Current Waveform Control of a Three-Phase AC-DC Converter with Resistive Shunt Harmonic Impedance Behaviour

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***Abstract*—The amount of harmonic producing loads (e. g. power electronic equipment), which distort the voltage waveform in the electric power distribution system, increases steadily and the propagation of harmonics in the grid degrades the power quality.**

In the literature, several solutions for damping harmonic propagation and waveform distortion have been proposed. Many studies are based on the converter topologies with their corresponding control strategies, which act as active filters. The control strategies for those three-phase topologies are in many cases based on the p-q theory.

The active filters and/or passive filters are frequently applied solutions for compensation of harmonics. However a considerable attenuation of harmonic propagation can be obtained by bidirectional converter topologies which behave as a controlled impedance for harmonics. The corresponding control strategy is based on a current-loop controller with duty-ratio feedforward. It has been demonstrated in single-phase converter topologies that the converter with this control strategy behaves like a resistive shunt harmonic impedance (SHI).

In this paper the authors propose the implementation of the control strategy of the single-phase converter on a three-phase PWM-bidirectional converter. Unlike the control strategy of three-phase active filters, this control strategy will not use the p-q theory. It will be demonstrated that this application will behave as a resistive shunt harmonic impedance and will reduce the harmonics and decrease the propagation of harmonics on the grid and thus damp the voltage distortion of the low-power supply system.

***Index Terms*—Current control, power system harmonics, three-phase pulse width-modulated (PWM) power bidirectional converters.**

I. INTRODUCTION

THE use of (energy saving) equipment based on power electronics (e.g. adjustable speed drivers, low-energy light bulbs,…) increases steadily. However this equipment produces line current harmonics and thus distorts the voltage waveform on the electric power distribution system. The distortion of the voltage and current waveform in the grid degrades the power quality of the energy supply.

Since a few years there is a great interest in power quality (mainly quality of the mains voltage wave-shape and reliability of the energy distribution). Several regulations and guidelines (e.g. IEEE 519-1992, IEC61000, etc.,) are published to limit the current and voltage harmonic distortion.

Since the amount of renewable energy sources (e.g. photovoltaic cells and wind turbines) has increased, more inverters are needed to connect those sources to the grid.

It could be useful to implement inverters which combine both advantages: connection of power electronic equipment to the grid that causes no deterioration of the current and voltage waveforms and damp harmonic propagation on the grid.

In the literature several solutions for damping harmonic propagation and waveform distortion, harmonic isolation and compensation, power factor correction, and/or their combinations have been proposed [1]-[6].

The objective of the research of the authors is to implement and compare two solutions found for single-phase [16]-[21] and three-phase systems [6] into a specific three-phase low-power system (<10kVA). It will be demonstrated that the topology with the control strategy described in [20], [21] and adapted to the three-phase topology will behave as a resistive shunt harmonic impedance.

II. IDENTIFICATION OF THE PROBLEM

Nonlinear and harmonic producing loads can be classified into identified and unidentified loads. Most of the high-power nonlinear equipment is classified as identified loads, because they can be located by the utilities.

Low-power harmonic producing loads used as utility interfaces for domestic purposes (e.g. PCs) are in most cases not traceable and are widespread on the power supply grid. Therefore they will be classified as unidentified nonlinear and harmonic producing loads [7].

Because the amount of harmonic current injection caused by the identified loads can be determined and is usually a

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large amount, high-power customers or electric power utilities can implement an appropriate solution (e.g. passive and active filters).

Due to the non-traceability of the low-power harmonic producing loads, a global solution to damp the total harmonic propagation is needed, but is unfeasible. Most of the power system and the polluting load parameters (behaviour, quantity, location) are unknown [19]. Above, individual compensation of each harmonic producing load is economical unfeasible. Therefore a global approach to mitigate the harmonic propagation is needed.

III. PASSIVE AND ACTIVE HARMONIC FILTERS

It is common knowledge that passive filters consisting of capacitors, inductors and resistors are broadly used to absorb the harmonic currents from distribution loads. The advantages (e.g. low cost and high efficiency) as well as the disadvantages (e.g. single-tuned filters need supplementary second-order filters to perform good filtering in a wide frequency range, possibility of resonances with amplification of harmonic currents) are well known.

