Elektrotechnisches Institut (ETI)
Prof. Dr.-Ing. Michael Braun
Prof. Dr.-Ing. Martin Doppelbauer
Prof. Dr.-Ing. Marc Hiller

Kaiserstr.12. 76131 Karlsruhe

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Authors:	Dennis Bräckle, Stefan Mersche, Mathias Schnarrenberger, Patrick Himmelmann, Marc Hiller
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Modular Multilevel Converters as active filters to mitigate low frequency current harmonics in converter fed grid applications

Dennis Braeckle*, Stefan Mersche*, Mathias Schnarrenberger*, Patrick Himmelmann*, Marc Hiller*
*Institute of Electrical Engineering (ETI) Power Electronic Systems
Karlsruhe Institute of Technology (KIT), Kaiserstr. 12, 76131 Karlsruhe, Germany
dennis.braeckle@kit.edu

Abstract

This paper describes a method to improve converter fed grid structures with Modular Multilevel Converters (MMC). In grids with decentralized energy production and bidirectional power flow, an increasing number of power electronic loads and sources make power quality an important issue to ensure grid stability. The MMC topology is highly suitable to meet the requirements of a low Total Harmonic Distortion (THD) and voltage stability due to its high quality output voltages. In combination with power line communication based on harmonic injection, MMCs compensate low frequency grid current harmonics and imbalances to improve the power quality. A standalone laboratory-scale converter-fed microgrid including low voltage MMCs shows the capability of the developed control algorithms.

1. Introduction

Renewable energy integration and decentralized generation have become more important in recent years and will continue in the future [1]. Most of these installations use power electronics for grid connection. Power quality plays an important role to meet the grid codes and ensure system stability. Modular Multilevel Converter (MMC) based topologies are a promising technology to act as active filters to improve the total harmonic distortion (THD) of currents and voltages. They deliver a high voltage quality and increased bandwidth compared to conventional two level converters [2]. In addition, MMCs can compensate unbalanced loads in the system.

Future grid topologies do not necessarily contain large rotating masses. Instead, power electronics based converters could provide the grid voltage and frequency or be connected as loads to the system. Here, the new approach allows the grid-forming converter to communicate with other converters in the system, using selective harmonic injection and detection to delegate grid-supplying tasks among the installed converters. Therefore, no additional current and voltage sensors for acitve filtering are required. A droop control based method allows selective compensation of harmonics in grid currents. In addition, imbalanced load currents can be compensated and balanced. A laboratory-scale standalone microgrid shows the performance of MMC based active filters.

The first part describes the communication among converters using selective harmonic injection and detection. The second part deals with the laboratory microgrid setup. Measurement results verify the capability of MMCs in converter-fed grids as active filters to compensate low frequency harmonics and unbalanced load conditions.

2. Control algorithm to distribute filter activities among installed converters

The control algorithm is based on the assumption that a microgrid will have one converter that has the responsibility to generate the grid voltage defining its effective value and frequency. This converter does not need to deliver a significant amount of active power to the grid. It will be further referred to as the ”grid-forming converter”. The other converters in the microgrid will synchronize themselves to the grid-forming converter and optionally deliver additional grid services as described in this paper.

The idea of the proposed control algorithm is that the grid-forming converter injects harmonics into the grid voltage depending on the detected harmonic currents. Participating converters in the system measure this voltage and start injecting compensating currents to reduce the overall grid current THD at the point of common coupling (PCC).

The algorithm is divided up into two parts. First, the detection of harmonics and injection of grid voltage disturbances are investigated. Second, the detection of those information on the filter converter side is discussed. As a result, the overall THD is reduced and unbalanced currents are compensated.

2.1. Proposed control loop

Figure 1 depicts the control loop for identification and compensation of grid current harmonics. All voltages and currents are in an othogonal reference frame (Clarke transformation) using complex numbers. The grid-forming converter measures the current i_g delivered to the grid. This current is filtered to identify the occuring harmonics that need to be compensated. A transformation into a stationary rotational frame (SRF) using the harmonic voltage phase angle $n \cdot \gamma$, is applied. Here γ is the instantanious phase angle of the voltage and n is the order of the harmonic that is to be detected. A following low pass filter determines the amplitude i_n of the n^th current harmonic occurring in the grid currents. The constant k_n deliveres a reference value for the vonltage harmonic to be injected by the grid-forming converter. k_n is chosen in a way that the voltage measurement of the active filter converter is able to measure the harmonic voltage. The grid voltage fundamental frequency is then superposed with the low frequency voltage harmonics. The allocation of the n^th-current harmonic to the n^th-voltage harmonic is arbitrary. In addition, occurring negative sequence currents can be detected using the same methods [3].

