A Modified Direct Power Control Strategy Allowing the Connection of Three-Phase Inverter to the Grid through LCL Filters

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***Abstract*— This paper proposes a novel approach to adapt the conventional Direct Power Control (DPC) for high power applications with a third order LCL filter. The strong resonance present in the LCL filter is damped with additional effort in the system control. The application of DPC to the control of three-phase Voltage Source Inverter (VSI) connected to the grid through a LCL filter has not yet been considered. An active damping strategy for the LCL filter together with harmonic rejection control is proposed over the conventional DPC. The steady state as well as the dynamic performance of the proposed system is presented by means of the simulation results and compared with the conventional approach.**

Keywords - voltage source inverter, grid connected, direct power control, LCL filter

I. INTRODUCTION

Three-phase voltage source inverters are employed in many grid connected applications, such as static VAr compensators, UPS and distributed generating systems (e.g. PV, wind power, etc). In order to control the VSIs and achieve proper power flow regulation in the power system, the voltage oriented control, which allows for a good dynamic response obtained via an internal current control loop, is widely used [1]-[2]. As alternatives to this control method, many control strategies have been proposed in recent works such as predictive control [3] and direct power control (DPC) [4]-[5].

The use of direct power control is increasing in the recent past years due to the advantages, such as a very fast dynamic response and simplicity over other methods. On the other hand, the variable switching frequency and resulting spread spectrum are the disadvantages of the traditional direct power control. A constant switching frequency DPC without losing its advantages can be achieved based on direct torque control (DTC) methods described in [6], [7] . The basic idea of DPC approach is the direct control of active and reactive power without any internal control loop or PWM modulator. The switching states are selected using a switching table and the states are chosen based on the instantaneous error between the estimation and the desired active and reactive power. Substantial amount of work on this concept has been reported previously [4]-[5]. However, typically simple series inductors are used as the filter interfacing converter and mains. On the motor side the leakage inductance is up to 30% and often an LCL filter is not necessary. However, on the grid side with very low inductance (maximum 5%) it is very difficult to meet the IEEE519 without an LCL filter. An LCL filter can achieve reduced levels of harmonic distortion at lower switching frequencies and with less overall filter stored energy. On the other hand the LCL filter may cause both dynamic and steady state distortion of the input current due to resonance. In a traditional PWM converter switched with space phasor modulation or the selective harmonic elimination the resonance might not be excited due to the fact that there may be no voltage harmonic produced by in the inverter at the resonance frequencies. However, active or passive damping is still necessary during transients and grid voltage disturbances. As in the case of DPC the harmonic spectrum is spread, it is absolutely essential to damp the resonance. Even with the fixed switching frequency approach of DPC also does not guarantee a presence of resonant frequency voltage component.

Several methods have been proposed to damp the supply current oscillations [8]-[9]. However, the damping controller produces a voltage component to be added to the converter modulation index reference, which is not possible with Direct Power Control since the switching states are selected by an Optimum Switching Table, and not through a current control PWM loop. In this paper a novel strategy of output LCL filter active damping based on active and reactive power is proposed and its influence on the converter behavior is presented.

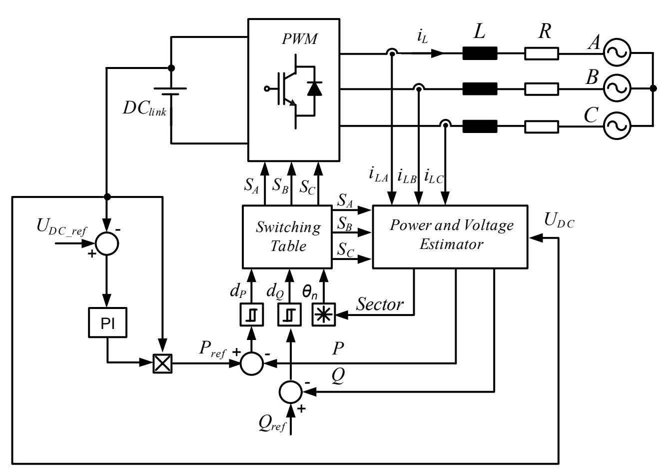


Figure 1. Block Scheme of Conventional Direct Power Control.

