Mitigation of harmonic distortion and voltage dips in electrical distribution networks

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***Abstract*— Due to the growing share of converter fed loads and converter coupled distributed generation units in the distribution network, power quality issues become more and more important. The behavior of the existing converters, in most cases peak rectifiers, may result in a distorted network voltage. The recent interest in power factor correction converters shows the importance of resistive converter behavior. Resistive converters damp network oscillations, but their damping potential is dependent of their power level. Power factor correction converters with a programmable damping resistance as secondary control function can be used to reduce the voltage distortion on the grid independently of their power level. With these converters it is possible to set a harmonic input resistance independent of the fundamental input impedance. Consequently, the harmonic input resistance remains low, even when the input power of the converter is decreased. Most attention is paid to the damping of voltage harmonics. However, this control strategy allows also to mitigate voltage dips. Experimental tests on a 1 kW prototype of a digitally controlled full bridge bidirectional converter show the practical behavior of the algorithm. The reaction of the control algorithm on voltage harmonics and voltage dips is examined.**

I. INTRODUCTION

Power quality issues can be divided in two categories, firstly the reliability of the utility grid and secondly the quality of the mains voltage waveform. The quality of the voltage mainly involves three phenomena: voltage harmonics, voltage dips or swells and flicker. The intense use of power electronic controlled electrical loads (e.g. personal computers) has lead to a severe increase of current harmonics drawn from the distribution system. These current harmonics induce voltage harmonics, due to the impedance of the utility network. Voltage dips originate from fault currents in the electrical network or inrush currents of electrical motors and transformers. The flicker phenomenon can be attributed to pulsating loads (e.g. photocopiers, microwaves etc.).

Although network reliability is concerned to have the most direct financial impact, all power quality issues cause major economical losses. For instance, poor power quality may result in the overheating of transformers, damaging of capacitor banks and malfunctioning of electronic equipment, and finally in the falling-out of electrical machinery and/or utility network elements [1]. Due to these drawbacks, power quality issues have troubled power system engineers since the large-scale introduction of converter fed electrical loads [2], [3].

The research concerning the behavior of grid-coupled converters has been stimulated by the advent of high performance digital controllers. Due to the digital controller, more complex control algorithms only result in a few extra lines of programming code, avoiding the extra cost and development time of additional circuit complexity. This research has resulted in the programming of a resistive converter with programmable damping resistance, as has been stated in [4]–[6]. Due to the implementation of the programmable damping resistance as secondary control function on existing grid-coupled converters, it is possible to mitigate harmonic pollution of the distribution network [7], [8]. A beneficial side-effect of this implementation is the ability to damp grid voltage dips by using the proposed current control strategy.

II. CONTROL STRATEGY DESCRIPTION

The topology of the full-bridge ac-dc bidirectional converter is depicted in Fig. 1. The converter consists of an EMI-filter (capacitance C_g) on the ac-side of the converter, and a boost-type full-bridge converter with two input inductors $\frac{L}{2}$, switches S_1 to S_4, and a buffer capacitor C_{bus} at the dc-side of the converter. The converter is controlled by means of a digital signal processor (DSP).

The quantities to be measured for the control of the converter are the inductor current $i_L(t)$, grid voltage $v_g(t)$ and bus voltage $v_{bus}(t)$. These analogue control variables must be converted into digital quantities by the analogue-to-digital converter of the DSP. The process of sensing the control variable, adjusting the sensor output to the appropriate range and the analogue-to-digital conversion can be represented by a division of the analogue control variables by their respective reference values I_L^{ref}, V_g^{ref} and V_{bus}^{ref}. The reference impedance Z_{in}^{ref} is defined as $\frac{V_g^{ref}}{I_L^{ref}}$. The digital dimensionless quantities ($i_{L,n}$, $v_{g,n}$ and $v_{bus,n}$, where *n* indicates the number of discrete time steps T_s) are used by the digitally implemented controller to calculate the duty-ratio d of switch S_2. The computed PWM signals are presented to the switches of the full-bridge converter (Fig.1, dashed lines).

