopoly and the only power company in this country that operates the generation facilities, transmission/distribution network, and the retailing till today. TPC’s network is a typical south-north longitudinal and isolated system as illustrated in Fig. 1. Major load centers are located in the northern part of Taiwan and most of the power are supplied from the central and southern area through three parallel 345 kV corridors. In 2011, the total generation capacity of TPC has reached 40.25 GW.

TPC is in pace with other developed countries in promoting renewable energy developments aggressively. More recently, TPC is planning the fourth stage wind power development project with 12 WTGs and a total installed capacity of 14.8 MW at an investment of US$44.2 million from 2012 to 2015. In addition, TPC has been approved to invest US$112 million to develop solar PV energy from 2008 to 2011 as the first stage. The total installed solar PV capacity is 10 MW and will be completed in 2 MW, 3.5 MW, and 4.5 MW increments from 2009 to 2011.

Since 2010, the installed capacity of renewable energy has reached 3,341 MW in Taiwan. Based on government target, installed capacity of renewable energy is projected to be around 10,858 MW in 2030 as shown in Fig. 2. Of the renewable energy installed capacity, 2,502 MW will come from hydro, 3,156 MW from wind power, 2,500 MW from solar photovoltaic (PV), 1,369 MW from wastes, 1331 MW from biogas, ocean energy, geothermal and hydrogen fuel cell.

The renewable energy plays a critical role in this policy. The government also approved the Renewable Energy Development Act in July 8, 2009. Based on the energy policy white paper published in 2010, the renewable energy as a whole, including solar, wind, hyrdo, biomass and so on, should reach 8% of electricity generation, and 20% of installed capacity in year 2025.

The renewable energy is expected to grow in the coming years as the government policy outlines. Major renewable energy development will be presented in this paper.

The Smart Grid Strategic Initiatives of the government and TPC’s smart grid development are the main effort of the smart grid development. This paper introduces the main component of this research program and the current status of various demonstration sites.

Table 1. Taiwan Power Company’s generation capacity in 2010

<table>
<thead>
<tr>
<th>Thermal</th>
<th>Nuclear</th>
<th>Hydro (pump)</th>
<th>Renewable</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.194G</td>
<td>5.144 G</td>
<td>2.6 GW</td>
<td>2.306 GW</td>
<td>40.25G</td>
</tr>
<tr>
<td>(75.02%)</td>
<td>(12.78%)</td>
<td>(6.47%)</td>
<td>(5.73%)</td>
<td>(100%)</td>
</tr>
</tbody>
</table>

*: including pumped storage hydroelectricity.

Fig. 1. Target of renewable energy installation outlined by the Bureau of Energy, Ministry of Economic Affairs. (X axis: Year; Y axis: MW)

Fig. 2. Organization of smart grid and AMI research under Taiwan’s smart grid strategic initiatives.
A Single-phase-to-three-phase Power Converter
with an Active Buffer and a Charge Circuit

Yoshiya Ohnuma  Student Member  (Nagaoka University of Technology)
Jun-ichi Itoh  Member  (Nagaoka University of Technology)

Keywords: single-phase-to-three-phase power converter, indirect matrix converter, power factor correction

This paper proposes a new circuit configuration and a control method for a single-phase-to-three-phase power converter with power decoupling function. The proposed converter does not require a large inductor and large smoothing capacitors in the DC link part. Large smoothing capacitors are conventionally required in such converters to absorb the power ripple with a frequency that is twice that of the power supply. Further, conventional converters require a large boost inductor in order to control the input current. The proposed topology is constructed by using an indirect matrix converter with an active buffer to decouple the power ripple. In the proposed control method, half of the input power is supplied directly to the inverter. Therefore, the efficiency of the proposed circuit will be higher than those of the conventional Power factor correction (PFC) circuits. In addition, the transfer ratio between the input and output voltages is obtained to be 0.707 because of the connected charge circuit.

Fig. 1 shows the main circuits of the proposed converter. In the DC link part, an active buffer circuit consisting of a small capacitor and a switch is connected to a charge circuit. The charge circuit is similar to a boost chopper circuit but has a smaller inductance value because the circuit is operated in the discontinuous current mode (DCM) for controlling the current.

Fig. 2 shows a control block diagram of the proposed circuit. The duty ratio commands are determined from the input voltage \( v_{in} \), the input phase \( \theta \), which is calculated by using a phase locked loop (PLL) and the capacitor voltage \( v_c \). Note that the maximum input current \( I_{INp} \) is calculated from that the maximum capacitor voltage \( V_{Cmax} \) and the value of the minimum capacitor voltage obtained by using the voltage sensor. The gate pulses are obtained through space vector modulation.

Fig. 3 shows operation waveforms of a 1-kW-class prototype circuit with a 100 \( \mu \)F capacitor and a small 0.25 mH inductor. Using this circuit, good sinusoidal waveforms of the input and output currents can be obtained. In addition, it is confirmed that the input and output currents total harmonic distortion (THD) are 3.54% and 4.91%, respectively. The capacitor voltage can be controlled by adapting the proposed control method. These experimental results demonstrate the validity of the proposed circuit configuration and control method.

