Online Grid-Adaptive Control and Active-Filter Functionality of PWM-Converters to Mitigate Voltage-Unbalances and Voltage-Harmonics – A Control Concept Based on Grid-Impedance Measurement

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Abstract— This work presents a control concept for a PWM-converter switching with medium-low frequencies (2.5 kHz) based on grid-impedance measurement to adapt the converters control online to variable grid-conditions and to improve the voltage-quality at the converters connection point. Thus, this work contributes to the actual problem of connecting distributed renewable energy sources to the grid. To improve the voltage-quality, additional active-filter functionality is implemented to mitigate unbalances and harmonics (5th and 7th). To meet these control objectives with medium-low switching-frequencies, and thus with medium-low control-frequencies (5 kHz), the control-design is done using discrete time-domain analysis. The theoretical approaches are verified in experiments on a 22 kVA laboratory setup composed of a voltage-source back-to-back converter connected with an LCL-filter to the mains, an interior permanent-magnet synchronous-machine and a grid-impedance analyzer. The results reveal that stable converter operation is reached over a wide range of grid-impedances and that it is possible to improve the voltage-quality with the additional active-filter functionality adapting the measured grid-impedance for the control.

I. INTRODUCTION

Today, the large amount of renewable energy sources connected to the grid challenges both, grid operators as well as the manufacturers producing renewable energy production systems. The worldwide interest in green energy forces manufacturers of power-converters to design systems for a wide variety of electrical operating conditions [1].

Commonly, this is done by taking system design tradeoffs into account, e.g. the control dynamics of the converter is reduced in order to guarantee stable operation under a wider set of grid-impedances [2]. These trade-offs can lead to non-optimal solutions based on the actual connecting conditions. Among these trade-offs, the high amount of installed distributed energy generation devices forces grid operators to formulate technical rules to connect renewable energy systems to the mains to guarantee stable grid-operation [3].

The interests for the converter manufactures and the grid-operators are linked by the stiffness of the grid, i.e. the equivalent grid-impedance that is seen from the converters connection point. To limit the supply-voltage distortion caused by the power-converter, the current-waveforms of the currents injected to the grid are regulated by standards where the limit values depend on the stiffness of the grid, e.g. formulated by the German medium-voltage VDN requirements [4].

Commonly, renewable energy production units are connected as shunt devices to the mains, i.e. the apparent power is delivered by injecting fundamental currents. One approach to improve the power-quality of the mains is to implement additional active-filter functionality (AFF) to the converters and their control. Different approaches exist in literature where active-filter functionality is implemented in addition to the fundamental control of converters. Approaches, where the active-filter functionality of grid-connected converters is realized by placing additional current-sensors to non-linear loads to compensate their current-harmonics at the main connection point are presented in [5] and [6]. Studies dealing with design tradeoffs and the impact of such additional active-filter functionality to the hardware of grid-connected converters can be found in [7] and [8].

The former paragraphs reveal that the stiffness of the grid is important to determine the interaction between the converter and the power network, i.e. the mains current distortion depends on the converters voltage and the converters stability. To reduce undesired interactions and therefore to avoid undesired power quality degradation at the converters connection point, different approaches based on modifications of the converters control are presented in literature [2]. A promising approach to reduce undesired interactions and to overcome the aforementioned problems is to adapt the control to the equivalent grid-impedance seen from the local connection point to the control of the grid-connected converter. To determine the equivalent grid-impedance at the converters connection point, three different
approaches are widespread in literature. The equivalent grid-impedance is calculated based on the knowledge of the network configuration and the physical system parameters, estimated based on disturbances which already exist in the mains (noninvasive methods) or measured by injecting specific disturbances to the mains (invasive methods). Approaches, referred to as noninvasive methods can be found in [9] or in [10]. Approaches based on invasive methods are presented in [11], [12] or in [13].

In [14] the basic idea of using an identified grid-impedance to improve the voltage-quality at the converters connection point is presented for a shunt-connected active-filter application. The work proposes a grid-impedance method in combination with a voltage feedback active-filtering to control the harmonic line-currents to mitigate the harmonic grid-voltages at the converters connection point. The results achieved in [14] show that a converter connected as a shunt device is able to improve the voltage-quality and the knowledge of the equivalent grid-impedance gives superior performance.

