Research Laboratory for Testing Grid Connected Devices under Grid Voltage / Grid Impedance Variations and Microgrid Conditions

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Keywords

«Fault ride-through», «Grid-connected converter», «Impedance analysis», «Test bench», «Transmission of electrical energy»

Abstract

Distributed (renewable) energy sources and a growing amount of loads are connected to the grid via (switched) power electronics. To investigate the grid-integration of these devices, a test bench was built up, which offers the possibility to vary the impedance and the voltage (in amplitude, waveform and frequency) at the PCC during operation. For this purpose, the test bench includes a transformer-based *Grid Voltage Emulator*, a *Grid Impedance Emulator* as well as a *4Q-AC-Source*. Due to the increasing use of power electronics, the grid tends to behave capacitively in some load cases. To cover this topic as well, the test stand also includes a binary graded capacitor bank to emulate volatile capacitive loads. The design, realization and operation of the respective components is described in this paper. In addition, various experimental results regarding the grid voltage and impedance emulator are presented focusing e.g. on the current commutation of highly inductive loads. Furthermore, measurements of different devices under test, like an impedance analyzer or an active resonance damper, are shown.

Introduction

The electric power supply in many countries is changing from a centralized energy generation to a distributed and decentralized renewable energy generation [1]. Many of these renewable energy sources are connected to the grid via power electronics. Due to the decentralized energy generation, the power distribution network is getting less stable and harder to operate, why only centralized power plants like coal-fired or nuclear power plants cannot realize the grid control. In addition, the small and medium decentralized power plants have to take part in the grid control. Therefore, new control strategies for grid-connected inverters like the grid-forming control [2,3] instead of the grid-following control are needed. Compared to centralized power plants, the decentralized energy generation and grid-feeding via power electronics is offering a way higher dynamic behavior, but also a higher volatility regarding the amount of the provided energy, what must also be taken into consideration.

The grid integration of these decentralized power plants can be investigated in different ways: simulations, field tests and laboratory tests. Simulative analysis is a fast approach, but often simplifications have to be done, why the real and detailed behavior and interaction of the grid-connected devices cannot be figured out. Practical field tests and measurements with the real hardware setup are the most realistic way of investigation, but they are very expensive and time consuming. Furthermore,

the parameters like e.g. the grid impedance cannot be influenced, why investigations have to be done at different places to cover a broad range of scenarios. As the previous explanations reveal, laboratory tests are offering a cost and time saving option to investigate the grid-integration of power electronic devices. Additionally, the investigations can be carried out in a safe environment, what is advantageous especially when new hardware or control setups are investigated. To emulate the relevant grid characteristics, appropriate devices had to be designed and developed for the laboratory test bench.
Beside the frequency, the amplitude and the waveform of the voltage as well as the impedance at the (internal) point of common coupling ((I)PCC) are the main characteristics of a grid. Due to e.g. load changes, voltage sags/swells as well as interruptions, caused by failures, can occur. The short-circuit power and with this the impedance of the grid is also varying, especially when the grid is fed by a relevant amount of renewable energy sources, since the energy fed to the grid is depending on the time of day and the season.

This paper is dealing with the design and the development of a *Grid Voltage Emulator* and a *Grid Impedance Emulator*. Additionally, a (commercial) four-quadrant grid-simulator (*4Q-AC-Source*) can be integrated to vary not only the amplitude of the voltage, but also the waveform and the frequency to realize e.g. distorted voltages or frequency variations at the PCC. Furthermore, a *Resonance Generator* consisting of binary graded capacitors can be used to emulate a capacitive load / a capacitive grid. This allows the creation of a resonance point, whose resonance frequency depends on the capacitance of the *Resonance Generator* and the inductance of the *Grid Impedance Emulator*.
One main target of the development was to vary the grid parameters online, that means while the devices under test (DUTs) are connected to the grid and are operating according to their respective purpose. Hereby, not only the steady state, but also the transient behavior of the DUTs can be investigated. Exemplary steady state investigations are the behavior while long-term under-/overvoltage or the operation under distorted/unsymmetrical PCC voltages. Transient investigations are e.g. fault ride through tests (symmetrical or unsymmetrical) or the emulation of switching operations in the grid, which can result in a change of the short-circuit power of the grid and with this in a change of the impedance at the PCC. For the online variation of the grid parameters, IGBTs instead of e.g. thyristors or electromechanical switches are applied to change between voltage or impedance levels. Different issues as switching of highly inductive loads or short-circuit protection of the transformers secondary windings when switching between the voltage levels were considered and will be discussed. Experimental tests and measurements of the emulators itself as well as of selected DUTs, e.g. of the impedance analyzer, will be presented.

For the medium voltage-level, several publications can be found regarding a grid emulation, e. g. [4,5]. Some groups of researchers were already dealing with the topic of voltage and impedance emulation or micro grid at the low-voltage level, e.g. [6,7] in a laboratory scale (up to 30 kVA) or [8] (several 100 kVA, depending on the configuration). Also, several members of the *European Distributed Energy Resources Laboratories* (*DERlab*, ref. [9]) are focusing on this topic.
Nevertheless, only a few articles regarding voltage and impedance emulation can be found in the literature, although the topic is relevant and actual in the context of the transformation of the electric power supply. Therefore, this article would like to offer a contribution to this topic regarding the design, realization and operation of such a test bench.