Other solutions for harmonic compensation and power factor correction are pure active filters and hybrid active filters. In [7], [8] the authors classify those active filters in two types: series active filters and shunt active filters. The shunt active filter is based on the following:

- detection of the instantaneous non-linear load current;
- extraction of the harmonic current from the load current;
- injection of the compensating current into the grid to cancel out the harmonic current.

The series active filter for reduction of current harmonics is based on the following:

- detection of the instantaneous supply current;
- extraction of the harmonic current from the detected current;
- applying of the compensating voltage across the grid connections to cancel out the harmonics in the current.

It is obvious that active filters and/or passive filters are possible solutions for complete compensation of harmonics. One important drawback is the high initial cost and the running costs.

In the literature there are many studies on how to suppress current harmonics, voltage waveform distortion and to improve the power factor. Those studies can be classified into two main domains: studies based on the converter topologies [1], [2], [9]-[11] and studies based on the improved control strategies [4], [12]-[15]. One of the solutions for considerable attenuation of harmonic propagation is a shunt active filter based on voltage detection with an analog [3] or digital control [12]. In those solutions the three-phase ac-voltages are detected at the point of installation and the harmonic components of the supply voltage are extracted (by means of the p-q theory [13]) and transformed into three-phase compensating currents. Other solutions are based on current waveform control [4], [6], [14] of the ac-current. But most of all those control strategies are applied to active filter topologies.

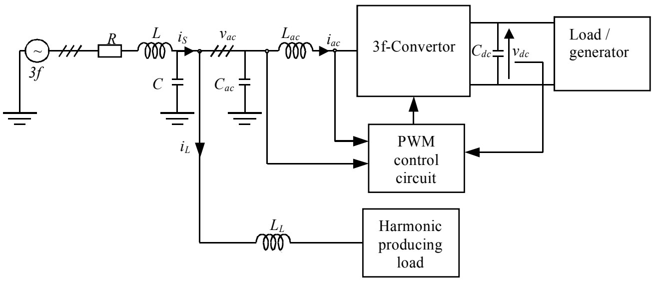

Fig. 1. Three-phase power distribution system.

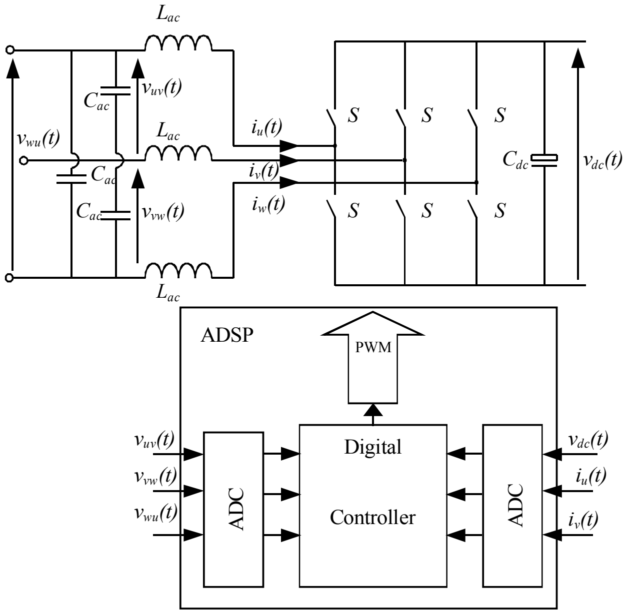

Fig. 2. Converter system configuration with control system.

In this paper the authors propose to implement a three-phase PWM-bidirectional converter connected to the grid as shown in Fig. 1. The converter does not act as an active filter where the harmonic component of the supply current i_S or the non-linear load current i_L is cancelled out by a compensating current, but as a resistive shunt harmonic impedance that provides a considerable reduction of the harmonic propagation.

