DC-link voltage oscillation influence on grid connected converter power quality

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***Abstract*—The natural turn to renewable energy sources, from fossil fuel based electrical energy generation, has led to significant increase in number of grid connected converters. Following this, the influence of the power electronics elements on power quality characteristics of the distribution networks needed to be investigated. It can be proven that different number of control parameters, ranging from the modulation techniques to the current controller parameters, can influence the power quality, in the first place total harmonic distortion of the injected currents. This paper will present the influence of the DC-link circuit voltage oscillation influence on the grid connected converter power quality characteristics. Experimental results are acquired using advanced laboratory prototype for testing renewable energy based distributed resources, developed at the Faculty of Technical Sciences in Novi Sad.**

***Index Terms*—Renewable energy sources; DC-link voltage oscillation; Power Quality; Grid Connected Converter.**

I. Introduction

With the constant growth of the population, the humanity is facing a difficult challenge in offering sustainable solutions for the development. This is particularly underlined by the constant increase in standard of living, closely followed by the increase in energy demand [1]. This trend, resulting in several worldwide energy crises, has forced the humanity to turn to more sustainable energy resources found mostly in renewable energy technology. Renewable energy sources (RES) are, by their very definition, more in accordance with the sustainable development key principles. With major benefits over classical, fossil fuel based energy sources, the share of renewable energy conversion systems has taken over a significant part of the worldwide energy supply. This has particularly been the case for the electrical energy generation [2, 3].

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On the other hand, the introduction of distributed energy sources facilitated the change in previously passive distribution network. The power system control had to adopt a more decentralized approach, while preserving the system stability and reliability. Furthermore, vast diversity of the primary sources and the conversion technologies, having no standardized approach, has led to different grid integration issues [4-7].

Recent advances in the power electronics converters and their respective control put a new perspective on the field of RES. With a sharp decline in power electronic components prices and constant development that exceeds previous component limits, it is now almost impossible to imagine the renewable energy conversion system without a power electronic converter. These converters usually play the integral part of the grid integration, thus being designated as grid connected converters (GCC). The introduction of such an interconnecting element will help make the application of the RES systems somewhat standardized. In that regard, the GCC will claim the pivotal role in the future energy market, meanwhile trying to fulfill the power quality requirements proposed by the relevant documentation [8].

However, the introduction of a significant number of these, non-linear elements in the power system will lead to several issues related to the power quality. Most of the currently known constraints, offered by the relevant documents (i.e. Grid Code) refer, first and foremost, to total harmonic distortion of the injected current, while other power quality criteria are usually easier to fulfill. Focusing on the total harmonic distortion of the injected currents, it is shown that there are numerous control parameters that can have positive or negative impact on the distortion level [8-10].

This paper will present the influence of the DC-link voltage oscillation on the power quality characteristics of the grid connected converter. The experimental results will be obtained using advanced laboratory station for control of electrical drives, developed at the Faculty of Technical Sciences. In order to exclude the influence of grid distortion, and therefore the influence of PLL unit parameters, ideal sinusoidal voltages are applied at the point of common coupling (PCC). Voltage fluctuation in the DC-link circuit can consequently be noticed only when the GCC supplies the energy to the power system. Analyzing the injected current spectrum, it can be shown that there is a direct correlation between the DC-link voltage oscillations and current total harmonic distortion.

II. GRID CONNECTED CONVERTER CONTROL STRATEGY

The control algorithm for the GCC is implemented using well-known equations from the instantaneous power theory [11]. Basic voltage oriented control in synchronous reference frame is applied. Using standard PLL techniques the alignment of the grid voltage vector to the *d*-axis is achieved [12]. Therefore, feed-forward control of the active and reactive power is performed in a PQ open-loop control structure [13]. Additionally, the control structure was adapted with a standard algorithm to offer the FRT capabilities required by the grid code. Fault detection algorithm based on the voltage signal averaging was used [14]. The implemented control structure is illustrated in Fig. 1.

The parameters of the classical synchronous reference frame PLL, presented in Fig. 2, are optimized based on the damping ratio and the natural frequency as follows:

$$G_{PLL}\left(s\right)=\frac{V_gK_ps+V_gK_i}{s^2+V_gK_ps+V_gK_i}=\frac{2\xi\omega_ns+\omega_n^2}{s^2+2\xi\omega_ns+\omega_n^2} \tag{1}$$

$$\xi=\frac{\left|ln\delta\right|}{\sqrt{\pi^2+(ln\delta)^2}}\wedge t_{set}=-\frac{lny}{\xi\omega_n} \tag{2}$$

$$K_i=\frac{\omega_n^2}{V_g}\wedge K_p=\frac{2\xi}{\sqrt{V_g/K_i}} \tag{3}$$

In order to be capable of reliable tracking even under sever grid voltage conditions, the classical PLL can be improved using several well-known techniques [15].