Typically the LCL filters are designed with as large capacitance as possible to reduce the inductance for a given attenuation factor at the switching frequency. This decreases the overall costs, volume and weight. However with higher capacitance value, the converter draws larger harmonic current from the distorted supply. As in the DPC approach on the converter side inductor power is regulated, the control has no influence on the harmonics drawn by the capacitor from the supply. Therefore a harmonic rejection control is proposed to reject the effect of grid voltage harmonics. It will be shown later in the paper that the proposed active damping amplifies the low order harmonics depending on the damping factor. The harmonic rejection control automatically compensates this effect without compromising with the damping factor.

II. DIRECT POWER CONTROL – MAIN CONCEPT

The basic principle of the Direct Power Control (DPC) was proposed by Noguchi [4] and is based on the well know Direct Torque Control (DTC) for induction machines. In the DPC, the active and reactive powers replace the torque and flux amplitude used as the controlled output in the DTC. The basic concept consists in appropriately selecting the switching states from a switching table based on the errors present in the active and reactive powers, which are limited by a hysteresis band as presented in Fig. 1.

Two important aspects must be considered to guarantee the correct operation of the system:

- Correct selection of the switching states;
- Accurate and fast estimation of the active and reactive power.

In order to correctly estimate the power and at the same time reduce the numbers of implemented voltage sensors, Noguchi proposes the use of voltage vector estimation. The implementation of such approach involves the computation of the time derivative of measured currents, which may increase the noise in the control loop, thus increasing distortion.

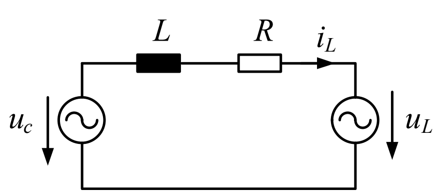


Figure 2. Equivalent Circuit of a grid connected Three-Phase VSI with L filter.

Recently the Virtual Flux strategy was proposed [5], which assumes basically that the line voltage and the ac-side inductors to be quantities related to a virtual ac motor. Making an analogy with ac motors, R and L (Fig. 2) represent respectively the stator resistance and the stator leakage inductance and the line voltage u_L, represents the machine's electro-motive force.

Appling the flux definitions (1) and the voltage loop equation (2), the line virtual flux can be estimated

$$\overline{\psi}_L = \int \overline{u}_L \cdot dt \tag{1}$$

$$\overline{u}_L = \overline{u}_C - R \cdot \overline{i}_L - L \cdot \frac{d\overline{i}_L}{dt}. \tag{2}$$

Neglecting the series resistance of the line inductor, the line virtual flux can be calculated based on the measured line current i_L and the voltage u_C known from the DC link voltage and the converter switching states

$$\overline{\psi}_L = \int \overline{u}_C \cdot dt - L \cdot \overline{i}_L . \tag{3}$$

Based on the line virtual flux and current the active and the reactive power can be estimated as developed in [5].

$$P = \omega \cdot (\psi_{L\alpha} \cdot i_{L\beta} - \psi_{L\beta} \cdot i_{L\alpha}) \tag{4}$$

$$Q = \omega \cdot (\psi_{L\alpha} \cdot i_{L\alpha} + \psi_{L\beta} \cdot i_{L\beta}) \tag{5}$$

III. DESCRIPTION OF THE PROPOSED SYSTEM

The proposed system adapts the conventional Direct Power Control strategy to be used with a third order LCL output filter. The LCL filter attenuates the switching ripple substantially and the overall size of the LCL filter is lesser compared to only L filter. The proposed DPC concept with active damping and active harmonic rejection is shown in Fig. 3. The DPC basic idea to control the instantaneous active and reactive powers through the appropriate selection of the switching states based on the instantaneous errors between the reference and the estimated values are retained. Active harmonic rejection and active damping are included in addition.