The article is structured as follows: First, the setup of the components of the test bench will be described. Subsequently, the entire test stand and possible components are discussed, what will be followed by the experimental results. The article is concluded by a summary and an outlook.

Setup of the Grid Voltage Emulator, the Grid Impedance Emulator and the Resonance Generator

The single-phase setups of the *Grid Voltage Emulator* and the *Grid Impedance Emulator* are shown in Figs. 1a and 1b, respectively. The main component of the *Grid Voltage Emulator* is a three-phase four-wire transformer (primary voltage 400 V, rated power 50 kVA, 4 % short-circuit voltage) with eight taps for different secondary voltage levels (20%, 40%, 60%, 70%, 80%, 90%, 100%, 110%). The voltage levels can be preselected by manual switches. Switching within operation is realized via the IGBT switches, which will be discussed in detail afterwards.

Beside the IGBTs for switching during operation, the *Grid Impedance Emulator* consists of inductors, which are connected in series. A preselection can be done by the manual switches. Additionally, it is possible to short-circuit the inductors to vary the inductance of the preselection. For this purpose, the taps of the inductors are wired to connectors at the front of the cabinet (see Fig. 6, the first connectors from the bottom).

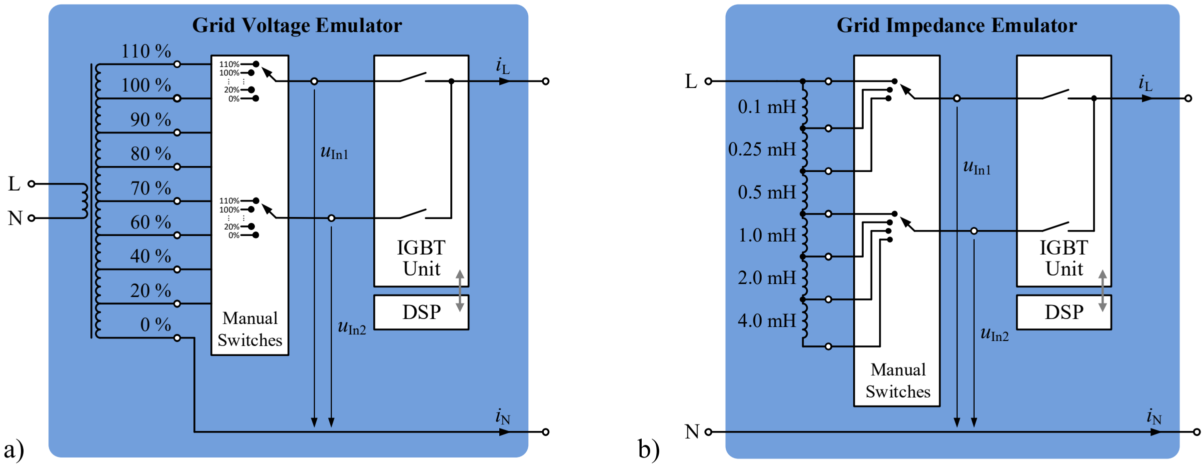


Fig. 1: Single phase setup of a) the Grid Voltage Emulator and b) the Grid Impedance Emulator