In general an imbalance in the grid currents can be described as a the "'first negative harmonic"'. This means that the same control as for the other harmonics can be used with one slight modification: An imbalance in the voltage is highly undesireable. Therefore, another harmonic must be chosen to communicate the imbalance to the other converters.

The current harmonic compensations for each n-th harmonic occurring is not necessarily implemented in a single active filter converter. Depending on the grid structure and power capability of each system, the compensation is distributed. In fig. 1 the detection for one harmonic component is shown but can be extendet to multiple harmonics and distributed to other converters. The injected voltage harmonics are detected by any arbitrary grid feeding or active filter converter in the system. The filter converter measures the grid voltage $\underline{u}_\mathrm{g}$. For the n^th harmonic, the converter detects the voltage harmonic using also a SRF and a low pass filter. In addition with the constant k_n^{-1} the amplitude $\hat{i}_\mathrm{n}$ of the n^th grid current harmonic is calculated. The set point for those currents is zero for total compensation. A current controller is used to calculate the set points for the converter output voltage $\underline{u}_\mathrm{c}$. The filter converter is connected with an inductor to the grid. As a result a harmonic current is injected.

The dynamics of this power line based control loop mainly depends on the filter constants of the low pass filters in fig. 1. The current controllers are simple PI-controllers in the SRF of the respective current harmonic. Using MMC based structures allows a high bandwidth and a compensation without significantly increasing switching losses [2].

To improve the performance of the system, more advanced harmonic detection methods like proportional-resonant (PR) loops or second-order generalized integrators can be used [4]. It is also possible to use more advanced current controller with dead beat behavior to reduce the number of current controllers required. However, the presented structure works up to the 19^th harmonic in the laboratory standalone grid with a 60 Hz fundamental frequency. A structure adapted from fig. 1 also identifies unbalanced currents resulting in a balanced grid current under imbalanced load conditions. Further, the decentralized structure of compensation possibilities allows a distribution of fundamental frequency current and harmonic compensation currents.

3. Laboratory-scale standalone grid

The theoretical elaboration for compensating harmonic and unbalanced grid currents using MMCs is verified with a laboratory standalone grid.

Figure 2 shows the structure of the standalone grid. A DC-AC MMC with half bridge cells [5] is used as the grid-forming converter providing an standalone grid. At the point of common coupling (PCC) an MMC based active filter is connected with an inductor L. In addition, a diode rectifier, a conventional

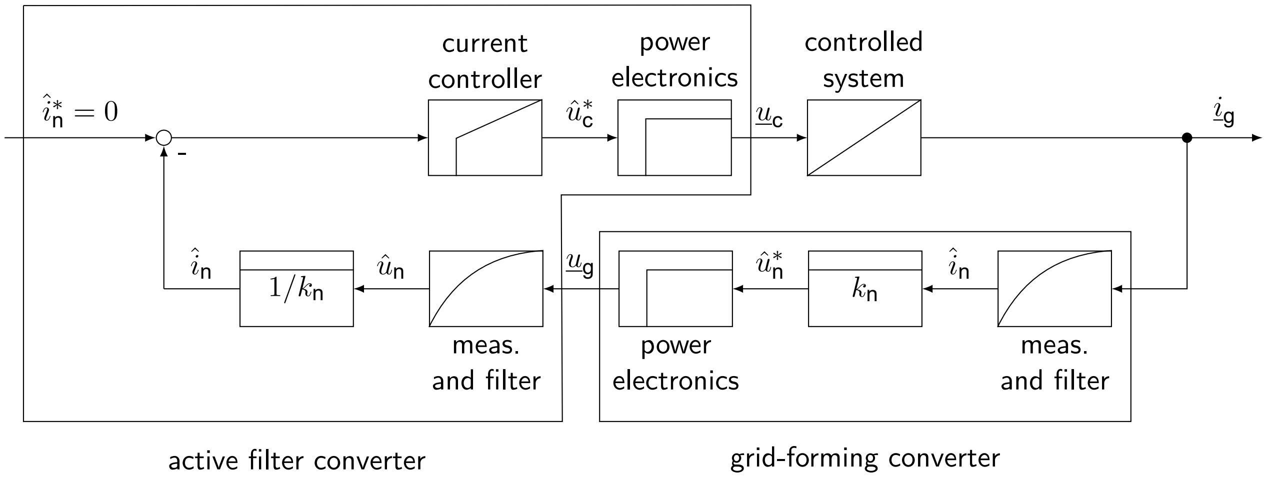

Fig. 1: control diagram of the injection of harmonic voltages and currents for active filtering