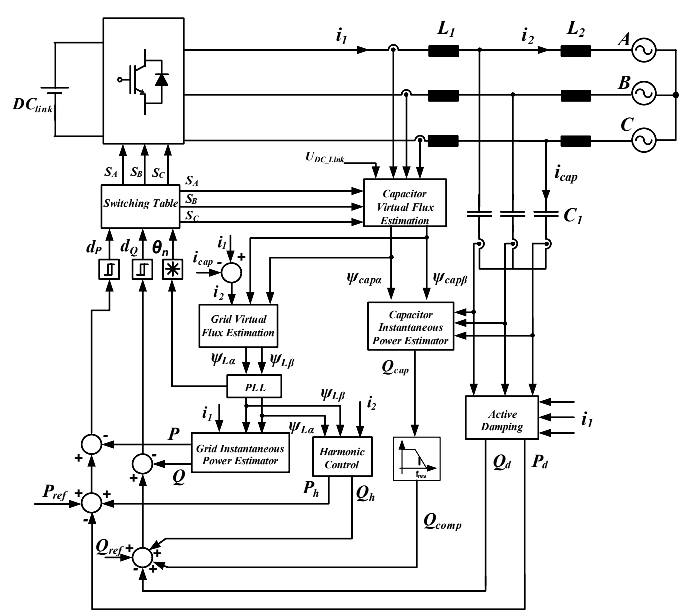


Figure 3. Block Diagram of the Proposed System.

Since the switching states are selected via a switching table, there is no modulation index or common control signal within the control loops where the active damping control signal can be directly added. To overcome this limitation the active damping control as well as the individual harmonic rejection control have to be implemented by acting directly in the active and reactive power components. These control signals have to be added to the fundamental references (P_{ref} and Q_{ref}). Both control features will be explained in details in the next sections.

Another important issue that has to be considered is the mains virtual flux estimation, which differs from the conventional concept with a series inductor as a filter. An equivalent simplified circuit is illustrated in Fig. 4 and the proposed concept is further explained in the following sections.

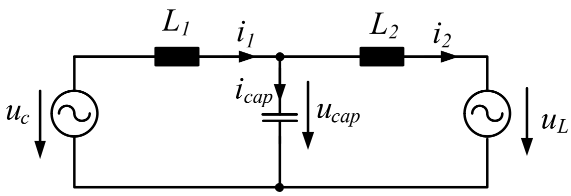


Figure 4. Equivalent Circuit of a grid connected Three-Phase VSI with LCL filter.

First the capacitor virtual flux is estimated as

$$\overline{\psi}_{cap} = \int \overline{u}_c \cdot dt - L_1 \cdot i_1 \,. \tag{6}$$

The mains virtual flux can then be estimated based on the capacitor and the mains side inductor virtual fluxes, which in turn is the product of the mains side inductance and its current. In order to avoid another current sensor the mains current can be estimated though the converter side and capacitor current measurements

$$\overline{\psi}_L = \overline{\psi}_{cap} - L_2 \cdot \left(\overline{i}_1 - \overline{i}_{cap}\right) . \tag{7}$$

The converter side active and reactive powers are estimated similar to the conventional DPC

$$P = \omega \cdot (\psi_{L\alpha} \cdot i_{1\beta} - \psi_{L\beta} \cdot i_{1\alpha}) \tag{8}$$

$$Q = \omega \cdot (\psi_{L\alpha} \cdot i_{1\alpha} + \psi_{L\beta} \cdot i_{1\beta}) \,. \tag{9}$$