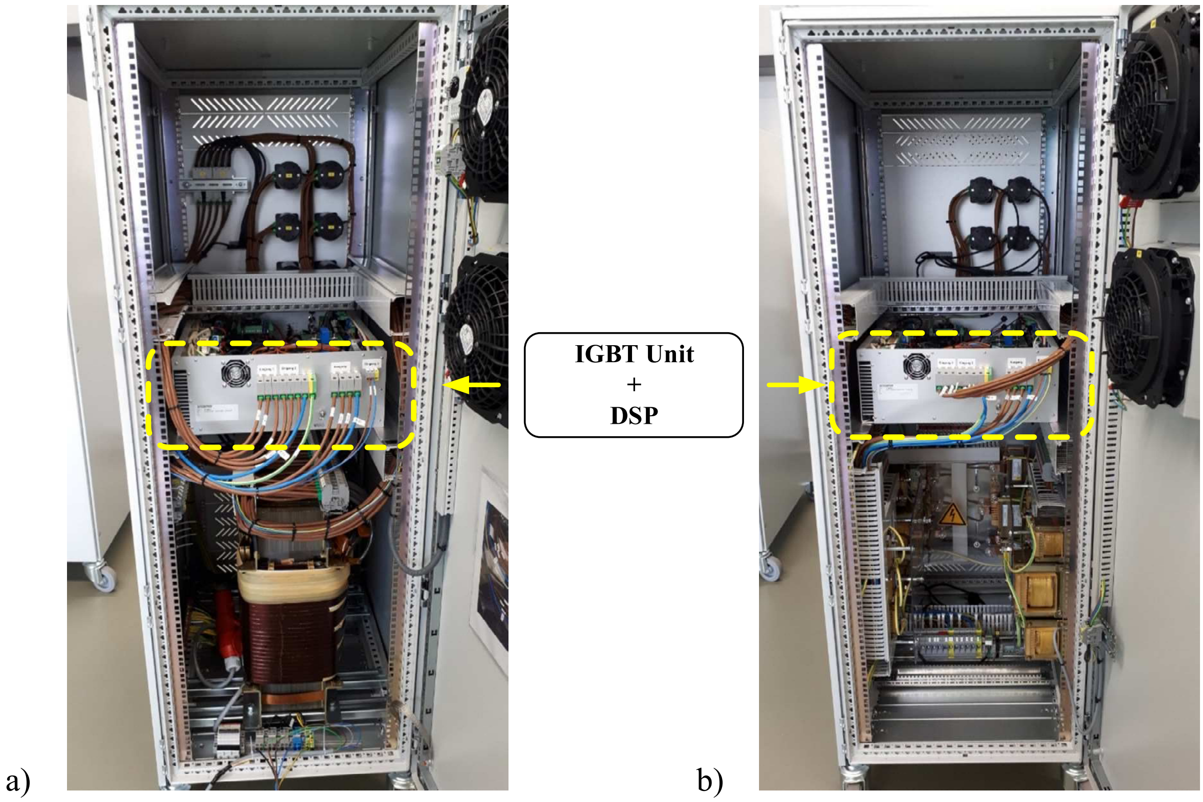


Fig. 2: Photograph of a) the Grid Voltage Emulator and b) the Grid Impedance Emulator

At both emulators, the IGBT switches are controlled by a Texas Instruments TMS320F28377D digital signal processor (DSP). Both input voltages u_{In1} and u_{In2} as well as the three phase currents i_L and the neutral conductor current i_N are measured. By this, an overvoltage and an overcurrent protection can be realized. In addition, the phase angle of the voltages can be derived by the voltage measurement and with this the phase angle of the switching operation can be chosen (e.g. in the zero crossing or the maximum of the voltage, see experimental results). This can be advantageous for some applications like the suppression of inrush currents at capacitive loads. The single-phase schematic of the IGBT unit is shown in Fig. 3a.

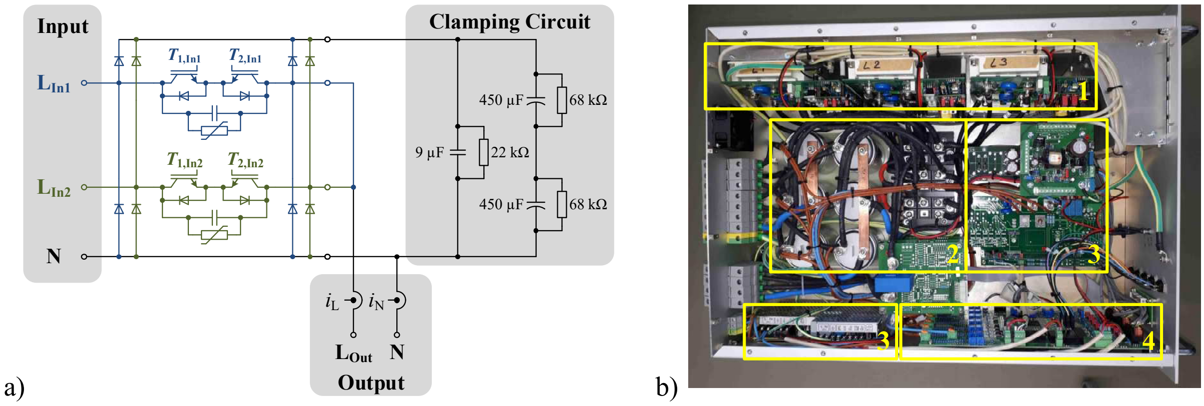


Fig. 3: IGBT unit: a) Single-phase setup b) photograph (IGBT modules (1), electrolytic capacitors and diodes of the clamping circuit (2), power supply (3) and DSP and analog signal processing (4))

Per input branch, two antiserial connected IGBTs (Semikron SKM400GM17E4, V_{CES} = 1700 V, I_{Cnom} = 400 A, ref. [10]) are used. The current carrying capacity of the IGBTs is overrated intentionally far above the maximum currents (I_{max} = 60 A_{RMS}) of the emulators in order to take e.g. inrush currents of capacitive loads or grid-connected induction machines into account. To protect the IGBTs from high du/dt stress and overvoltage, a snubber capacitor and a varistor are connected directly on the screw terminals of the IGBT modules. For the switching of highly inductive loads, an additional clamping circuit was integrated into the IGBT units, consisting of a low-inductive film capacitor and electrolytic capacitors, also including discharging resistors. The clamping is realized by diode rectifier modules (International Rectifier 90MT160K, V_{RRM} = 1600 V, I_{FSM}(50Hz) = 770 A). In Fig. 3b, the afore mentioned components can be seen in the photograph of the IGBT unit.
The design of the clamping circuit was carried out on the basis of a single-phase worst-case scenario:

- the maximum inductance of the *Grid Impedance Emulator* is about 8 mH. Taking the inductances of the *Grid Voltage Emulator* and a possible inductive load into account, the maximum series inductance is assumed to be about L_{max} = 12 mH,
- the maximum load current is 60 A_{RMS},
- the load gets completely disconnected from the IPCC,
- the load is disconnected at the time, the load current has reached its peak value.