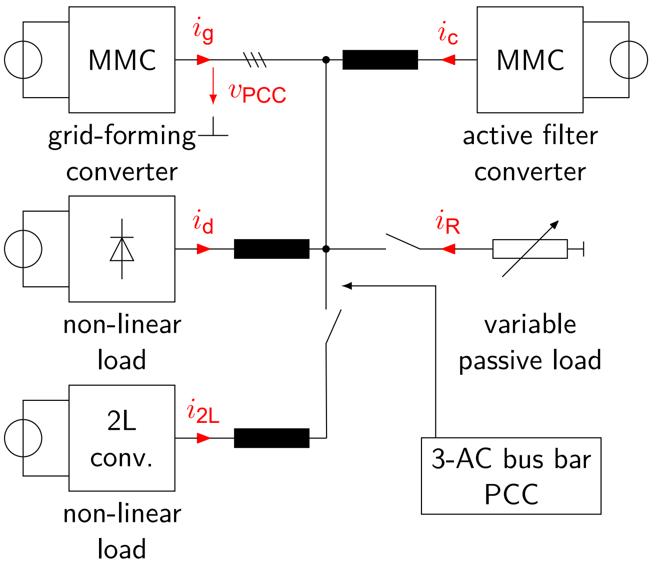

Fig. 2: laboratory-scale standalone grid. An MMC is the grid-forming converter. Another MMC is participating as an active filter. In addition, a non-linear load, a variable passive load and a conventional 2L converter can be connected to the grid.

2L-converter to act as sink or source and a variable passive load are coupled. Using the proposed control strategy, other converters can support the grid-forming converter during steady state operation by injecting current harmonics or reactive currents.

3.1. Implementation

Table 1 lists the system setup and parameters of the microgrid. The grid forming converter generates a 3-phase sinusoidal voltage system with no additional filter and provides the grid current i_g. The converter systems are not synchronized. The system is tuned to compensate the 5^{th} and 7^{th} harmonic, as well as a occurring negative sequence system caused by an unbalanced load. The low pass filters from section 2.1 are implemented as moving average filters with a length of one period of the fundamental frequency. The dynamics of the overall system are highly dependant on the filter characteristics. The chosen filter is a trade off between detection capability of harmonics and dynamics of the overall system.

Tab. 1: Setup of the standalone grid

power rating of the connected MMCs	10 kVA
control frequency (active components)	8 kHz
non-linear load	15 kVA
passive load	10 kW
power rating of 2L converter	25 kVA
PCC voltage	370 V
PCC frequency	60 Hz

4. Measurement Results

The proposed control strategy for harmonic compensation using MMC based active filters is verified with the standalone grid described in section 3.

4.1. Identification of Current Harmonics

First, the identification of current harmonics by the grid-forming converter is shown. Here only the diode rectifier based load is connected and draws current i_d from the standalone grid. The active filter is controlled to 0 A. Figure 3 shows the voltages

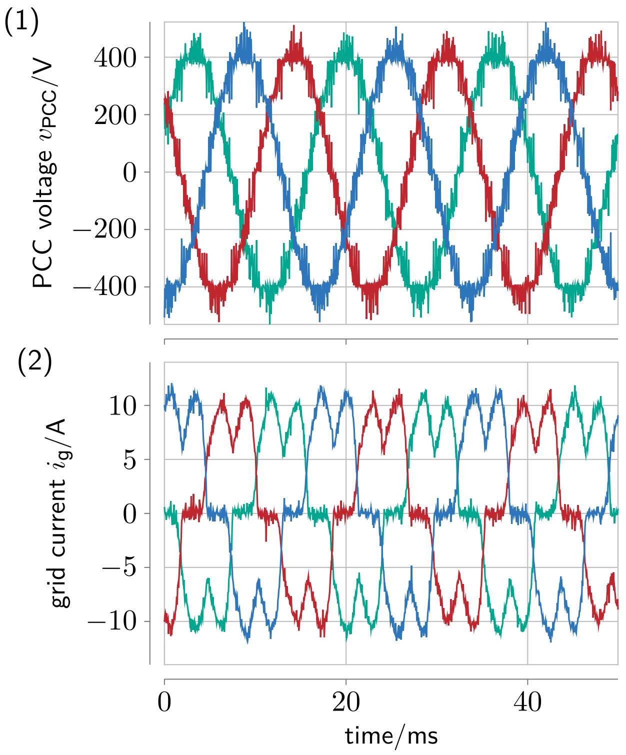

Fig. 3: (1) PCC voltages v_PCC with injected harmonics, (2) grid currents i_g drawn by the diode rectifier

v_PCC of the PCC of the standalone after the injection of voltage harmonics as well as the grid currents i_g. The grid forming converter identifies the 5^th and 7^th current harmonic and injects the corresponding voltage to the grid. In fig. 3 it can be seen that the voltage harmonic have no obvious impact on the output voltage.

However, fig. 4 shows the low frequency harmonic content of the grid voltage. Before the injection (blue), the harmonic content of low frequent harmonics is near zero because of the high voltage quality of the MMC. The 5^th and 7^th harmonic are then injected by the control algorithm and are detected by the compensating converters in the system.