Since both active and reactive powers are controlled in the converter side, the capacitor reactive power drawn from the supply must be properly compensated to meet the reactive power command on the supply side. This is done by adding the estimated capacitor reactive power (10) to the fundamental reactive power reference (Q_{ref}).

$$Q_{comp} = \omega \cdot (\psi_{cap\alpha} \cdot i_{cap\alpha} + \psi_{cap\beta} \cdot i_{cap\beta}) \,. \tag{10}$$

IV. Active Damping

Several methods have been proposed for damping, which usually are based on quantities such as voltages and/or currents [8], [9]. However, as explained previously in the paper, the damping with DPC can only by obtained through modifying the power references. A good damping of the LCL filter resonance frequency is achieved by connecting a resistor in series with the filter capacitor or in parallel with the converter side inductor. The main disadvantage of such strategy is that the necessary value of the damping resistance for satisfactory dynamics usually results in very high losses. It is possible to avoid these additional losses by emulating this resistor in the control software. An active damping strategy can be applied effectively because the resonance frequency of the output filter is usually inside the bandwidth of the VSI control loops. The filter corner frequency is designed to be at least three times lesser than the switching frequency to achieve a good attenuation and the fastest control frequency possible is two times the switching frequency. This means that control has at least six samples at the resonant frequency, which are sufficient for achieving good damping.

Firstly the passive damping concept is reviewed followed by a comparison with the proposed active damping strategy. To clearly show the effect of the damping effect caused by the resistor in series to filter capacitor the grid and converter side inductor resistances are ignored.

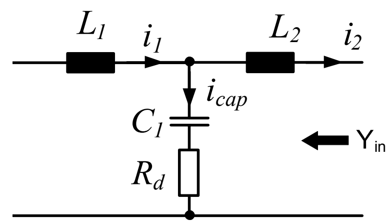


Figure 5. Equivalent output stage with passive damping.

The input admittance of the output LCL filter with passive damping shown in Fig. 5 is given by

$$Y_{in} = \frac{L_1 L_2 s^2 + C_1 R_d s + 1}{(L_1 + L_2)s\left(\dfrac{L_1 L_2}{L_1 + L_2} C_1 s^2 + C_1 R_d s + 1\right)} \,. \tag{11}$$

Based on that, bode diagram plots for different resistor values are shown in Fig. 6.

To emulate the resistor in series to the capacitor, a voltage proportional to the capacitor current is subtracted from the inverter voltage reference, as shown in the equivalent circuit of Fig. 7. This controlled voltage source provides effective damping at the filter resonant frequency. The resistor in series to the capacitor is retained to clearly show the difference in the active and passive damping factors.

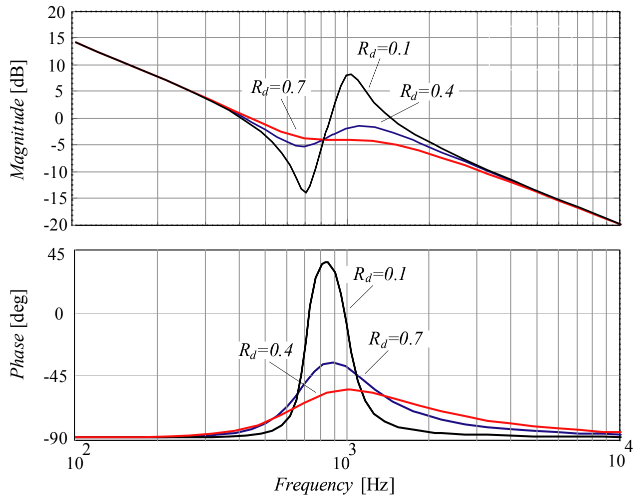


Figure 6. Bode Plot of LCL filter input admittance with passive damping.