With these worst-case assumptions, the maximum energy stored in the inductances is

$$E_{L,max} = \frac{1}{2} \cdot L_{max} \cdot \left(\sqrt{2} \cdot I_{max}\right)^2 = \frac{1}{2} \cdot 12\,\text{mH} \cdot \left(\sqrt{2} \cdot 60\,\text{A}\right)^2 = 43{,}2\,\text{Ws}. \tag{1}$$

Neglecting any ohmic losses, this energy has to be stored in the capacitors in addition to the initial energy of the capacitor. The voltage depending energy difference stored in a capacitor is

$$\Delta E_C = \frac{1}{2} \cdot C \cdot \left(U_2^2 - U_1^2\right), \tag{2}$$

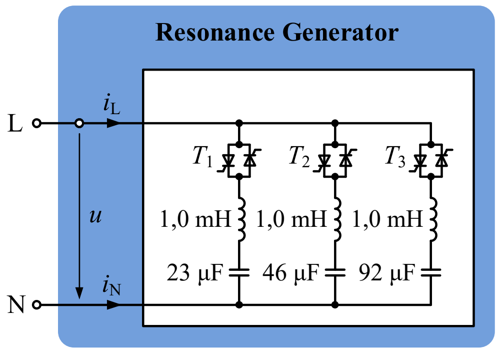
where the initial voltage U_1 is the peak input voltage of 325 V und U_2 is the final voltage. With this, the final voltage U_2 at the capacitor can be calculated:

$$U_2 = \sqrt{\frac{E_{L,max}}{\frac{1}{2} \cdot C} + U_1^2} = \sqrt{\frac{36\,\text{Ws}}{\frac{1}{2} \cdot 234\,\mu\text{F}} + \left(325\,\text{V}\right)^2} \approx 689\,\text{V}. \tag{3}$$

This voltage is within the permissible voltage range, which is limited to 800 V due to the clamping circuit capacitors rated voltage.

Another component of the test bench, the *Resonance Generator*, is used to emulate a variable capacitive load and with this a frequency-variable resonance point in combination with the inductance of the *Grid*

Impedance Emulator. The single-phase setup of the *Resonance Generator* is shown by Fig. 4a and consists of three binary graded capacitors, which can be switched by anti-parallel thyristors. The series inductors are offering an additional degree of freedom regarding possible resonance frequencies, which are in the range of about 200 Hz to 3 kHz. A more detailed view on the *Resonance Generator* is given by [11].



a)

b)

Fig. 4: Resonance generator: a) single phase setup and b) hardware setup

Overall Setup of the Research Laboratory

The overall setup of the research laboratory including an exemplary selection of grid-connected devices is given by Fig. 5.

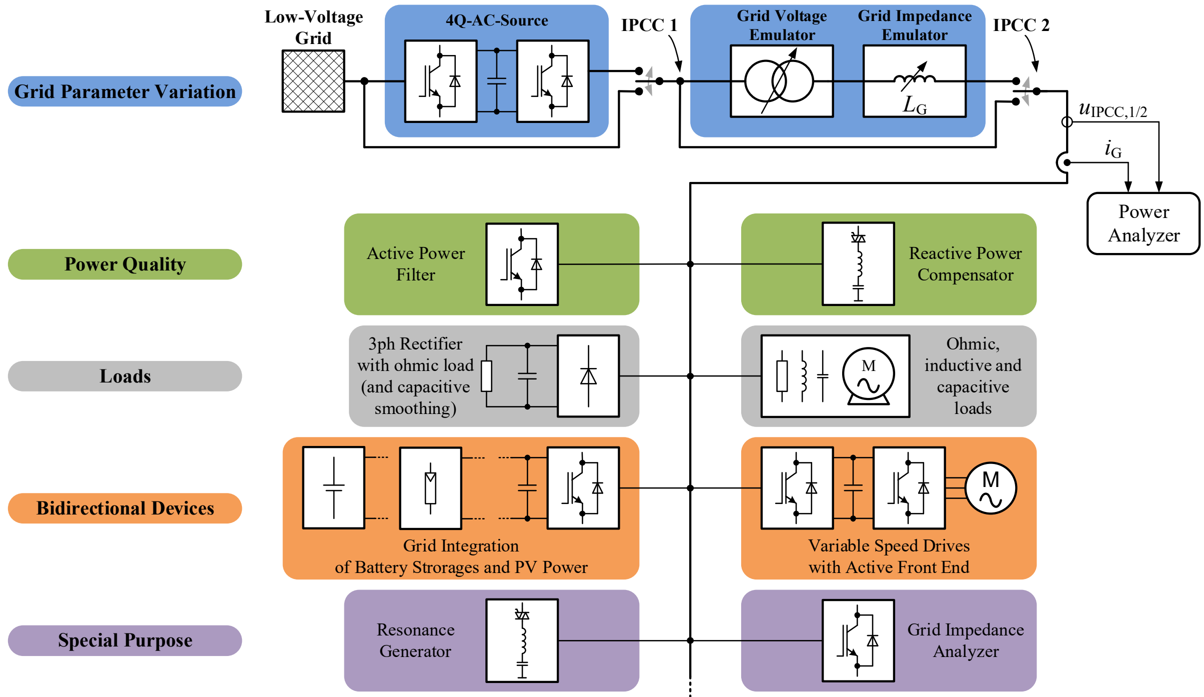


Fig. 5: Overall setup of the research laboratory with an exemplary selection of grid connected devices

The setup can be divided in the following groups:

- Grid Parameter Variation: Including the previously mentioned *Grid Voltage Emulator* and *Grid Impedance Emulator* as well as the *4Q-AC-Source*.
- Power Quality: Compensation of fundamental reactive and distortion power by an *Active Power Filter* (*APF*, with voltage controlled resonance damping capability) and a *Reactive Power Compensator*.