Assuming that the alignment of the synchronous reference frame d-axis to the voltage vector at the PCC was achieved, the value of the voltage vector in the q-axis would become zero leading the active and reactive power to be proportional with the d-axis and q-axis currents respectively.

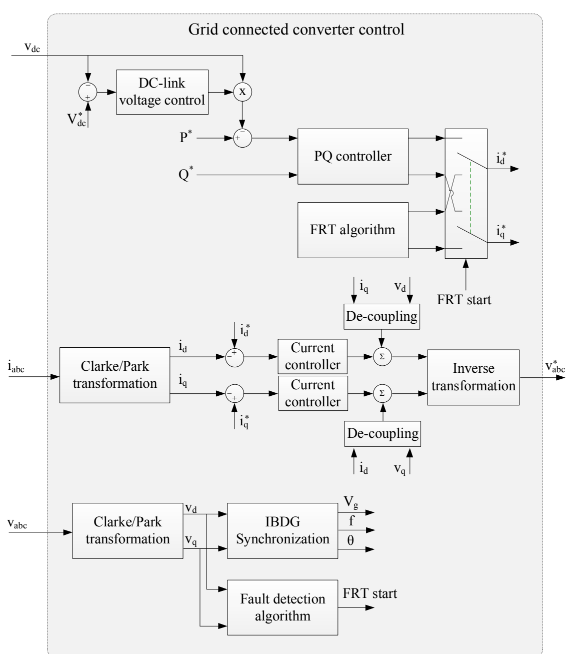

Fig. 1 Open loop control of the grid connected converter

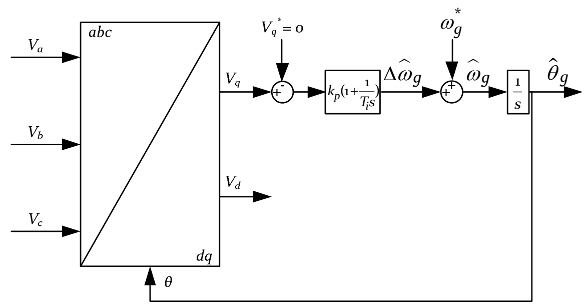

Fig. 2 Synchronous frame phase-locked loop.

The values of the active and reactive power can be obtained using the following equations:

$$P=\frac{3}{2}(e_di_d+e_qi_q)=\frac{3}{2}e_di_d \tag{4}$$

$$Q=\frac{3}{2}(e_qi_d-e_di_q)=-\frac{3}{2}e_di_q \tag{5}$$

In order to achieve a PQ open-loop control only the DC-link voltage controller is necessary. The reference values for the d- and q-axis currents are calculated directly, using desired power values and the eqs. 4-5 as:

$$i_d^*=\frac{1}{v_d^2+v_q^2}\cdot\left(v_d^2\cdot P-v_q^2\cdot Q\right) \tag{6}$$

$$i_q^*=\frac{1}{v_d^2+v_q^2}\cdot\left(v_q^2\cdot P+v_d^2\cdot Q\right) \tag{7}$$

As can be noted in Fig. 1 the DC-link voltage controller will modify the active power reference in order to compensate for the power flow from the primary energy source.

Regulation of the DC-link voltage, d- and q-axis currents to their respective reference values is based on the proportional-integral (PI) controller. With simple implementation these controllers still offer satisfactory dynamic responses, while they are not computationally very demanding. The transfer function of the implemented controllers is given in eq. 8.

$$G_{PI}=K_P\cdot\left(1+\frac{1}{T_is}\right)=K_p\frac{1+T_is}{T_is} \tag{8}$$

The voltage reference signals, acquired at the output of the current controllers are fed to the converter modulation algorithm. From the two groups, current controlled and voltage controlled modulation, the latter, more common are used in this paper. With the well known influence of the modulation technique on power quality characteristics presented in [9], the sinusoidal pulse width modulation (PWM) technique was selected. The gate drive signals, for the three-phase grid connected converter, are generated based on the principle illustrated in Fig. 3. Known limit of this modulation technique is the utilization of the DC-link circuit, where:

$$U_{l\max}=\frac{\sqrt{3}}{\sqrt{2}}\frac{V_{DC}}{2}\approx 0.612\cdot V_{DC} \tag{9}$$

However, in regard to the main focus, the utilization of the DC-link circuit is out of the scope for the particular paper.