The most desirable behavior to attenuate harmonic oscillations of the grid voltage is achieved with a high positive value of the input conductance for harmonics g_h. Therefore, a novel

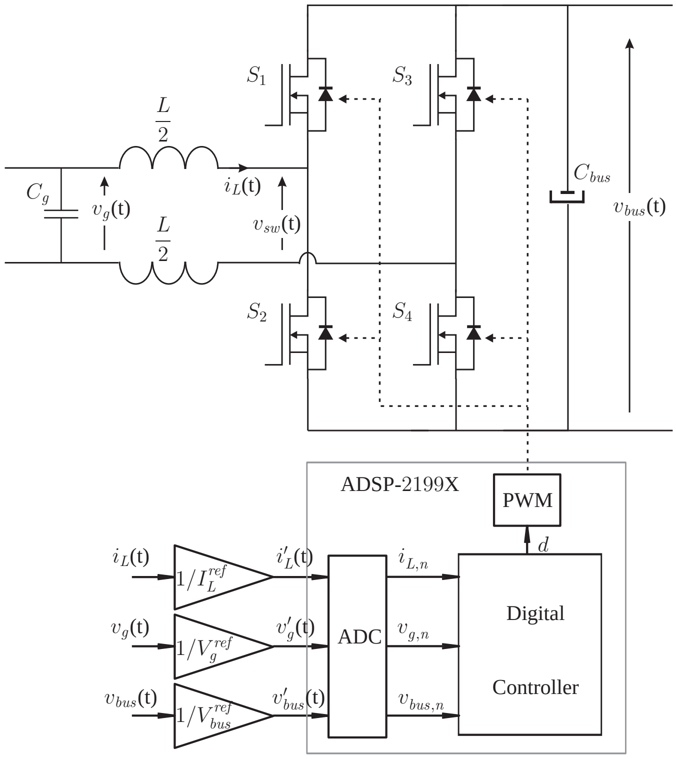

Fig. 1. Topology of the full-bridge bidirectional converter with digital controller

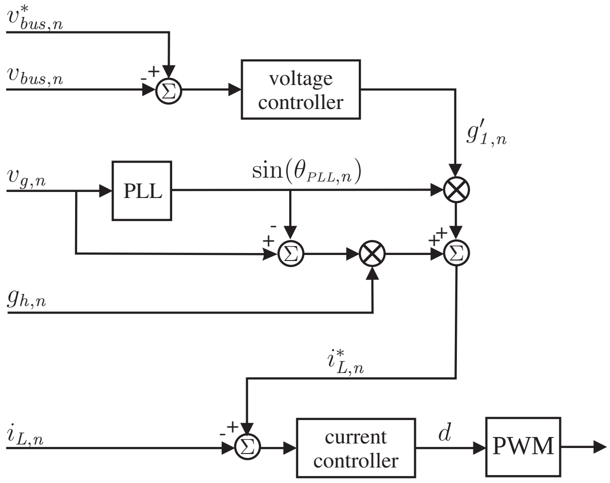

Fig. 2. Control strategy for a grid-connected converter with programmable resistive impedance

control strategy was proposed in [4], [5], [9]. This control strategy was implemented on a boost PFC converter [4], [5] and a full-bridge converter respectively [9]. The control scheme used to implement the programmable damping resistance function is depicted in Fig. 2. The depicted control scheme uses two controllers: a bus voltage controller and an inductor current controller. In order to be able to shape the inductor current as pleased, the current control loop must be fast enough, while the bus voltage controller can be much slower. The controllers have been designed regarding the prescriptions made in [10].

The output voltage controller obtains a constant bus voltage by changing the dimensionless digital value of the fundamental input conductance $g'_{1,n}$. This prescribes the amplitude of the reference value for the fundamental inductor current $i^*_{L,1,n}$ and thus the amount of fundamental power exchanged with the grid. The reference value for the fundamental inductor current $i^*_{L,1,n}$ is the product of the fundamental conductance $g'_{1,n}$ and a sinusoidal reference signal $\sin(\theta_{PLL,n})$:

$$i^*_{L,1,n} = g'_{1,n} \sin(\theta_{PLL,n}). \tag{1}$$

The phase of the sinusoidal reference signal θ_{PLL} is locked to the phase of the mains voltage by using a phase locked loop (PLL) [11].