The work presented here continues with the abovementioned approaches of adapting the equivalent grid-impedance to the control of grid-connected PWM-converters. The focus of the proposed investigations is set to the control of PWM-converters switching at medium-low frequencies, as for example used in high power windmill systems or high power photovoltaic stations. With the proposed control concept it is possible to implement additional active filter functionality to the converters fundamental power injection to improve the power quality at the PCC. To mitigate or compensate voltage-unbalances and 5th- and 7th-voltage-harmonics a current is injected with the converter which leads to a voltage-drop across the equivalent grid-impedance. Once, this voltage-drop has the same magnitude but opposite phase in relation to the existing grid-impedance to the converters connection point, unbalanced- and harmonic-voltage compensation is achieved. Thus, with applying the proposed grid-adaptive control concept with additional active-filter functionality to high-power devices, a high contribution to improve the voltage-quality in distributed renewable energy production networks is reached. It is assumed that the available calculation power is sufficient to run the control implementation issues to realize a practical control approach.

This paper is structured as follows: In the second chapter a system description is given. The underlying grid-model as the basis to implement the additional active-filter functionality is shown the third chapter. An overview about the control design is presented in the fourth chapter. The theoretical basis to implement additional active filter functionality to the converters control as well as measurement results are summarized in the fifth and sixth chapters. The paper will be closed by a conclusion in the last chapter.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Value (per unit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_{LL}$</td>
<td>Line-to-Line Voltage (rms)</td>
<td>400 V (1.0)</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Angular grid frequency</td>
<td>$2\pi$ 50 Hz (1.0)</td>
</tr>
<tr>
<td>$I_L$</td>
<td>Nominal line current (rms)</td>
<td>31.0 A (1.0)</td>
</tr>
<tr>
<td>$L_{fg}$</td>
<td>Grid-side filter inductance</td>
<td>2 mH (0.086)</td>
</tr>
<tr>
<td>$L_{CS}$</td>
<td>Converter-side filter inductance</td>
<td>2 mH (0.086)</td>
</tr>
<tr>
<td>$C_f$</td>
<td>Filter capacitance</td>
<td>64.8 $\mu$F (0.148)</td>
</tr>
<tr>
<td>$C_{DC}$</td>
<td>DC-link capacitance</td>
<td>2200 $\mu$F (5.0)</td>
</tr>
<tr>
<td>$f_{ref}/f_{switch}$</td>
<td>Control/Switching frequency</td>
<td>5 / 2.5 kHz (100 / 50)</td>
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**II. DRIVE SYSTEM AND GRID-IMPEDANCE MEASUREMENT DESCRIPTION**

In Fig. 1 a block diagram of the proposed system is presented. The system is composed of a PWM-driven (sinus-triangle with third harmonic sub-oscillation) voltage-source converter connected to the grid with a LCL-filter. The LCL-filter is designed to meet the harmonic-current characteristics at the converters connection-point defined by the German VDN-requirements [4]. The grid-side filter-characteristic (in per-unit quantities) of the converters output-voltage to the line-side current is presented in Fig. 2 for three different
grid-conditions (blue line: ideal ‘stiff’ grid-conditions $S_{SC}/S_N=\infty$, green-line: ‘medium’ grid-conditions $S_{SC}/S_N=24.4$, red-line: ‘weak’ grid-conditions $S_{SC}/S_N=14.4$). The system parameters and the underlying base quantities are summarized in Table I. A grid-impedance analyzer is added to the system to measure the grid-impedance for adapting this information to the converters control. The grid-impedance analyzer and the implemented measurement principle are summarized in [12]. A practical issue that should be considered for the system with the grid-impedance analyzer added to the setup presented in Fig. 1 is, that the measured impedance consists of the grid-impedance in parallel to the LCL-filter impedance. To extract the information about the grid-impedance, the LCL-filter admittance has to be subtracted from each admittance measurement.