4.2. Compensation of Low Frequency Current Harmonics

In the operational point from section 4.1 the active filter MMC is connected to the grid. The filter starts

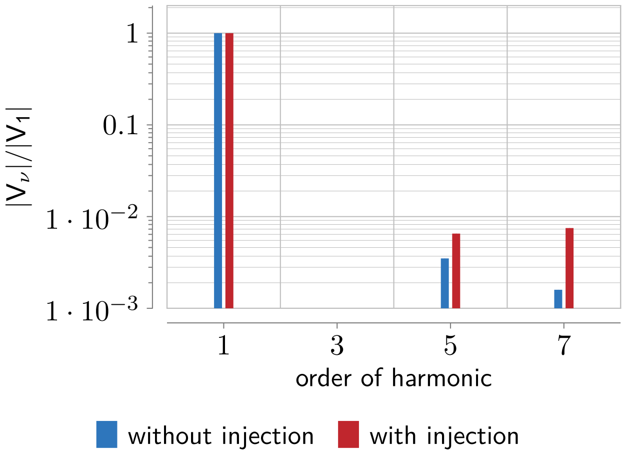

Fig. 4: harmonic content of the grid voltage without harmonic injection (blue) and with harmonic injection (red)

injecting compensating currents i_c to the grid in a way, that improves the harmonic content of the grid currents i_g to the grid forming converter.

Current and Voltage Waveforms

Figure 5 shows the steady state operation of the system when the load current is compensated. Figure 5 (1) are the grid voltages v_PCC at the PCC. The grid currents are depicted in fig. 5 (2). In comparison to fig. 3 (2) the grid currents i_g mainly contain the fundamental frequency after compensation. Figure 5 (3) shows the corresponding load currents i_d drawn by the diode rectifier. The filter currents i_c are shown in fig. 5 (4). The currents contain the 5^th and 7^th harmonic of the load current. No additional active power is delivered to the grid. The filter is capable of compensating the low frequency current harmonics of the grid currents to improve the system power quality.

Current Spectrum Analysis

The Waveforms presented in section 4.2 are analyzed regarding their harmonic content before and after compensation.

Figure 6 shows the spectrum of the measured currents before (Figure 6 (1)) and after (Figure 6 (2)) compensation of the 5^th and 7^th harmonic of the load current. First, the filter converter is connected to the grid but does not inject any current. The grid current's 5^th and 7^th harmonic $i_{\mathrm{g},5}$ and $i_{\mathrm{g},7}$ are then mitigated to the filter currents $i_{\mathrm{c},5}$ and $i_{\mathrm{c},7}$. The