The reference signal for the total inductor current $i^*_{L,n}$ is constructed by taking the sum of two signals: on the one hand the reference value for the fundamental inductor current $i^*_{L,1,n}$, on the other hand the reference value for the harmonic inductor current $i^*_{L,h,n}$. The latter is the product of the programmable damping resistance $g_{h,n}$ and the harmonic content of the measured grid voltage $v_{g,h,n}$, which is the difference between the sampled grid voltage $v_{g,n}$ and $\sin(\theta_{PLL,n})$. The reference value for the harmonic inductor current $i^*_{L,h,n}$ can thus be written as:

$$i^*_{L,h,n} = g_{h,n} \left(v_{g,n} - \sin(\theta_{PLL,n}) \right). \tag{2}$$

Finally, the reference signal for the total inductor current $i^*_{L,n}$ is given by:

$$i^*_{L,n} = g_{h,n} \left(v_{g,n} - \sin(\theta_{PLL,n}) \right) + g_{1,n} \sin(\theta_{PLL,n}). \tag{3}$$

The first term of (3) has a very small value, since it only consists of harmonic currents. The second term consists of the fundamental current. The reference value of the desired inductor current $i^*_{L,n}$ is then compared to the measured inductor current $i_{L,n}$. The difference is calculated and presented to the current controller, resulting in the duty-ratio d.

III. POWER QUALITY ISSUES

A. Grid voltage harmonics

The most obvious reason to implement a programmable damping resistance function on a grid-coupled converter, is to damp the harmonic oscillations in the utility network. This potential has been analyzed thoroughly in [5].

In Fig. 3, the behavior of the converter with programmable damping resistance with sinusoidal grid voltage is depicted. As can be seen, the programmable damping resistance does not affect the standard operation of the converter. In Fig. 4 the inductor current of the converter with distorted grid voltage is depicted. The grid voltage contains a 3rd harmonic component (amplitude of 10%) and a 17th harmonic component (amplitude of 5%). The figure shows that the inductor current also contains these harmonics, but that the waveform of the inductor current is not longer equal to the waveform of the grid voltage. This effect can be attributed to the fact that the conductance $g'_{1,n}$ is smaller than the harmonic conductance

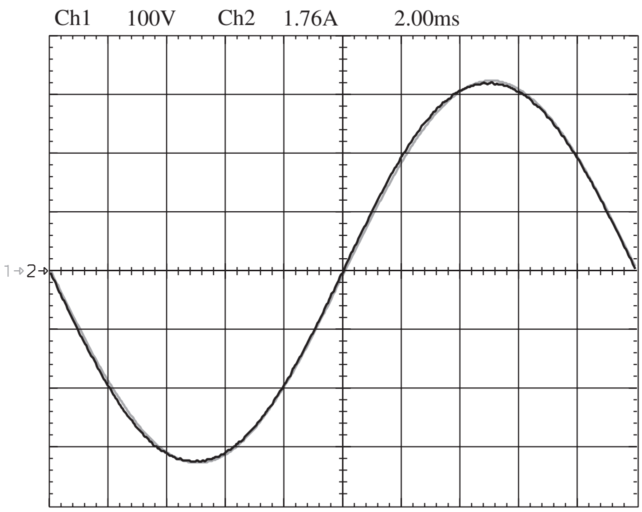

Fig. 3. Full bridge bidirectional converter with sinusoidal line voltage: Grid voltage (gray line), inductor current with feedforward (full black line).

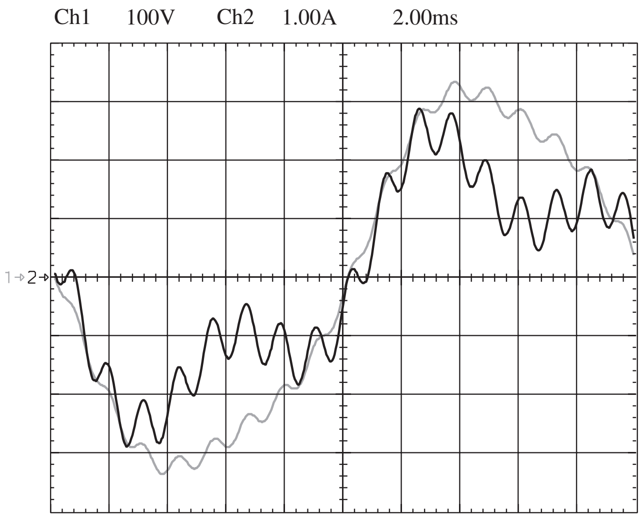

Fig. 4. Full bridge bidirectional converter with distorted grid voltage: Grid voltage (gray line), inductor current with feedforward (full black line).

g_h. Consequently, the harmonic content of the grid current is bigger than the harmonic content of the grid voltage. The grid impedance combined with the absorbtion of harmonic currents causes the mitigation of harmonic voltages.