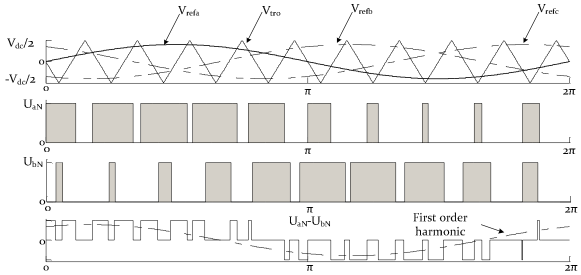

Fig. 3 Three-phase pulse width modulation technique

When the complete scope of the control strategy is summarized, it can be noted that the DC-link voltage oscillation will mainly influence the modulation technique (where the normalization is performed based on the actual DC-link voltage) and the DC-link voltage control (thus being translated to the current controller).

III. Experimental Results

The behavior of the GCC was tested on an advanced laboratory prototype, developed at the Faculty of Technical Sciences [16, 17]. The laboratory setup, representing a scaled model of the grid connected RES based system, comprises of the state-of-the-art hardware in the field of electrical drives and control. In Fig. 4, modular and highly versatile dSPACE processor board, designated by ①, executes the control algorithm for the GCC designated by ②. In order to provide adjustable grid voltages for testing under different operating conditions (i.e. ideal sinusoidal voltages), grid emulator ③ is connected at the point of common coupling [17]. Two distribution cabinet designated by ④ and ⑤ hold switching and protection gear. Data acquisition, control signals and measured signals are routed through adapter block indicated by ⑥. Additionally, in order to allow testing of different RES types (i.e. wind, wave and solar energy conversion systems, co-generation systems, electrical energy based storage systems), various electrical machines ⑦, torque controlled drives, which emulate primary energy sources ⑧, and DC/DC ⑨ converters complete the setup.

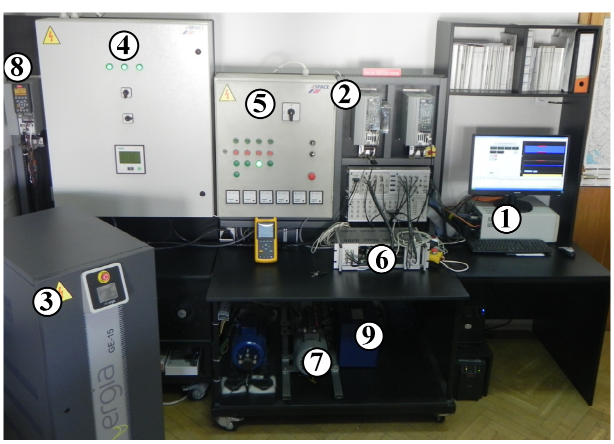

Fig. 4 Advanced laboratory station for control of grid connected distributed energy resources

Using the capabilities of the grid emulator, close to ideal sinusoidal voltages, with THD less than 0.5 %, were set at the point of common coupling. With the low content of higher harmonics, the impact of the voltage distortion on the current control, and thus the current spectrum, will be minimized. The values of the voltage at the PCC, prior to the connection of the converter are given in Fig. 4. After the GCC starts delivering active (and reactive) power to the system, due to the injected current harmonic distortion, the voltage at the PCC will become distorted, as presented in Fig. 5. This can happen when the GCC is connected to a “weaker” grid, where the short-circuit power level of the grid is close to power level of renewable energy system, i.e. most commonly the case in distribution networks.

The DC-link voltage, provided by a three-phase diode rectifier, is presented at Fig. 6. It can be clearly noted that oscillations exist not only when the GCC is connected to the grid, but also during an idle state. However, during the operation of the GCC, the oscillations clearly increase. In addition, due to the DC circuit charging and discharging cycles, the oscillations have an identifiable pattern. The peak values of the pattern are determined by the load of the GCC, while the spectral components remain constant.