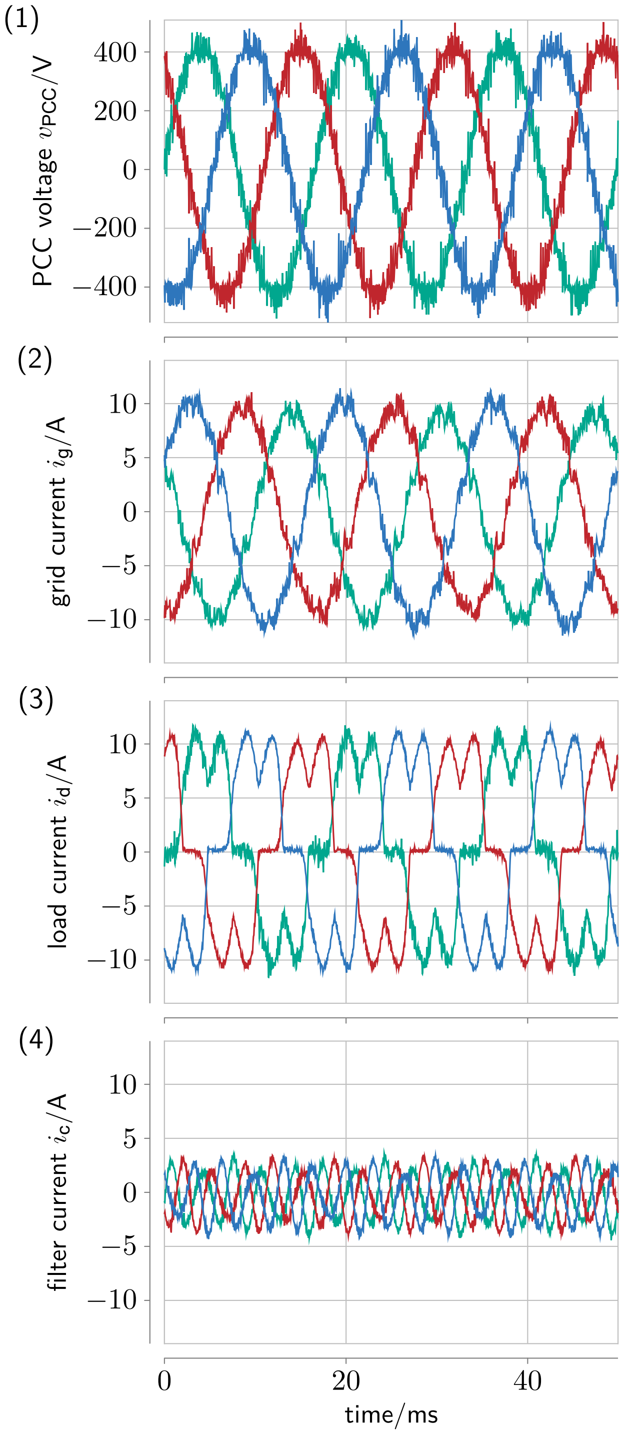

Fig. 5: compensation of load current harmonics. (1) grid voltages, (2) grid current, (3) load current, (4) filter current provided

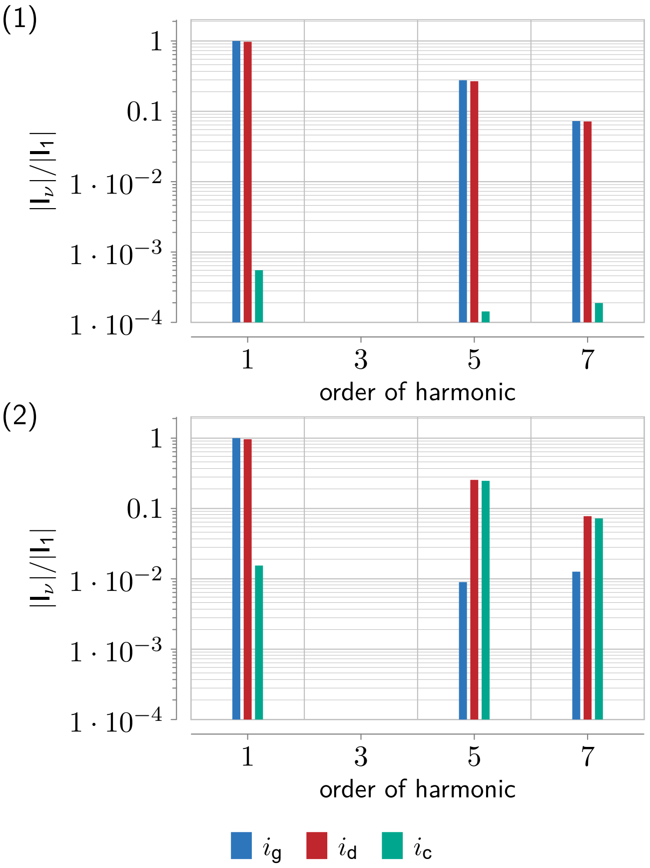

Fig. 6: spectrum of the measured currents. (1) before compensation, (2) after compensation

grid current harmonics are reduced by a factor of 100, resulting in a improved THD of the grid current of 0.81 % compared to 6.60 % before the compensation. In addition, the fundamental frequency filter current increases to compensate the converter losses. The results show a steady state stability of the system compensating low frequent current harmonics.

4.3. Compensation of Unbalanced Grid Currents

This section describes the compensation of an unbalanced load. As presented in section 2.1 unbalanced load currents are identified in the same manner as low frequent harmonics. The unbalanced load is a variable load resistor connected to the grid from fig. 2. The diode rectifier from section 4.2 is disconnected from the grid.

Figure 7 depicts the stationary operation under unbalanced load conditions. The load is connected only to two phases of the feeding grid. The grid currents in fig. 7 (1) are compensated to be symmetrical. The load currents in fig. 7 (2) are unbalanced between the three phases. The grid-forming