$$Z_{\text{grid}}(s) = U_{\text{grid}}(s)/I_{\text{grid}}(s)$$

$$Z_{\text{line}}(s) = U_{\text{line}}(s)/I_{\text{line}}(s)$$

$$Z_{\text{conv}}(s) = U_{\text{conv}}(s)/I_{\text{conv}}(s)$$

$$Z_{\text{LCL}}(s) = U_{\text{LCL}}(s)/I_{\text{LCL}}(s)$$

Fig. 3: Equivalent one-line circuit-diagram of converter connected to a non-ideal grid

III. GRID-MODEL FOR CONTROL DESIGN

In Fig. 3 the applied one line circuit-diagram of a converter connected to a non-ideal grid is presented. The converter, here modeled as a voltage-source $U_{\text{conv}}$, is connected via an LCL-filter $Z_{\text{LCL}}$ to the point of common coupling (PCC). The non-ideal grid behavior is modeled by a frequency- and time-dependent equivalent grid impedance $Z_{\text{grid}}$ and a virtual voltage-source $U_{\text{grid}}$.

Applying Kirchhoff’s law to the equivalent grid-model leads to the mesh equations presented in (1) and (2), whereas $I_{\text{line}}$ and $U_{\text{PCC}}$ describe the currents and voltages at the PCC.

$$U_{\text{grid}} = Z_{\text{grid}}(f,t)I_{\text{line}} + U_{\text{PCC}}$$

$$U_{\text{PCC}} = Z_{\text{LCL}}(f)I_{\text{Line}} + U_{\text{Conv}}$$

To further analyze the interaction between the converter and the non-ideal grid, the Helmholtz-Theorem is used. Superimposing the two independent voltage sources (the virtual grid-voltage and the converter-voltage) leads to the equations presented in (3) and (4) for the line-side current $I_{\text{line}}$ and the voltage $U_{\text{PCC}}$ at the PCC.

$$I_{\text{line}} = \frac{U_{\text{grid}} - U_{\text{conv}}}{Z_{\text{grid}}(f,t) + Z_{\text{LCL}}(f)}$$

$$U_{\text{PCC}} = \frac{U_{\text{grid}}Z_{\text{LCL}}(f) + U_{\text{conv}}Z_{\text{grid}}(f,t)}{Z_{\text{grid}}(f,t) + Z_{\text{LCL}}(f)}$$

IV. CONTROL DESIGN

The control of the converter is implemented in a voltage-oriented control scheme. Thus, a cascaded control scheme composed of inner-current control (CC) and outer DC-link voltage-control (VC) is used. To synchronize the converter control with the voltage at the PCC a phase-locked loop (PLL) algorithm based on Double Second-order Generalized-Integrators (DSOGI-PLL) is implemented [15].

A. DC-Link voltage control

The PI-based DC-link voltage-control is presented in Fig. 4. The PI-controller parameters shown in the two blocks on the left (proportional gain $K_p$, integral time constant $T_i$) are designed based on [16]. To decouple the DC-link control dynamics from the current-control dynamics, adaptive notch-filters (ANF) are used. The notch-frequencies are chosen to filter the 100 Hz component (unbalance in 50 Hz dq-frame) and the 300 Hz component ($5^{th}$ & $7^{th}$ harmonic in 50 Hz dq-frame) from the d-current reference-signal.

B. Fundamental Current control and Active Damping

The proposed current-control in space-phasor form is presented in Fig. 5. Here, the fundamental converter-side current is controlled with a PI-based current control. The cross-coupling terms between the transformed d- and q-converter-side current components are considered by introducing feed-forward compensation to the control loops (not shown in the figure). In [16] it is shown that appropriate PI-current controller tuning for a converter system with LCL filter is achieved using the sum of the two LCL filter inductances. The PI-controller parameters (proportional gain $K_p$, integral time constant $T_i$) are designed based on [16]. To decouple the DC-link control dynamics from the current-control dynamics, adaptive notch-filters (ANF) are used. The notch-frequencies are chosen to filter the 100 Hz component (unbalance in 50 Hz dq-frame) and the 300 Hz component ($5^{th}$ & $7^{th}$ harmonic in 50 Hz dq-frame) from the d-current reference-signal.
selective harmonic current control is achieved [19], resonant current-controller in unbalanced resonant current-control impulse-invariant implementation for resonant-controllers is summarized based on [22]. Different approaches exist in literature to implement selective harmonic current-control with high performance, e.g. presented in [20]. The proposed unbalanced and harmonic current-control is implemented using one dq-reference frame rotating with the fundamental positive voltage sequence. A generic transfer-function of a resonant current-controller in s-domain is presented in (5).