IV. TOPOLOGY AND CONTROL STRATEGIES

The topology of the three-phase PWM-bidirectional converter is depicted in Fig. 2. The converter topology consists of an input filter and a boost-converter with three

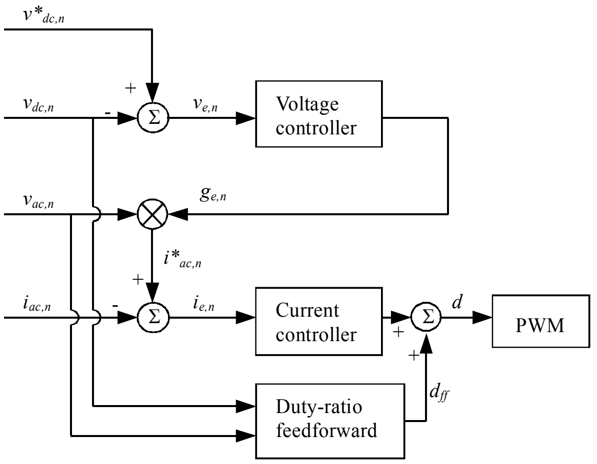

Fig. 3. Two-loop control scheme with duty-ratio feedforward.

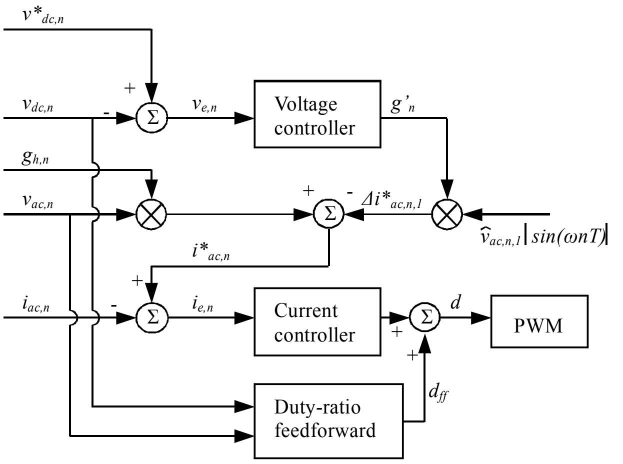

Fig. 4. Control strategy for a programmable input impedance.

inductors L_{ac}, six switches S and a capacitor at the dc-side.

The first control strategy that will be implemented is based on a current-loop controller with duty-ratio feedforward [16]-[18], [21]. This control strategy is applicable to low-power single-phase converters. The object of this paper is to apply this strategy to a three-phase bidirectional converter. The control strategy will be implemented in several stages.

In the first stage the control strategy that will be implemented consists of two PI-controllers [16]-[18], Fig. 3: an ac-current control loop and a dc-voltage control loop. To obtain a constant dc-voltage, the dc-voltage controller balances the input and output powers of the converter by changing the desired input conductance $g_{e,n}$. The product of the input conductance $g_{e,n}$ and the ac-voltage $v_{ac,n}$ of the converter yields the desired ac-current of the converter. The ac-current controller commands the PWM-unit, which controls the switches S. In [16] it has been demonstrated that this control scheme shapes the ac-current proportional to the ac-voltage, thus obtaining resistive behaviour at the ac-side of the converter.

It is proven in [19], [20] that those power converters are able to mitigate the harmonic voltage distortion if they behave as a controlled resistive impedance for harmonics. A controlled impedance which remains effective for reducing harmonic distortion in the case of unknown and varying power system impedances and resonances conditions, should have a positive resistive behaviour for all harmonics. In [3], [7] [19] it has been shown that shunt active compensators behaving as linear resistive shunt harmonic impedances (SHI) for harmonics, can provide a considerable reduction of the harmonic propagation throughout the distribution feeder.

To improve the resistive behaviour of the unidirectional converter a new control strategy for the current control loop was proposed in [18]. This control strategy will be implemented in a second stage. The new control strategy adds a steady-state duty-ration d_{ff} (duty-ratio feedforward) to the output of the previous current control loop. This steady-state duty-ratio is calculated and will contain values of the ac-voltage v_{ac} and dc-voltage v_{dc}.