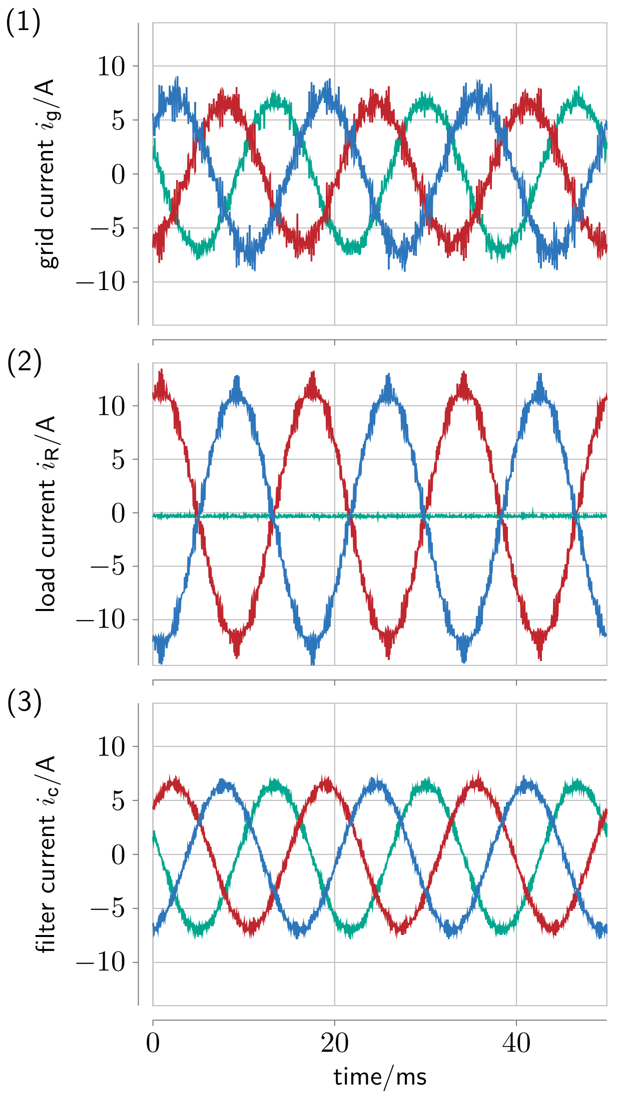

Fig. 7: compensation of an unbalanced load. (1) grid current i_{g}, (2) load current i_{R}, (3) filter current i_{c}

converter detects the imbalance and injects a 19^{th} harmonic to the grid voltage. The filter converter injects the corresponding compensation currents i_{c} in fig. 7 (3). As a result, the imbalance is mitigated from the grid-forming converter to the filter and the grid currents become a symmetrical 3AC-system.

4.4. Combination of Compensating Harmonics and Imbalances

The results presented in sections 4.2 and 4.3 can be combined into a simultaneous compensation due to the chosen voltage harmonics for identification and communication. Figure 8 shows the filter working in stationary operation under unbalanced load as well as compensating low frequency current harmonics. It can be seen, that stable operation is possible with different loads and grid supply activities at the same time. The grid currents are shaped

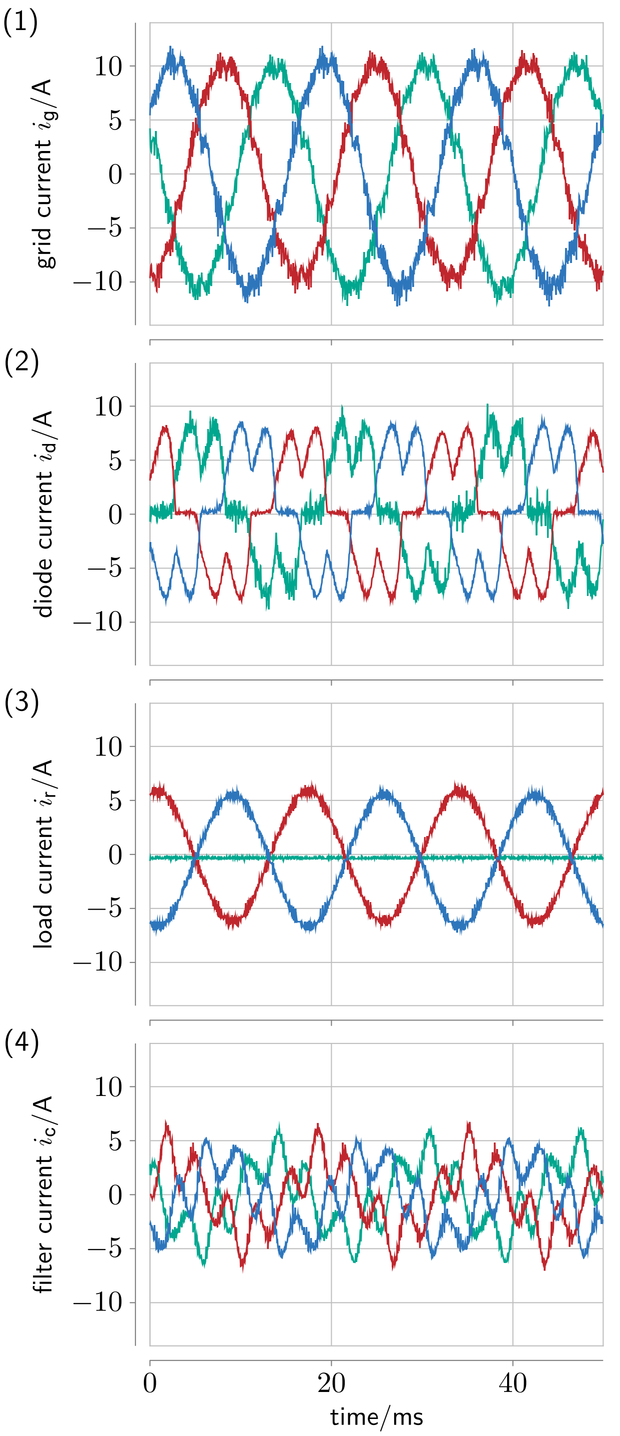

Fig. 8: simultaneous compensation of low frequency harmonics and an unbalanced load: (1) grid current i_{g}, (2) diode rectifier current i_{d}, (3) unbalanced load current i_{r}, (4) filter current i_{c}

sinusoidal and symmetrical.