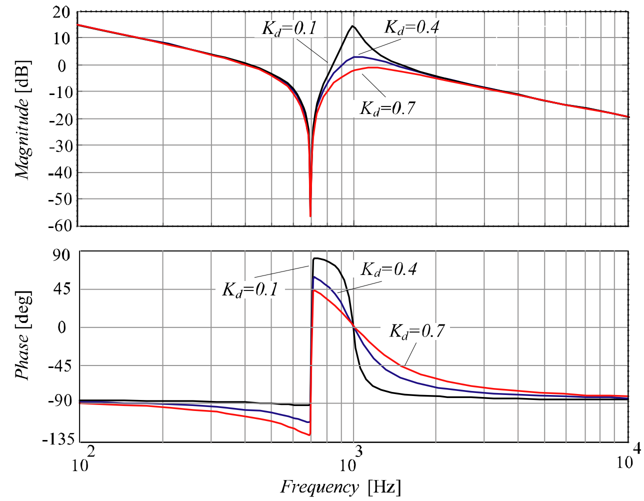


Figure 8. Bode Plot of LCL filter input admittance with active damping.

When adding the active damping approach to the output LCL filter equivalent circuit, the input admittance transfer function is then modified as shown in (12).

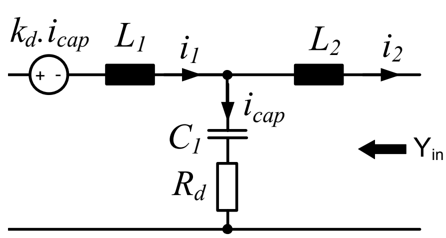


Figure 7. Equivalent output stage with active damping.

It can be clearly seen in the below expression that active and passive damping are very similar. The active damping factor though has the same units, as the passive damping factor it is not 100% equivalent to the passive damping. The active damping factor is influenced by the two inductor values. If the grid side inductance is significantly higher than the converter side inductance the active and passive damping tend to be exactly similar. In practice, the active damping factor value is adjusted to compensate the effect of the inductances.

$$Y_{in} = \frac{L_1 L_2 s^2 + C_1 R_d s + 1}{(L_1 + L_2)s\left(\frac{L_1 L_2}{L_1 + L_2} C_1 s^2 + C_1\left(R_d + k_d \frac{L_2}{L_1 + L_2}\right)s + 1\right)} \quad (12)$$

By setting the passive resistance to zero, the behavior of the active damping can be seen clearly as shown in the bode plots of Fig. 8 for different active damping factors (k_d)

The active damping control loop reduces the harmonics allocated in the LCL filter resonance band however increases the low order harmonics present in the capacitor current to some extent especially with high damping factors. One solution to this is to select a somewhat smaller damping factor, so that the low order harmonic currents are not amplified much and at the same time the damping is sufficient. However, in the presence of active harmonic rejection control whose details are presented in the next section, this effect is automatically compensated.

The method explained till now can be readily incorporated for the VSI switched with control methods that generate voltage references. However, to obtain the equivalent power references for the DPC controlled VSI, the proportional voltage source with the desired damping factor (k_d) is multiplied by the converter side current (complex conjugated in the Stationary Reference Frame) to obtain the power quantities

$$P_d = \mathrm{Re}\left\{k_d \cdot i_{cap\_\alpha\beta} \cdot i_{1\_\alpha\beta}^{*}\right\} \quad (13)$$

$$Q_d = \mathrm{Im}\left\{k_d \cdot i_{cap\_\alpha\beta} \cdot i_{1\_\alpha\beta}^{*}\right\}. \quad (14)$$

By solving equations (13) and (14), the active and reactive power references corresponding to the damping is given by

$$P_d = k_d \cdot \left(i_{cap\_\alpha} \cdot i_{1\_\alpha} + i_{cap\_\beta} \cdot i_{1\_\beta}\right) \quad (15)$$

$$Q_d = k_d \cdot \left(i_{cap\_\beta} \cdot i_{1\_\alpha} - i_{cap\_\alpha} \cdot i_{1\_\beta}\right). \quad (16)$$

After the switching ripple present in these quantities is reduced by using a low-pass-filter or any other method, both damping components are subtracted from the fundamental active and reactive power references as illustrated in Fig. 3.