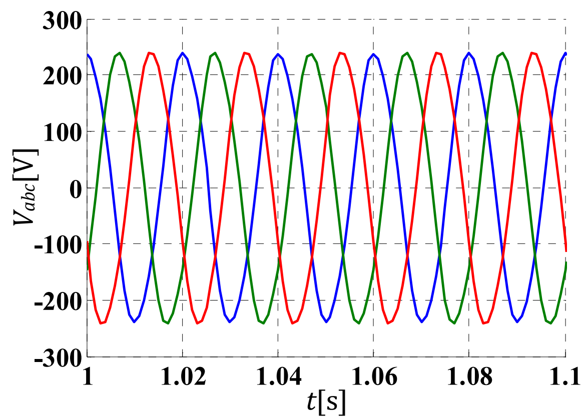

Fig. 4 Three-phase voltage waveform at the point of common coupling prior to the connection of the GCC

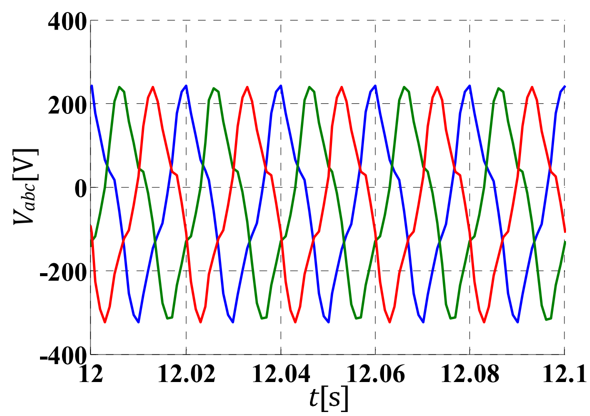

Fig. 5 Three-phase voltage waveform at the point of common coupling after the connection of the GCC

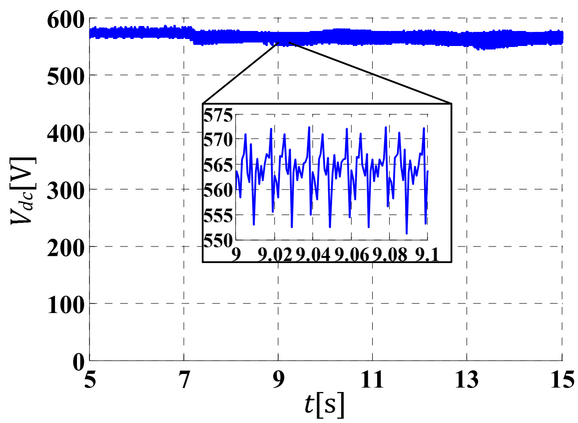

Fig. 6 Three-phase voltage waveform at the point of common coupling after the connection of the GCC

When such DC-link voltage signal is used in the control algorithm and more importantly for the modulation technique, these oscillations can cause the occurrence of the certain harmonics in the injected current. Furthermore, injected active and reactive power will contain the same harmonics, which can have an unfavorable influence on the system stability.

To provide the reliable date on the influence of the DC-link circuit oscillation, two tests were performed. First the modulation and the control are performed using the voltage signal given in the Fig. 6, while for the second test the average value of the DC-link voltage was used. In Fig. 7 and 8, the current waveforms and spectra are given for the actual and averaged DC-link voltage signal respectively. The results clearly demonstrate the propagation of the DC-link voltage to the injected current spectrum. The total harmonic distortion, during the modulation with the actual DC-link voltage value, was at 11.32 %. The most influential are the even harmonic numbers, with individual distortion of 8 % or less.

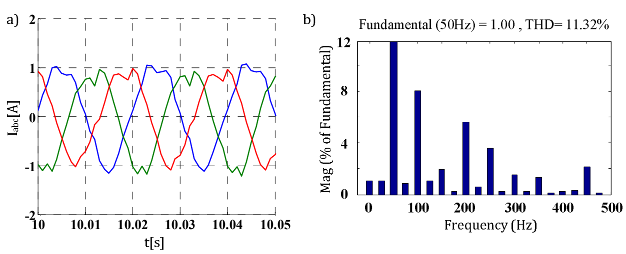

Fig. 7 Three-phase current waveform and spectrum for the modulation with actual DC-link voltage signal

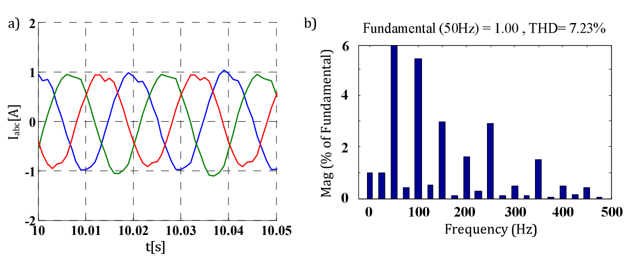

Fig. 8 Three-phase current waveform and spectrum for the modulation with averaged DC-link voltage signal

In order to have correlating results, the current reference was kept at a constant 1 A in the d-axis (active power injection). When the averaging of the DC-link voltage signal was performed, the total harmonic distortion dropped to a value of 7.23 %, while the domination shifted to a odd number harmonics like 3rd, 5th and 7th, having individual distortion lower than 4 %.