4.5. Distribution of Grid Support Among Participating Converters

Using the selective harmonic injection for different filter and support tasks allows a distribution of these functions among different participating converters. The corresponding identification filters have to be tuned accordingly. The measurements are done with an additional two-level converter providing the fundamental frequency current for the diode rectifier. The MMC based active filter compensates the low frequency current harmonics. As a result, the grid-feeding converter is under no-load operation and only provides the grid voltage and non-compensated harmonics. The results show that the different controllers on the systems do not interfere with each other and that the system stays stable under load conditions. Figure 9 depicts the corresponding measurements. The fundamental frequency load current is provided by the 2L converter. The information of the amplitude and phase is modulated onto the 17$^{\mathrm{th}}$ harmonic of the grid voltage. The MMC filter again provides the 5$^{\mathrm{th}}$ and 7$^{\mathrm{th}}$ current harmonic to keep the grid-forming converter near no-load operation.

4.6. Transient of Identification and Compensation

In this section the transient during the activation of compensation is presented. Figure 10 (1) depicts measurements of the grid phase voltages. Figure 10 (2) shows the grid currents i_{g} of the grid-forming MMC. For $0\,\mathrm{s} \leq t \leq 0.04\,\mathrm{s}$ the grid-forming converter delivers all of the load currents i_{d} (Figure 10 (3)). At $t = 0.02\,\mathrm{s}$ harmonic voltages are injected to compensate the 5^{th} and 7^{th} harmonics with the active filter MMC according to the control scheme presented in fig. 1. At $t = 0.04\,\mathrm{s}$ the measured values are accurate enough to enable the compensation. Figure 10 (4) shows the filter currents i_{c}. As a result, the active filter MMC mitigates the low frequency harmonics of the grid currents i_{g} in Figure 10 (2) to higher frequencies. Here, an additional feed forward path in comparison to fig. 1 is implemented. The system is in steady state operation after $\Delta t \approx 16\,\mathrm{ms}$.