In [18] the authors demonstrate that the converter with feedforward has a resistive harmonic impedance of

$$Z_{in,h} = \frac{1}{g_e} = \frac{Z_{in}^{ref}}{g_{e,n}}, \text{ with } Z_{in}^{ref} = \frac{V_{ac}^{ref}}{I_{ac}^{ref}} \tag{1}$$

and V_{ac}^{ref} and I_{ac}^{ref} the reference values of the control variables $v_{dc}(t)$ and $i_{ac}(t)$. But for a digital controller the dimensionless quantities $i_{ac,n}$, $v_{ac,n}$ and $v_{dc,n}$ are used as input of the controller

$$i_{ac,n} = \frac{i_{ac}(t)}{I_{ac}^{ref}} \tag{2}$$

$$v_{ac,n} = \frac{v_{ac}(t)}{V_{ac}^{ref}} \tag{3}$$

$$v_{dc,n} = \frac{v_{dc}(t)}{V_{dc}^{ref}} \tag{4}$$

In [20], [21] it is demonstrated that when the control strategy with duty-ratio feedforward, depicted in Fig. 3, is applied, the input conductance of the harmonics decreases for lower power levels, together with the damping potential of the converter. This is due to the fact when this control strategy is applied, the input conductance g_h for harmonics always remains equal to the input conductance g_1 for the fundamental.

To obtain a desirable behaviour of the converter, i.e. a converter with considerable damping of harmonic resonances, the converter should have a high, constant harmonic input conductance g_h and a variable input conductance g_1 of the fundamental. Therefore a new control strategy depicted in Fig. 4 is needed. The input conductance for harmonics is an external input and can be programmed to be constant. The input conductance for the fundamental changes with the product of the output of the dc-voltage controller g'_n and the fundamental component of the line voltage $v_{ac,n,1}$. The result

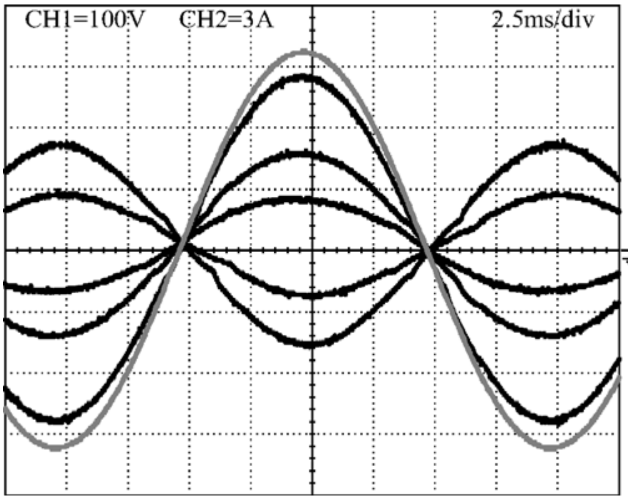

Fig. 5. AC-current (black traces) and ac-voltage (gray trace) of the boost PFC converter at full power, with sinusoidal ac-voltage.

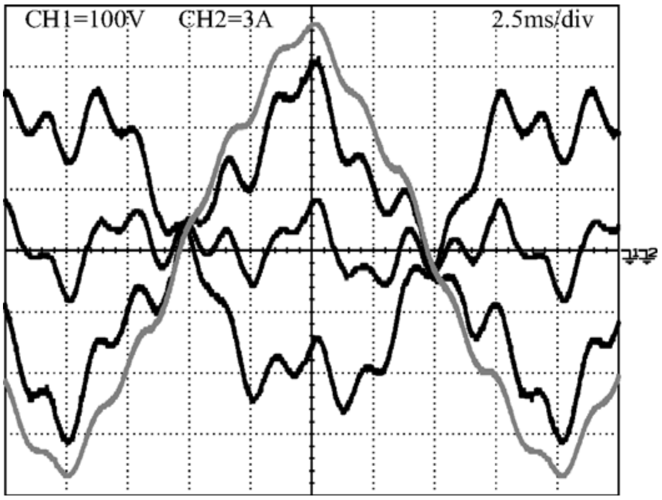

Fig. 6. AC-current (black traces) and ac-voltage (gray trace) of the boost PFC converter for ac-voltage with 5th harmonic distortion.

$\Delta i^*_{ac,n,1}$ adjusts the desired value of the ac-current $i^*_{ac,n}$. As the input conductance for harmonics g_h is known, the input conductance for the fundamental g_1 can be calculated as $g_1 = g_h - g'$. To obtain the fundamental component of the ac-voltage, a phase-locked loop (PLL) is employed. The value of the conductance determines the power level of the converter at its ac-side and even the direction of the power flow. When $g' \leq g_h$ the converter absorbs fundamental power from the grid, when $g' \geq g_h$ the converter delivers fundamental power to the distribution system while the damping feature for harmonics remains, and thus the converter works as an inverter. This control strategy will be implemented in a third stage.