The d- and q-axis currents during the two tests can be seen in Figs. 9 and 10 respectively. The dynamic behavior of the current controllers is the same for both cases, with the oscillation clearly being higher during the modulation with actual DC-link voltage. Therefore, the averaging of the DC-link voltage signal has no negative impact on the system control and performance.

Values of the active and reactive power, due to the same dynamics, will be given only for the case of the control with the averaged DC-link circuit voltage. Even though the q-axis controller has regulated the voltage correctly, the origin of the reactive power component is the misalignment of the PLL, due to distorted voltages (shown in Fig. 5).

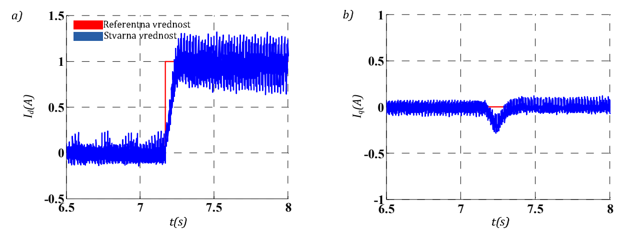

Fig. 9 Actual and reference values of the d-axis (a) and q-axis (b) currents for the modulation with actual DC-link voltage signal

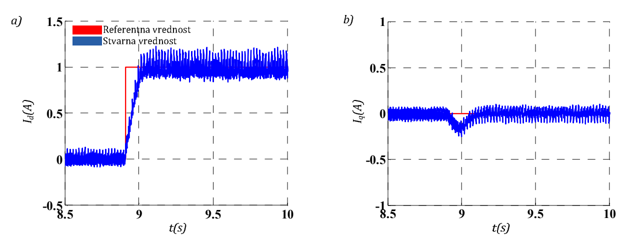

Fig. 10 Actual and reference values of the d-axis (a) and q-axis (b) currents for the modulation with averaged DC-link voltage signal

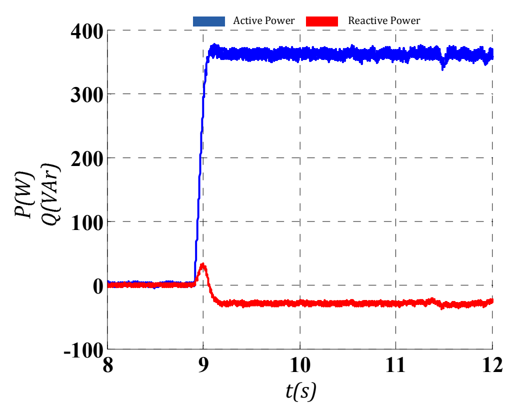

Fig. 11 Active and reactive power values during the experiment

IV. Conclusion

With the constant development in renewable energy technology, the role of the grid connected converter becomes more clearly defined. As one of the key elements of the future energy market, grid connected converter will have to abide by the increasingly more rigorous requirements for the connection. Therefore, the proper control of the grid connected converter will play an important role in the near future. Moreover, the robust control with improved power quality characteristics will be compulsory.

This paper demonstrates the influence of the DC-link voltage oscillation on the power quality characteristics of the injected currents. The DC-link circuit voltage oscillations are related to the constant cycling of the DC circuit, i.e. charging and discharging. Clearly, when the actual DC-link voltage signal was used, the total harmonic distortion of the currents was significantly higher, than the case where averaged value was applied. Additionally, no negative impact resulting from the averaging was found. The higher current harmonic content could further propagate to the injected power, possibly causing the oscillations in the system.

In order to further improve the power quality characteristics additional improvements in the control structure are necessary. Future research will aim at lessening the impact of the distorted voltage on the synchronization unit, while the compensation of the current higher harmonics also needs to be considered. In addition, with advanced filtering methods of the DC-link voltage signal, even further improvements could be achieved.

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