Fig. 4 shows the efficiency and the input power factor of the proposed circuit. The input power factor (PF) of over 99% is achieved. In addition, a maximum efficiency of 94.6% is obtained for the 1-kW prototype circuit.

The basic operation and validity of the proposed method are confirmed by experimental results.
High Performance Velocity Estimation for Controllers with Short Processing Time by FPGA

Manuel Nandayapa  Student Member  (Nagaoka University of Technology, mnandaya@stn.nagaokaut.ac.jp)
Chowarit Mitsantisuk  Member  (Nagaoka University of Technology, chowarit@stn.nagaokaut.ac.jp)
Kiyoshi Ohishi  Senior Member  (Nagaoka University of Technology, ohishi@vos.nagaokaut.ac.jp)

Keywords: velocity estimation, disturbance observer, motion control, FPGA, robotic, ball screw

At present, the most commonly implemented velocity estimation methods are the M and T methods. The proposed velocity estimation method reduces the calculation time by eliminating the division operation and prevents reduction in resolution owing to a short sampling time. In addition, the proposed method shows a high performance across a wide range of velocities. Program implementation in FPGAs has a low computational cost and a high calculation speed.

The proposed method uses a short sampling time and the fast clock signal (of the order of nanoseconds) of FPGAs. The proposed method is based on the M method, and the positions used to estimate the distance are almost the same. The difference between the methods is the processing time, with the M method using $T_s$ and the proposed method using a shorter time interval $T_p$ (see Fig. 1).

The proposed method uses the Eq. (1), which involves the resolution of the encoder $e_P$, the processing time $T_p$, and the number of processing times $m$ that are necessary between the present position $\theta(k)$ and the previous position $\theta(k - m)$.

$$\dot{\omega}(k) = \frac{2\pi(2^n)(\theta(k) - \theta(k - m))}{(e_P)(T_p)(m)} \quad \text{(1)}$$

The parameters $n$, $m$, $e_P$, and $T_p$ are chosen to obtain a simple subtraction.

In Table 1 the maximum, minimum, and mean values obtained from the experimental results are presented. The three cases show that the proposed method presents less deviation from the constant value. Figure 2 shows the experimental results.

<table>
<thead>
<tr>
<th>Method</th>
<th>Measure</th>
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<th>100 rad/s</th>
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<td></td>
<td>Mean</td>
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</table>

![Fig. 1. The Proposed method of velocity estimation](image)

Fig. 1. The Proposed method of velocity estimation

![Fig. 2. Experimental results of three methods with constant velocity using low, medium, and high values](image)
GA-Based Practical Auto-Tuning Technique for Industrial Robot Controller with System Identification

Eui-Jin Kim Student Member (Nagoya Inst. of Tech., Hyundai Heavy Industries, ejkim78@hhi.co.kr)
Kenta Seki Member (Nagoya Inst. of Tech., k-seki@nitech.ac.jp)
Makoto Iwasaki Senior Member (Nagoya Inst. of Tech., iwasaki@nitech.ac.jp)
Sang-Hun Lee Non-member (Hyundai Heavy Industries, mrshlee@hhi.co.kr)

**Keywords:** industrial robot, auto-tuning, autonomous identification, genetic algorithm

This paper presents a practical auto-tuning technique based on a genetic algorithm (GA) for servo controllers of multi-axis industrial robots. Compared to conventional manual tuning techniques, the auto-tuning technique can help save an engineers’ time and the cost of controller tuning, reduce performance deviation among products, and achieve higher control performance. The technique consists of two main processes. One is an autonomous system identification process involving the use of actual motion profiles of a typical robot. The other is an autonomous control gain tuning process in the frequency and time domains involving the use of a genetic algorithm, which satisfies the required tuning specifications, e.g., control performance, execution time, stability, and practical applicability in industries. The proposed technique has been validated through experiments performed with the six-axis industrial robot shown in Fig. 1, which is used in arc welding, sealing, and material handling applications. The robot consists of six links, AC motors with encoders, RV and harmonic drive gears, and payload.

In this research, the whole auto-tuning process is performed as shown in the flowchart in Fig. 2, using the combination of the autonomous system identification process and the autonomous control gain tuning process. Both processes are individually optimized by the GA. At first, mathematical model parameters for each axis and pose are autonomously identified by the GA. Next, the second GA-based optimization process, divided into two steps in the frequency and time domains, is performed to tune the control gains for each axis on the basis of the identified model parameters. Fig. 3 shows the result of a performance evaluation. Here, POA denotes the averaged position accuracy; PAA, the averaged path accuracy; OV, the averaged overshoot; VI, the averaged vibration; and CT, the sum of cycle times. Even though the indexes of the path accuracy and overshoot for auto-tuning are nearly similar to those for manual tuning, they are fairly decreased in the case of vibration, cycle time, and especially position accuracy, resulting in a decrease in the total evaluation criterion “Score.”