V. Harmonic Rejection

In order to reduce the level of current harmonics injected to the grid a method to control the harmonics individually in their respective individual synchronous reference frame is introduced. This concept proposed in [10] was implemented to compensate the non-linear load harmonics, load unbalance, etc., through a shunt active filter with a *dq* reference frame based control. The basic idea behind this approach is the transformation of the three-phase voltages and currents into dc quantities, employing the synchronous reference frame transformation. The frame is kept synchronously rotating with the supply voltage fundamental by means of a PLL. Each harmonic quantity to be controlled is transformed into its own individual synchronous reference frame. The corresponding harmonic quantities appear as dc in their own reference frame, consequently a PI control is enough to guarantee zero steady state error. All other harmonics including fundamental will appear as harmonics with a different order and can be attenuated to extract the dc content using a moving average or low pass filter.

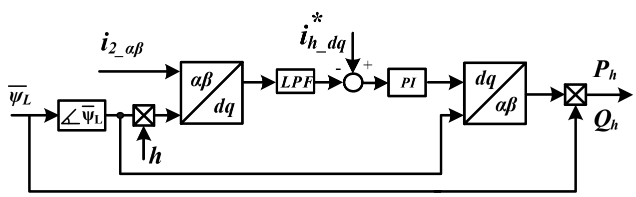


Figure 9. Closed loop individual harmonic current control.

The block diagram of Fig. 9 shows the basic idea of such approach. The mains side current in the Stationary Reference Frame $i_{2\_\alpha\beta}$ is transformed into an Individual Synchronous Reference Frame of the harmonic (h) of interest. For the case where the transformation is done in a Stationary Reference Frame (SRF), the space phasor relative rotational speed has exactly the same value of the harmonic order, as can be seen in Fig.10. On the other hand, if the transformation is based on the *dq* coordinates, the relative rotation speed is equal to n-1 where n is the harmonic space phasor rotational speed. For example, in the case of the 5^{th} harmonic which has a rotational speed five times faster than the fundamental space phasor and in opposite direction, the relative rotational speed is minus six.

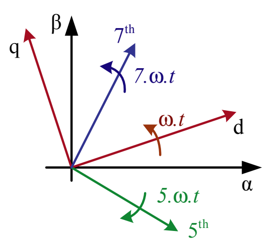


Figure 10. Fundamental and Harmonics Phasor Diagram.

In order to extract the dc component value (individual desired harmonic) from the output transformation either a low-pass or a moving average filter can be implemented. This dc quantity is then controlled with a PI compensator, which tries to eliminate the steady state error. The output of the PI controller is transformed back to the Stationary Reference Frame. The output of this individual harmonic current controller is multiplied by the virtual grid flux by using equations (4) and (5) to estimate the individual harmonic active and reactive power controller output, which will be overriding the fundamental active and reactive power references, as shown in Fig. 11 and effectively diminishing the amplitudes of the controlled harmonics.

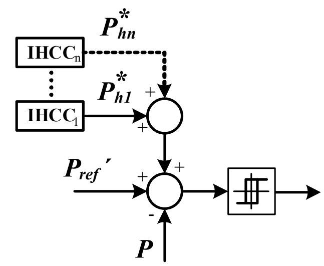


Figure 11. Overriding harmonic power controllers.

VI. Simulation Results

In order to confirm the effectiveness of the proposed system a MATLAB/Simulink model has been implemented. The steady-state as well as the dynamic performance of the proposed system are compared to the conventional DPC without active damping and harmonic rejection control. The electrical parameters for the simulation model are given in the Table I.

TABLE I. Electrical parameters for the simulation model.