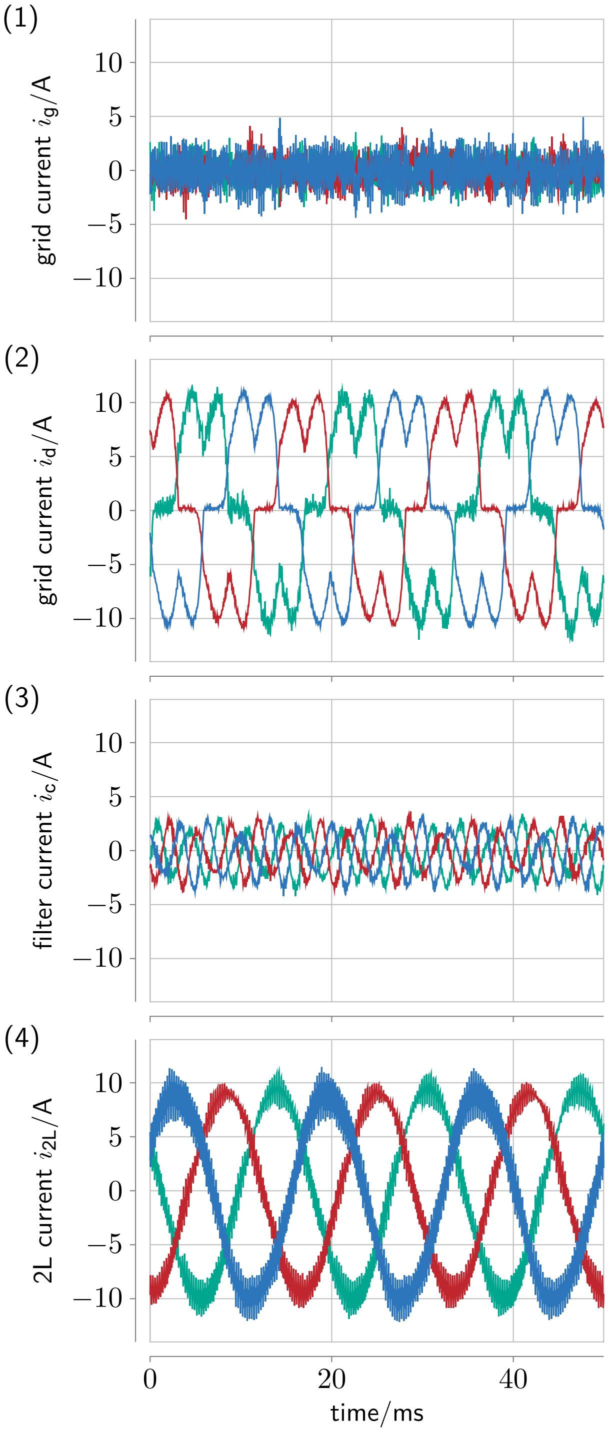

Fig. 9: compensation with different active filter converters simultaneously. (1) grid current i_{g}, (2) diode rectifier current i_{d}, (3) harmonic filter current i_{c}, (4) fundamental filter current i_{2L}

5. Conclusion

A new method to compensate current harmonics and unbalanced load currents in a converter-fed

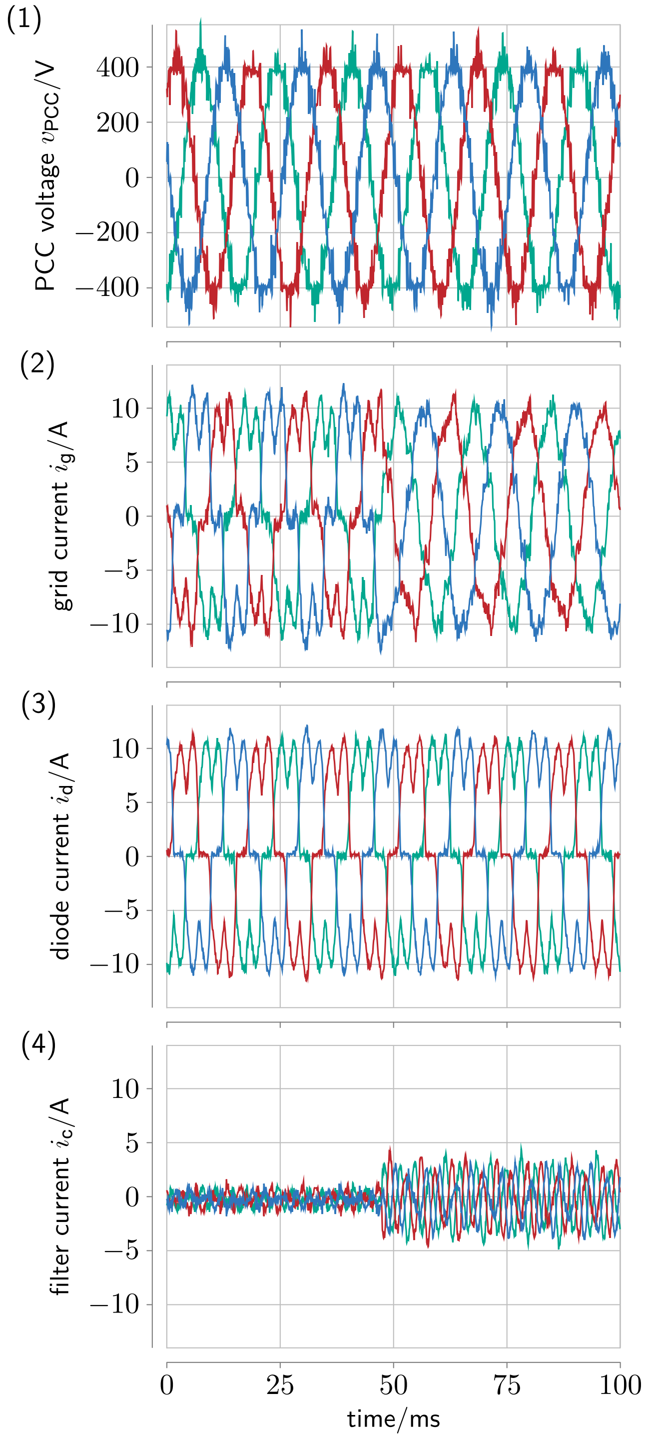

Fig. 10: measurement results of the laboratory scale standalone grid (1) grid voltages of the feeding MMC, (2) grid currents of the feeding MMC, (3) load currents of the diode rectifier, (4) filter currents of the MMC-active filter; at $t = 0.04\,\mathrm{s}$ the diode currents are compensated with the active filter MMC

standalone grid is presented. The grid-forming converter injects harmonics into the grid voltage according to the current harmonics that are to be compensated. The active-filter converter detects the voltage harmonics and injects the corresponding compensation currents. Modular Multilevel Converters are highly suited to perform this power line communication because of their available bandwidth. In addition, the compensation can be distributed among participating converters corresponding to their power rating. Measurements with a laboratory setup with an MMC based standalone grid and active filter verifies the theoretical approach. The low frequency load current harmonics are compensated and the overall THD of the grid current is improved.

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