A second control strategy that the authors will implement with the same converter topology is based on the p-q theory. Several control strategies for three-phases converters described in the literature, are based on the p-q theory [3], [5], [6], [12]-[15]. In reference [6] the authors propose to control the distorted current waveform, whose harmonic components are in phase with the terminal voltage harmonics, for reducing the harmonics of the voltage and current on the distribution system. The control of the ac-voltage is based on the p-q theory.

Comparing with the new control algorithm based on the current-loop controller and duty-ratio feedforward implemented in a bidirectional converter behaves as a resisive shunt harmonic impedance (SHI), the p-q method has an important drawback i.e. the control algorithm is more complex (transformation of the three phases to two phases, etc.) and thus the signal processors need more calculation time.

Advantages of the implementation of this new control strategy on a converter with SHI-behaviour are [19]:

- simple and flexible control strategy,
- no need to measure the polluting load current,
- effective for all harmonics and different resonance conditions,
- can be implemented as a secondary control function of an active power supply
- in a three-phase system, even when one of the phases has a shutoff, the converter/inverter still works.

V. PRACTICAL REALIZATION

For the experimental verification of the control algorithm a 10-kVA three-phase bidirectional converter will be employed. Fig. 1 shows the PWM converter system configuration. The converter has at the ac side three inductors L_{ac} of 2mH and three capacitors C_{ac} of 1µF and at the dc-side a capacitor C_{dc} of 500 µF. The switches are IGBTs IRG4 PH40UD. The ac-voltage is a three-phase 400 V grid, 50 Hz and the dc voltage is programmed to be 660V. The ADSP-21992 digital signal processor of Analog Devices controls the converter. The sampling of the input current and input voltage is synchronized with the switching of the converter, at 10 kHz.

The new control algorithm is experimental verified in [20] using a full-bridge single-phase ac-dc PFC converter. The experimental results are shown in Fig. 5 and Fig. 6. When the converter operates at different power levels with a sinusoidal ac-voltage, Fig. 5 shows the ac-voltage (gray trace) and the ac-current (black traces) of the converter. The power levels are 880 W, 467 W and 250 W input power at ac-side, and 249 W and 498 W of power supplied to the grid. In all cases, the distortion of the ac-current is low, so a sinusoidal grid voltage will not be distorted by converters operating with the proposed control algorithm. To validate the operation of the converter with the new control strategy when the line voltage is distorted, a voltage signal is supplied by a linear amplifier, consisting of a fundamental 50 Hz-voltage and different low-order harmonics (5% of 3rd , 5th an 11th harmonic). This voltage is shown in Fig. 6 as a gray trace. The harmonic resistance is chosen to equal the reference impedance Z_{in}^{ref}, while the fundamental input resistance is controlled by the dc-voltage controller and depends on the power level of the converter. The resulting ac-current waveforms are represented by the black traces in Fig. 6 for different power levels: 500 W delivered, 500 W absorbed and 0 W fundamental input power. These three waveforms display comparable harmonic currents, while their fundamental currents are visibly different. In case where no fundamental power is transferred, the ac-current consists only of harmonic currents. This shows that the harmonic input impedance of the converter is constant and resistive for harmonic components, indepentent of the power level of the converter.

VI. CONCLUSION

The authors propose to implement the control strategy described in [16]-[18], [20] and [21] into a three-phase bidirectional converter and to prove that this converter will behave as a controlled resistive impedance for harmonics.

The controlled and programmable resistive input impedance for harmonics will be independent of the input impedance for the fundamental component.

Complete compensation is only possible using true active filters. Converters with resistive shunt harmonic impedance behaviour have been demonstrated in single-phase topologies to provide a considerable reduction of the harmonic propagation.

Because the simplicity of the control strategy and the effectiveness of the damping function of the harmonics, most of the electronic systems connected to the grid can be equipped with these converter to optimize the damping potential throughout the voltage distribution system.

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