Rated output power	*P=500kW*
Phase voltage (RMS)	U_L*=230V*
DC-link voltage	*UDC-Link=750V*
Average switching frequency	*fs=3kHz*
Converter side inductance	L_1*=156uH*
Grid side inductance	L_2*=156uH*
Filter Capacitance	C_1*=325uF*

Although the proposed system includes two extra loops over the conventional DPC, the advantages of the DPC are retained. A response to a reference step of 25% of the rated power is shown in Fig. 12. The rise time of 600µs is achieved with an average switching frequency of 3kHz, which proves the effectiveness of the proposed approach.

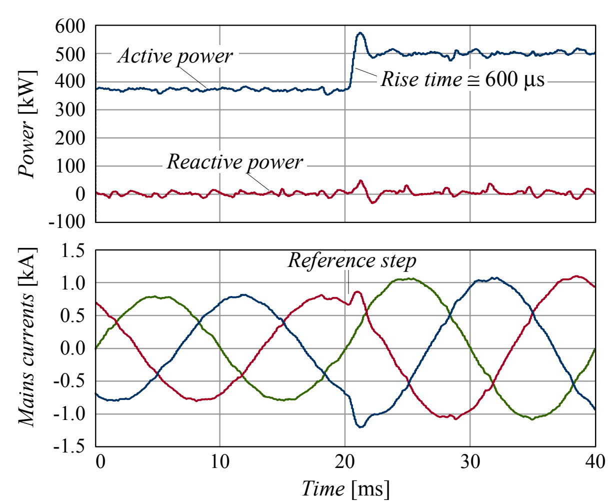
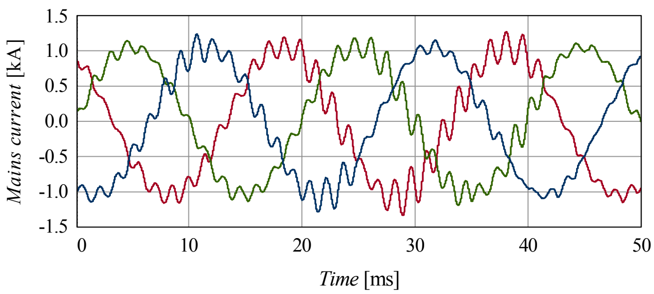
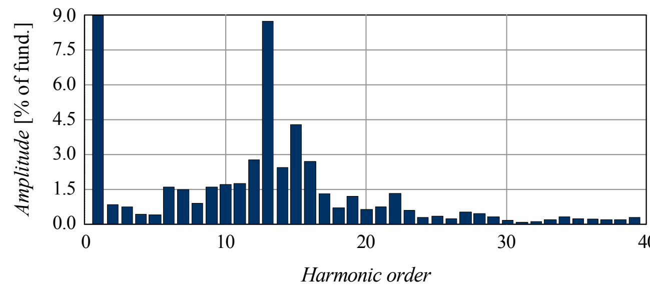


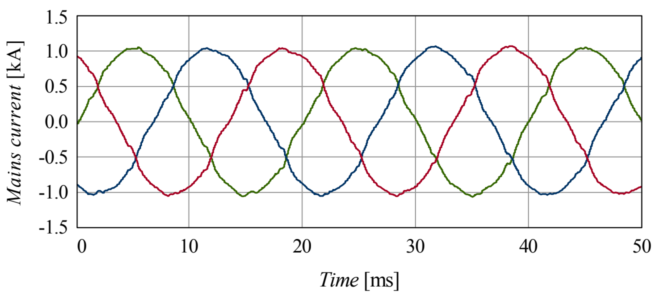
Figure 12. Response to a reference step of 25% of the rated power.



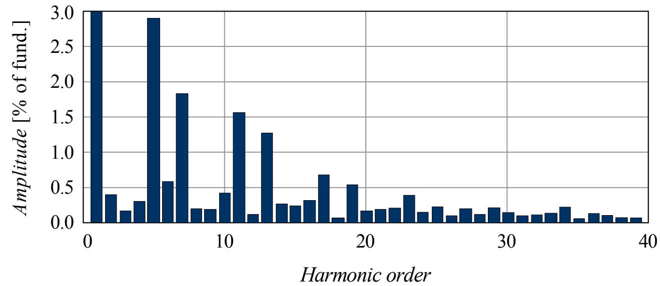
(a) Mains current provided by conventional DPC.