\[ G_{\text{Res,CC}}(s) = \frac{K_s s}{s^2 + (h \omega_{\text{Grid}})^2} \]  
\[ G_{\text{Res,CC}}(s) = K_{22} T_{\text{Con}} \frac{z^2 - 2 \cos(2 \omega_{\text{Grid}} T_{\text{Con}}) z + 1}{z^2 - 2 \cos(2 \omega_{\text{Grid}} T_{\text{Con}}) z + 1} \]

\[ K_{22} = -200, \quad K_{12} = -600, \quad \Phi_{12} = \frac{\pi}{2} + \frac{6 \omega_{\text{Grid}} T_{\text{Con}}}{z^2 - 2 \cos(6 \omega_{\text{Grid}} T_{\text{Con}}) z + 1} \]

Discretization is used. The 5th- and 7th-harmonic current-controller is implemented using impulse-invariant discretization with additional delay-compensation. The resultant resonant-controller transfer-functions are presented in (6)-(8).

V. ACTIVE-FILTER FUNCTIONALITY

Based on the control concept introduced in the former chapter it is possible to implement additional active filter functionality to the converters fundamental power injection to improve the power quality at the PCC. To mitigate or compensate voltage-unbalances and 5th- and 7th-voltage-harmonics a current is injected with the converter which leads to a voltage-drop across the equivalent grid-impedance. This voltage-drop should have the same magnitude but opposite phase in relation to the existing voltage-unbalances and voltage-harmonics at the converters connection point, then unbalanced- and harmonic-voltage compensation is achieved.

A. Unbalance and Harmonic Detection Methods

To provide additional active-filter functionality with the chosen control-concept, unbalanced and harmonic signal detection is required. The detection of unbalanced signals is implemented using the DSOGI-PLL approach. To provide accurate fundamental negative-sequence separation the second-order generalized integrators are discretized using third-order integrator approximation [23]. The harmonic signal-detection is implemented using Recursive-Discrete-Fourier-Transformation (RDFT).

B. Reference Generation for Harmonic-Voltage Compensation

The reference-currents for harmonic line-voltage compensation are derived using the grid-model described in the third chapter. Based on the Helmholtz-Theorem the two independent voltage sources (the virtual grid voltage and the converter-voltage) have been superimposed leading to the equations (3) and (4) for the line-side current \( I_{\text{line}} \) and the voltage \( U_{\text{PCC}} \) at the PCC. Assuming that harmonic voltage compensation at the PCC is achieved leads to the compensation condition presented in (9). Inserting this compensation condition into (3) and (4) leads to the reference current \( I_{\text{Comp}}^h \) to achieve harmonic-voltage compensation at the PCC (10),

\[ U_{\text{PCC}}^h = 0 \]
\[ I_{\text{Comp}}^h = I_{\text{line}}^h + \frac{U_{\text{PCC}}^h}{Z_{\text{Grid}}(h \cdot 50Hz, t)} \]

Assuming that the harmonic content of the virtual grid-voltage \( U_{\text{Grid}}^h \) remains constant during compensation, the compensation current is expressed as a function of the harmonic voltage and current contents at the PCC and is derived, as in (11) (by inserting the compensation condition
DC load-machine to maintain 1500 r/min to a four-quadrant converter-fed DC load conditions, an interior permanent-magnet back voltage-source converter with a LCL-filter impedance analyzer [12] and a two-level back-to-consist of a custom designed and self build grid-verify the proposed control concept. The setup additional three-phase multi-tap inductor is added board. In order to study weak grid conditions, an control is implemented on a dSPACE DS1006 nominal power in power generation mode. The resultant reference current \( I_{\text{Comp}} \) to achieve unbalanced voltage-compensation at the PCC is presented in (12).

\[
I_{\text{Comp}} = I_{\text{Line}} + \frac{U_{\text{PCC}}}{Z_{\text{Grid}}(50Hz,t)}
\]  

(12)

In Fig. 7 the resultant reference-current generation for unbalanced-voltage compensation based on the measurement of the equivalent grid-impedance at the converters connection point is summarized.