- Loads: Depending on the objective of the investigation, e.g. linear loads like passive devices or induction machines as well as non-linear loads like rectifiers can be integrated into the test bench.
- Bidirectional Devices: Grid feed of renewable energy or regenerative inverters.
- Special Purpose: The previously mentioned *Resonance Generator* to emulate a variable capacitive load and with this a frequency-variable resonance point in combination with the inductance of the *Grid Impedance Emulator*. The *Grid Impedance Analyzer* (also self-developed) is able to determine the impedance at the (I)PCC by means of a monofrequent current injection.

The photograph depicted in Fig. 6 is showing the *4Q-AC-Source*, the *Grid Voltage Emulator*, the *Grid Impedance Emulator* and the *Power Analyzer* (see also Fig. 5, blue highlighted and white, respectively).

Fig. 6: *4Q-AC-Source*, *Grid Voltage Emulator*, *Grid Impedance Emulator* and Dewetron DEWE2600 *Power Analyzer* (from left to right)

Experimental Results

In the following, an exemplary selection of tests and measurements of the emulators itself as well as of selected DUTs will be presented. The components used and a description of the test are presented in the form of a list, which is supplemented by the corresponding diagrams of the measurements. Components that are not mentioned are not used in the respective measurement.

Online Switching Between Voltage Levels

- *Grid Voltage Emulator*:
  - Input voltage: 230 V_{RMS} phase-neutral.
- Load:
  - $R = 10\ \Omega$, $L = 2.1$ mH.
- Description:
  - Grid voltage emulator in stand-alone mode.
  - Switching at t = 0 s (the time of the maximum of the load current) from 60% to 100% output voltage.
  - The output voltage is not interrupted, so the load is connected to the voltage source continuously.
  - After the switching operation, small oscillations can be seen in the output voltage
  - After the step in the output voltage, the output current is increasing according to the time constant of the load, which is about 0.2 ms.
  - Since all components are freely programmable, voltage sags and swells can be realized by switching between different voltage levels.
- Diagrams:

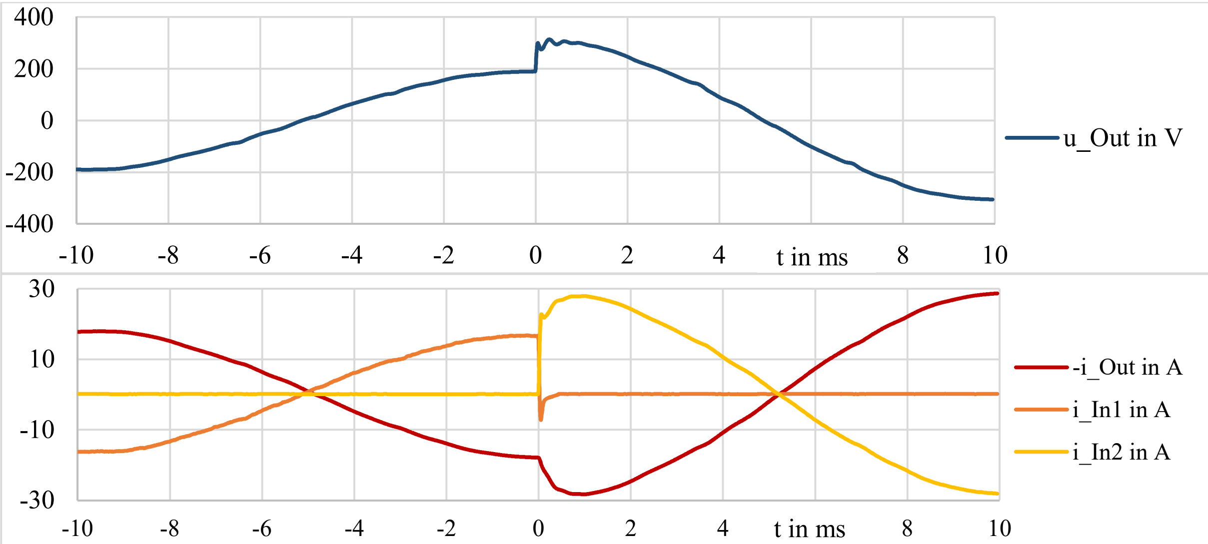


Fig. 7: Measured quantities: Online switching between voltage levels

Three-Phase Voltage Start up

- *Grid Voltage Emulator*:
  - Input voltage: 230 V_{RMS} phase-neutral.
  - Output voltage: 70% of the input voltage.
- *Grid Impedance Emulator*:
  - Stationary inductance: 1 mH.
- Load:
  - 5.5 kW induction machine in star connection with neutral conductor.
- Description:
  - Both emulators are connected in series.
  - The output voltages are switched on at their respective zero crossing.
  - Due to the series inductance, the high start-up currents are causing a reduction of the output voltages.
  - The output voltages are reaching their nominal level after the start-up currents decayed.
- Diagrams:

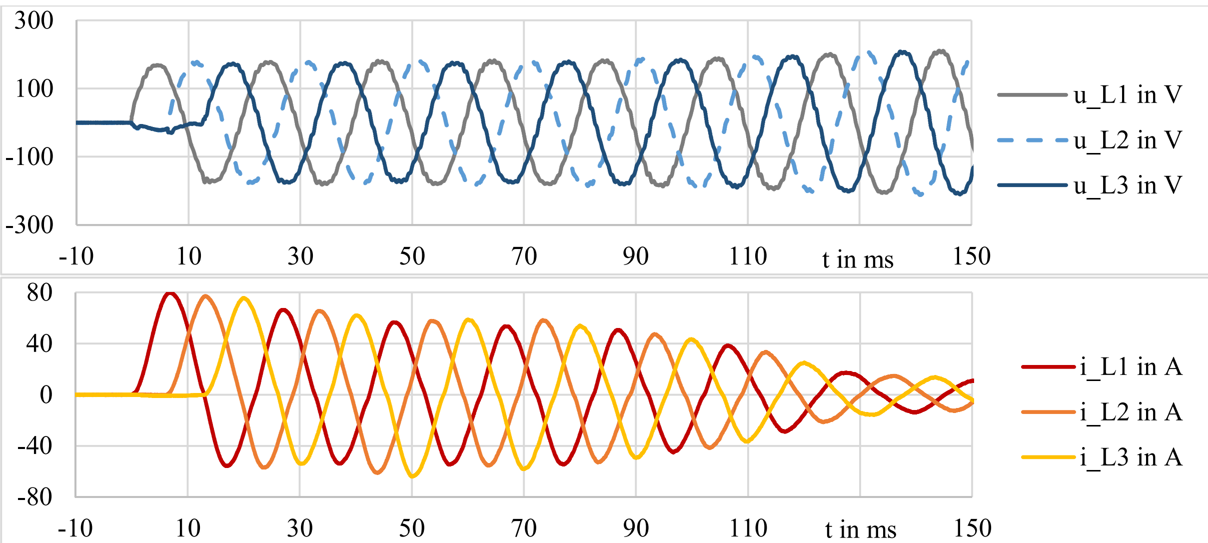


Fig. 8: Measured quantities: Three-phase voltage start up

Online Impedance Variation and Analyzation

- *Grid Impedance Emulator*
- *Impedance Analyzer*:
  - Monofrequent current injection, 15 A_{RMS}, 75 Hz.
- Description:
  - The grid impedance emulator switches from L = 1.5 mH / R = 0.08 Ω (values determined by dc measurement) to L = 0 mH / R = 0 Ω at t = 0 s.
  - At t = 1 s, the impedance analyzer has stationary tracked the change in the impedance (ΔL = 1.62 mH, ΔR = 0.071 Ω).
  - Compared to the dc measurement, the error is about 8% (inductance) and 11% (resistance), and with this in an acceptable range.
- Diagrams:

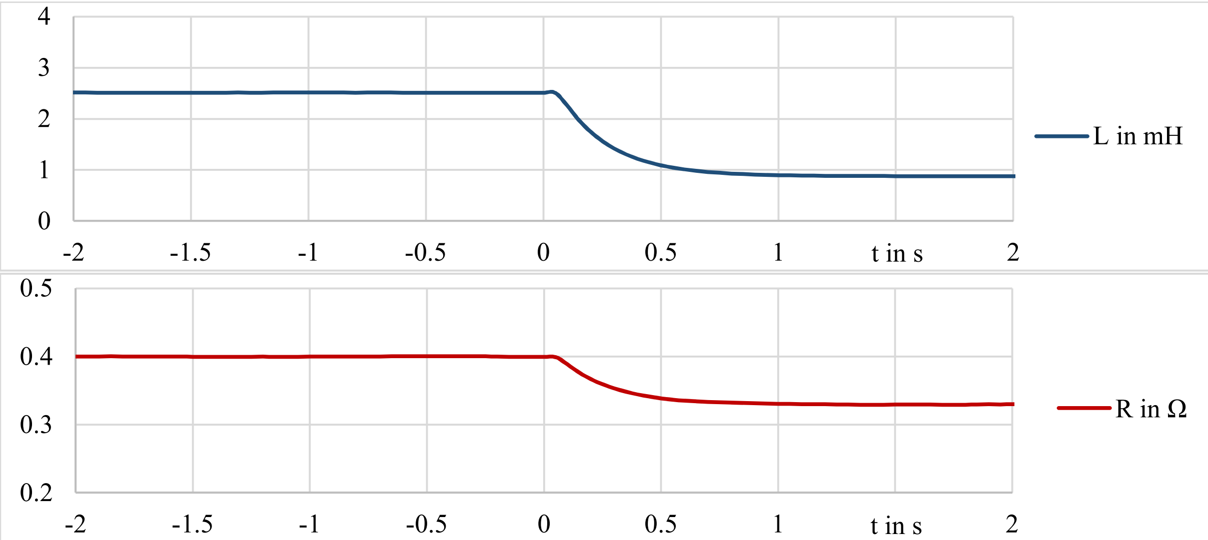


Fig. 9: Estimated quantities: Online Impedance Variation and Analyzation

Resonance Generation

- *4Q-AC-Source*:
  - Output voltage U_{IPCC2} (ref. Fig. 5): 140 V_{RMS} phase-neutral.
  - Distortion by a 5th harmonic with $U_{RMS,5}$ = 20 V.
- *Grid Impedance Emulator*:
  - L = 1.0 mH.
- *Resonance Generator*:
  - L = 1.0 mH, C = 92 µF, resonance point at about 290 Hz.
- *Active Power Filter*:
  - Connected to the grid, but no resonance damping activated.
- Description:
  - A resonance current can be clearly seen in the current of the Resonance Generator i_{RG}.
  - This resonance current is causing an additional distortion in u_{IPCC2}, resulting in a 5th harmonic of 60 V_{RMS}, which is three times the source voltage of 20 V_{RMS}.
  - Due to the limited bandwidth of the *APF*s fundamental current control and the massive distortion in the u_{IPCC2} voltage, the *APF* is also drawing a 5th harmonic current from the grid.
- Diagrams:

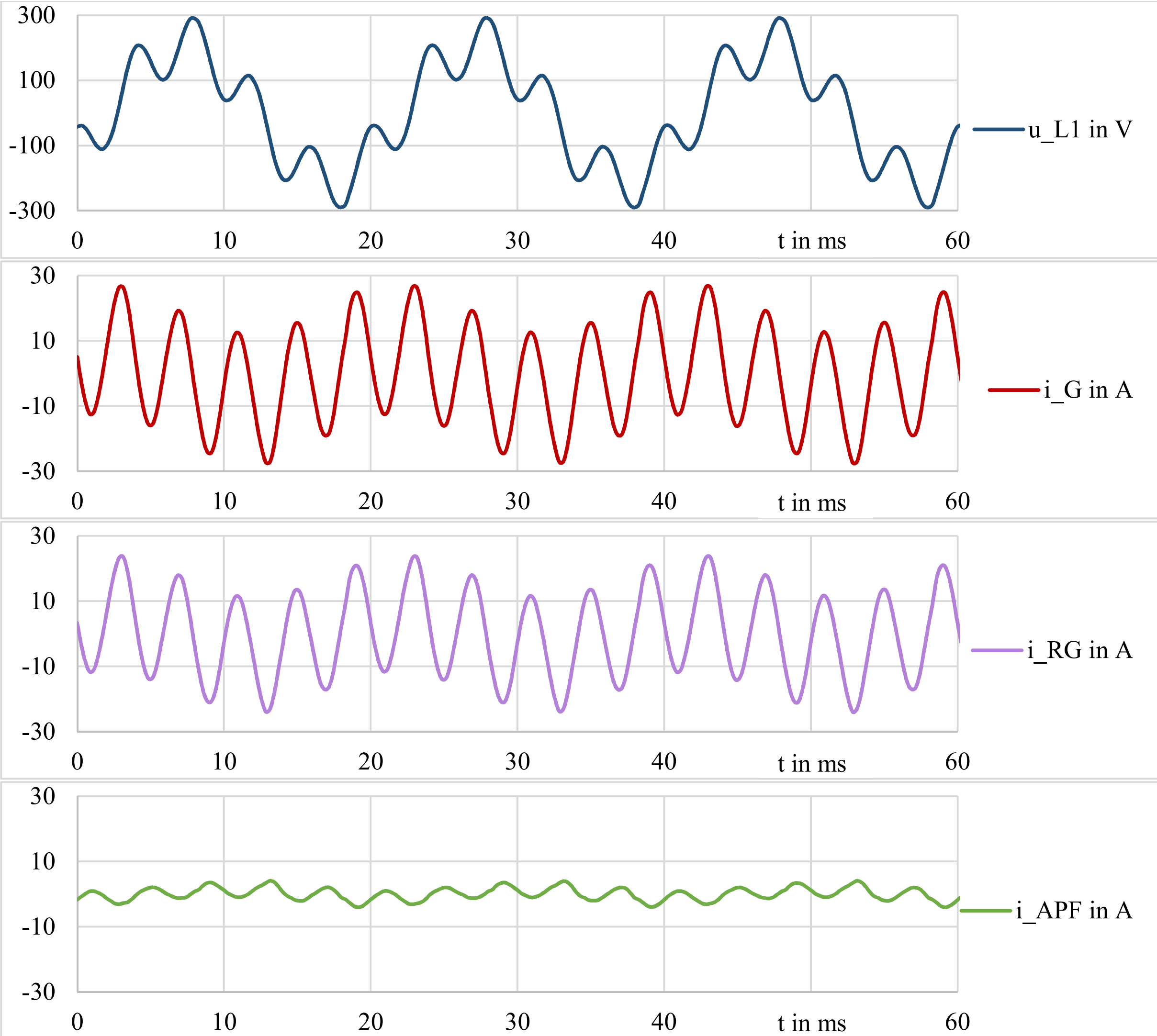


Fig. 10: Measured quantities: Resonance Generation

Resonance Generation and Damping

- Same setup of the *4Q-AC-Source*, the *Grid Impedance Emulator* and the *Resonance Generator* as described for the measurement "Resonance Generation".
- Active Power Filter:
  - Connected to the grid, resonance damping activated.
- Description:
  - The resonance damping of the *APF* is activated. Since the resonance damping is voltage controlled, the control objective is to compensate the distortion at the 5th harmonic in the voltage.
  - Due to the control objective, the *APF* is injecting a 5th harmonic current, which is eliminating the voltage distortion at the 5th harmonic.
  - With this, the excitation of the resonance circuit gets eliminated and the resonance current disappears. The current i_{RG} of the *Resonance Generator* consists mainly of the fundamental current.
- Diagrams:

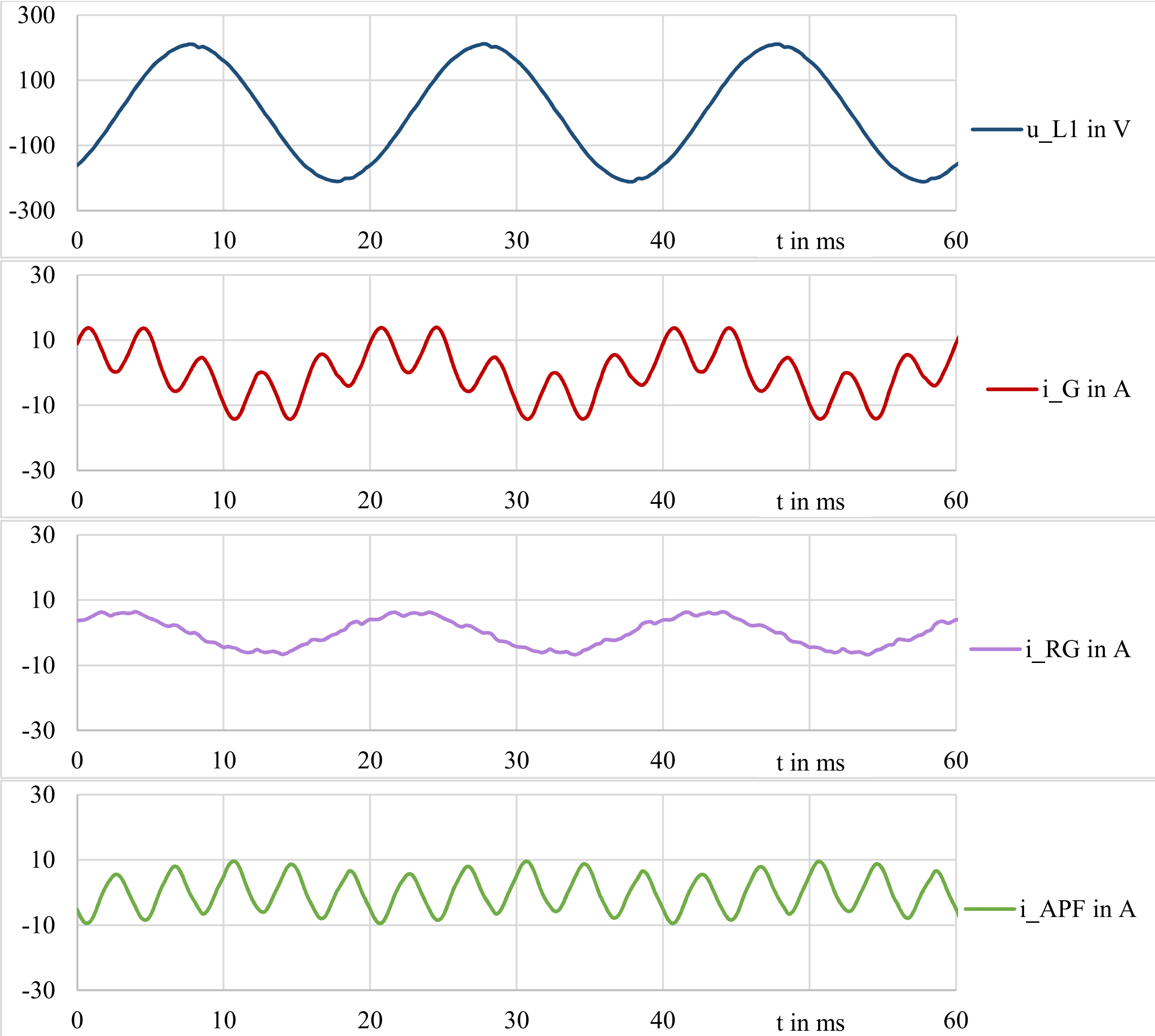


Fig. 11: Measured quantities: Resonance Generation and Damping

Conclusion and Outlook

More and more renewable energy sources and consumers are connected to the grid via (switched) power electronics. Since the grid parameters like voltage, frequency and impedance can vary, it is important to investigate the grid-integration and the interaction of these devices in a proper way and a wide range of parameters to ensure a safe and reliable operation.

For this purpose, a test bench was designed, developed and built up, which offers the possibility to carry out investigations in a laboratory environment and with this in a time and cost saving way. With the *Grid Voltage Emulator* and the *Grid Impedance Emulator* in combination with the *4Q-AC-Source* it is possible to influence all the mentioned grid parameters. In addition, the *Resonance Generator* offers the possibility of emulating capacitive loads and thus, in combination with the *Grid Impedance Emulator*, generating a defined resonance point in the grid. Tests and measurements show the operation and the performance of the components of the test bench, regarding the test bench itself as well as the devices under test.

For future work, it is planned to use the test bench regarding to its basic functionality for online voltage and impedance variation tests. Also, a major topic will be further investigations on resonance damping. Moreover, upcoming control schemes for grid-connected inverters like the grid-forming control will be a main focus of research.

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