B. Grid voltage dips

The proposed current control algorithm proves to be indispensable to provide damping for voltage dips as well. The potential of the converter to damp voltage dips is mainly dependent of the inductor current controller. The bus voltage sampling is executed at 100 Hz [12], which is slow compared to voltage dips. This difference in speed allows to neglect the influence of the bus voltage controller on the converter behavior during grid voltage dips.

The bus voltage controller balances the input and output powers of the converter by adjusting the value of the fictive conductance g'_1. The update of g'_1 is performed at every

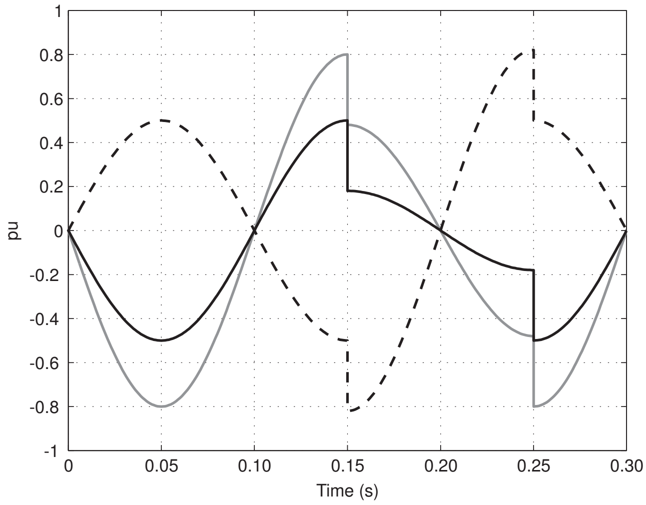

Fig. 5. Grid voltage and grid currents during a 40% voltage dip. Gray line: grid voltage, full black line: absorbing inductor current, dashed black line: injecting inductor current.

zero crossing of the input voltage. Since this value remains unchanged during half a period, we can assume that the value of the fundamental component of the inductor current is fixed during voltage dips.

The current controller shapes the inductor current based on the desired inductor current i^*_L. During voltage dips, i^*_L consists of a fixed share, viz the fundamental current, and of a variable share, which is constructed by multiplying g_h with the non-steady-state part of the input voltage. Due to the implementation of the programmable damping resistance, the occurring voltage dips will be seen as a disturbance, thus resulting in a corresponding proportionally shaped current. The response of the converter is dependent of the direction of the fundamental power flow. Where a power flow from AC to DC results in a decrease of the inductor current during a grid voltage dip, the opposite is true for a power flow from DC to AC, as can be seen in the simulation results depicted in Fig. 5. The pu values of the voltage and currents are related to their respective reference values V_g^{ref} and I_L^{ref}.

The inductor current variation can be predicted based on (3). The grid voltage during the dip is represented by $(1 - D)v_g$ with D the dip magnitude in pu. The variation of reference value for the inductor current $i^*_{L,n}$ from its steady state just before the dip can be written as:

$$\Delta|i^*_L| = g_h|v_g|D. \tag{4}$$

The above described variation of the inductor current of the converter, combined with the network impedance will damp the grid voltage dip. The rate of the damping is dependent on the cause of the dip, the network impedance and the nominal power of the converter.

If the duration of the dip does not allow to neglect the influence of the bus voltage controller, the damping behavior of the converter is neutralized due to the settling of a new steady state. The inductor currents in the new steady state are dependent on the grid voltage during the dip. The inductor currents will increase compared to the steady state before the dip, in order to compensate for the lower grid voltage. If the converter is absorbing power from the grid, this may deteriorate the voltage dip. However, if the converter is used as grid-connection for a distributed generation unit, the increased grid currents will damp the voltage dip.

IV. CONCLUSION

This paper describes the damping capability of a full-bridge bidirectional converter by means of the implementation of an alternative current control strategy. The current control strategy with a programmable damping resistance has been discussed and the behavior is validated. The impact of implementing the alternative current control strategy on harmonic voltage distortion was experimentally verified using a full-bridge converter. The behavior of the converter during voltage dips was simulated. The behavior of the converter is beneficial for the power quality of the utility grid.

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