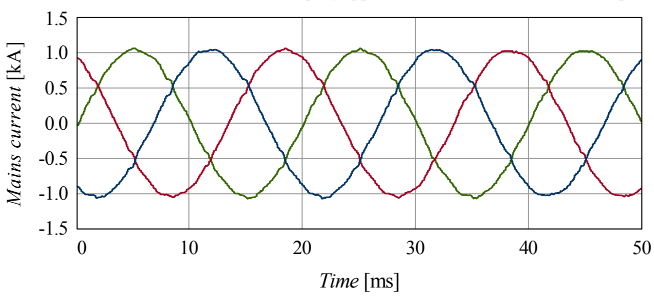
(b) Mains current harmonic spectrum of conventional DPC.



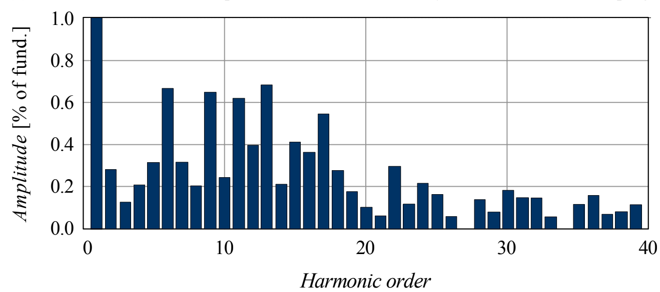
(c) Mains current when the active damping approach is add to the main DPC loop.



(d) Mains current harmonic spectrum of Modified DPC by addition of active damping.



(e) Mains current of proposed system, with active damping and harmonic rejection control loops added to the conventional DPC:



(f) Mains current harmonic spectrum of proposed system with active damping and harmonic rejection control loops added to the conventional DPC.

Figure 13. Simulation results of the conventional DPC and the modified approach when the active damping and individual harmonic rejection are include in the system.

The current oscillations caused by the LCL filter resonance when the conventional DPC is implemented can be clearly noted in steady-state mains current shown in Fig. 13(a) as well as in the harmonic spectrum shown in Fig. 13(b). A significant reduction of these oscillations when the proposed active damping is added to main loop is observed in Fig. 13(c). However the noise present in the capacitor current feedback, amplifies the low order harmonics as shown in Fig. 13(d). In order to reject supply voltage harmonics and to improve low order harmonic amplification by the active damping control, the individual harmonic rejection tuned to the 5^{th}, 7^{th} and 11^{th} harmonics are activated in the next step. The 5^{th} harmonic component was reduced from 3% of the fundamental to around 0.5% and the same behavior can be noted for the 7^{th} and 11^{th} as well in the harmonic spectrum presented in Fig. 13(f).

Although the proposed system includes two extra loops over the conventional DPC, the advantages of the DPC are retained. A response to a reference step of 25% of the rated power is shown in Fig. 12. The rise time of 600μs is achieved with an average switching frequency of 3kHz, which proves the effectiveness of the proposed approach

VII. Conclusion

The adaptation of the conventional DPC to inverter systems where a third order LCL filter is required was presented in this paper. Oscillations caused by the filter resonance were suppressed through a novel active damping approach acting together with an individual harmonic rejection control, both based on powers quantities. The effectiveness of the proposed system was proved via simulation results, which showed significant improvements on the steady-state behaviour when compared to the conventional DPC. The dynamic response to a reference step was not affected by the inclusion of the other control loops thus verifying a good performance of the system.

In a next step the concept will be verified on a laboratory model and finally extended to multi-level converter schemes.

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