VI. MEASUREMENT RESULTS

Measurements are carried out to validate the theoretical analysis under laboratory conditions.

A. Test-Bench Description

A 22 kVA laboratory test setup is used to verify the proposed control concept. The setup consist of a custom designed and self build grid-impedance analyzer [12] and a two-level back-to-back voltage-source converter with a LCL-filter (setting see Fig. 2). To emulate active load conditions, an interior permanent-magnet synchronous machine (PMSM) is used connected to a four-quadrant converter-fed DC load machine. The motor speed of the PMSM is set to 1500 r/min. The load torque is adjusted by the DC load-machine to maintain 15 % of the nominal power in power generation mode. The control is implemented on a dSPACE DS1006 board. In order to study weak grid conditions, an additional three-phase multi-tap inductor is added between the mains and the setups connection point.

B. Harmonic Line-Voltage Mitigation

The proposed active-filtering concept for harmonic-voltage mitigation at the PCC is studied for two different grid-conditions. First, the actual grid-condition of the institute’s laboratory, referred to as ‘medium’ grid, is considered for the measurements and second, an additional tap inductor is added between the mains and the setup connection point to emulate ‘weak’ grid-conditions for the measurements. During each measurement the equivalent grid-impedance is measured simultaneously by the grid impedance analyzer. The measured grid-impedance values are then delivered to the converters control via serial communication between the controls of the two converters. The measured grid-conditions during the experiments are summarized in Table II.

Fig. 8 presents the measurements for harmonic voltage-mitigation at the converter connection point for the actual voltage and grid conditions in the institute’s laboratory. In Fig. 8 (a)-(d) the waveforms and spectra for the line-voltages and line-currents are presented for the converter running in nominal power generation mode (active-filter functionality disabled). High 5th- and 7th-harmonic line-voltage contents can be observed in the measured line-voltage spectrum. In Fig. 8 (e)-(h) the waveforms and spectra for the line-voltages and line-currents are presented for the converter running in

<table>
<thead>
<tr>
<th>Grid-Conditions During Measurements</th>
<th>L_{\text{Grid}} (p.u.)</th>
<th>R_{\text{Grid}} (p.u.)</th>
<th>X_{\text{L,Grid}}/R_{\text{Grid}}</th>
<th>S_{\text{SC}} (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement for ‘medium’ grid (institutes laboratory conditions)</td>
<td>896.7 µH (0.039)</td>
<td>97.2 mΩ (0.013)</td>
<td>2.9</td>
<td>537 kVA (24.4)</td>
</tr>
<tr>
<td>Measurement for ‘weak grid’ (additional inductance, L = 500 µH / 0.022p.u.)</td>
<td>208.6 µH (0.063)</td>
<td>171.1 mΩ (0.024)</td>
<td>2.7</td>
<td>327 kVA (14.9)</td>
</tr>
<tr>
<td>Measurement for ‘medium’ grid (institutes laboratory conditions)</td>
<td>1100 µH (0.048)</td>
<td>363.2 mΩ (0.050)</td>
<td>1.0</td>
<td>317 kVA (14.4)</td>
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<tr>
<td>Measurement for ‘weak grid’ (additional inductance, L = 500 µH / 0.022p.u.)</td>
<td>828.7 µH (0.179)</td>
<td>140.1 mΩ (0.019)</td>
<td>9.3</td>
<td>122 kVA (5.6)</td>
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<tr>
<td>Measurement for ‘medium’ grid (institutes laboratory conditions)</td>
<td>668.6 µH (0.202)</td>
<td>243.4 mΩ (0.033)</td>
<td>6.0</td>
<td>107 kVA (4.9)</td>
</tr>
</tbody>
</table>

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additional active-filtering mode (active-filter functionality enabled). As it can be seen from the line-voltage spectrum, presented in Fig. 8, (f) the 5th- and 7th-harmonic voltage contents are reduced from 11.7 V to 9.78 V (5th line-voltage harmonic) and from 7.12 V to 5.31 V (7th line-voltage harmonic) by the proposed active-filtering concept.

Another experiment is carried out for weak-grid conditions. Fig. 9 presents the measurements for harmonic voltage-mitigation at the converters connection. Fig. 9 (a) and (b) present the spectra for the line-voltages and line-currents for the converter running in nominal power generation mode (active-filter functionality disabled). Once again, high 5th- and 7th-harmonic line-voltage contents are observed in the line-voltage spectrum. In Fig. 9 (c) and (d) the spectra for the line-voltage and line-current are presented for the converter running in additional active-filtering mode (active filter functionality enabled). As it can be seen, the 5th- and 7th-harmonic voltage contents are reduced from 12.3 V to 5.99 V (5th line voltage-harmonic) and from 8.27 V to 2.28 V (7th line voltage-harmonic) by the proposed active-filtering concept. The higher line voltage harmonic reduction is traced back to the higher grid-impedance for the ‘weak’ grid conditions. Here, a higher voltage-drop across the grid-impedance can be achieved with the same harmonic-current limitations as for ‘medium’ grid conditions leading to a higher line-voltage harmonic reduction.
C. Unbalanced Line-Voltage Mitigation

The proposed active-filtering concept for unbalanced-voltage mitigation at the PCC is also studied in the laboratory environment. Here, due to space limitations, only the measurements for the actual grid condition of the institute’s laboratory, referred to as ‘medium’ grid, will be presented. To evaluate the unbalanced-voltage mitigation capabilities the asymmetry factor \( Asym \) (introduced by the European standard EN 50160 [24]) is used. The definition is presented in (13).

\[
Asym[\%] = \frac{6(X_a^{\text{rms}} + X_b^{\text{rms}} + X_c^{\text{rms}})}{(X_a^{\text{rms}} + X_b^{\text{rms}} + X_c^{\text{rms}})^2} - 2 \cdot 100
\]

Fig. 10 presents the measurements for unbalanced voltage-mitigation at the converters connection point for the actual voltage and grid conditions in the institute’s laboratory. From these measurements it can be seen that unbalanced voltage mitigation is achieved with the proposed active-filter functionality by injecting unbalanced fundamental current waveforms to the grid. The voltage unbalances are reduced from 0.4 % to 0.25 %.

VII. CONCLUSION

This work presents a control concept to adapt variable grid impedances for the control of grid connected PWM converters switching with medium-low frequencies which are mainly used in high-power applications. The adaption of the grid impedance is achieved with an additional grid-impedance analyzer.

Based on the presented theoretical analysis and the measurement results, it can be concluded that with adapting the converters control online the grid-impedance, it is possible to include additional active-filter functionality to the converter. This leads, depending on the stiffness of the grid, to compensation or mitigation of voltage unbalances and voltage harmonics at the converters connection point. Thus, the converter is able to improve the power quality which contributes to the power networks stability.

The analysis is presented for PWM converters switching with medium-low frequencies and is based on grid-impedance measurement. The presented control concept is not limited to these assumptions. The ideas and analysis presented in this work can be extended for PWM-converters switching with higher or lower frequencies or it is possible to replace the invasive grid-impedance measurement by noninvasive grid-impedance determination (e.g. an observer-based approach).

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REFERENCES

Fig. 10: Measurement results: Unbalanced-voltage mitigation at the converters connection-point for medium grid-conditions (institutes laboratory conditions, \(S_{dc}/S_{ac} = 24.4\)): (a) Asymmetry factor of Line-voltages and Line-current, (b) Line-voltage waveforms and (c) Line-current waveforms (definition asymmetry factor based on IEC 50160).


