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AVERAGE CURRENT MODE CONTROL OF A VOLTAGE SOURCE INVERTER CONNECTED TO THE GRID: APPLICATION TO DIFFERENT FILTER CELLS

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In this paper the average current mode control of a grid connected inverter is investigated. Two control loops are used: the outer one controls the power flow from the source generator to the grid and the inner one controls the grid currents. This control method is applied to two system configurations with different filter cells, L- and LCL-filter. The comparison shows the effectiveness of the last configuration in terms of harmonics rejection. Simulations of the proposed method show performances in both transient and steady state.

K e y w o r d s: grid connected inverter (VSI), passive filter design, LCL filter, average current mode control (ACMC)

1 INTRODUCTION

The contribution of a renewable power source to the total power generation becomes more and more important. A full-bridge inverter is practically always used for interfacing this Green Power Source to the utility-grid.

The control of the energy flowing from the DC source, which is corresponding to an arbitrary renewable power source (wind turbine, photovoltaic cell, fuel cell, *etc*), to the grid must be done in order to track the maximum power point and to maintain a sinusoidal grid current with low harmonic distortion and a high power factor.

In order to lower the transmitted high frequency current ripple, due to the operation of the inverter, a passive filter consisting of inductors or combination of capacitors and inductors can be inserted between the inverter operating as a stiff voltage source and the grid that operates also as a stiff voltage source.

One of the aims of this paper is to address some comparisons for different filter types: two cases are considered L-filter and LCL-filter. Also the design of these filters will be presented.

We can note that the simplest and most common grid filter is the L-filter, which has three inductors connected in series, one in each phase.

The second part of this paper deals with the control of the system. The control loops includes a controller for the grid current and the DC link voltage.

As the DC source is a current source, it is necessary to include a link capacitor between the renewable power source and the grid inverter, to maintain a voltage source in the input of the last one.

The regulation of the system is performed by the DC voltage control loop, which permits to maintain the DC voltage as constant as possible. Then it is necessary to design a PI control because of the non-linearity between DC-link voltage and grid current that holds a constant DC voltage. The aim of this slower regulator is to keep the DC link capacitor voltage to its reference value by properly regulating the current injected into the mains.

On the other hand, the technique used in this paper is the Average Current Mode Control (ACMC) which permits to control the inductor current and to regulate the three phase inverter output. This method eliminates some problems observed when using the Current Mode Control such as noise immunity, the need for a slope compensator, instability at duty ratios exceeding 0.5, ... [4, 6].

ACMC is a current control technique that has an almost constant frequency and produces a user-defined current waveform. It has a fast response time and is capable of supporting a wide range of power circuit topologies. ACMC is based on a compensator circuit which compensate the poles of an integrating filter transfer function. It uses this integrating filter to produce an average current error signal that is compared to a triangular waveform to produce the required pulse width modulation signal [2].

2 SYSTEM DESCRIPTION, FILTER TOPOLOGY AND DESIGN

2.1. System description

The system is composed, as seen in Fig. 1, of a voltage source inverter (VSI) and a line filter.

As mentioned above, the source could be an array of PV panels, a wind turbine or a fuel cell source. Generally, a conversion process of the source generator output is used to adapt it to the DC-link voltage of the inverter.

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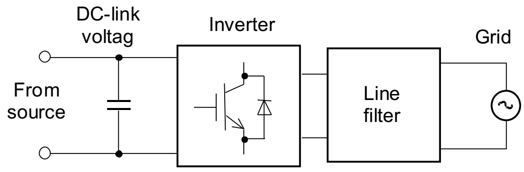

Fig. 1. Connecting DC source to grid via a VSI and a line filter.

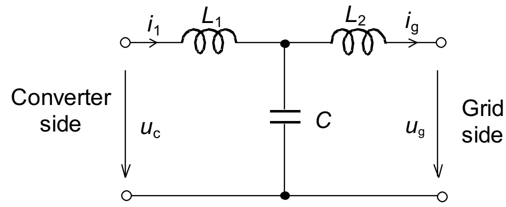

Fig. 2. LCL-filter: single-phase case.

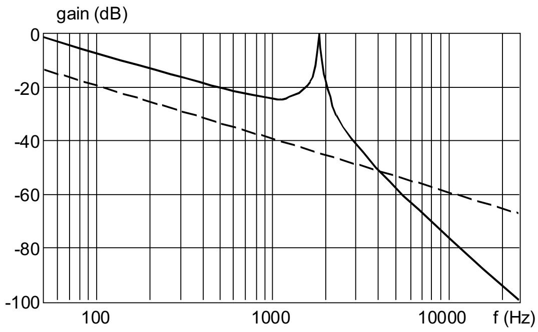

Fig. 3. Frequency responses, L-filter (dashed) and LCL-filter (solid) from output voltage to line current.

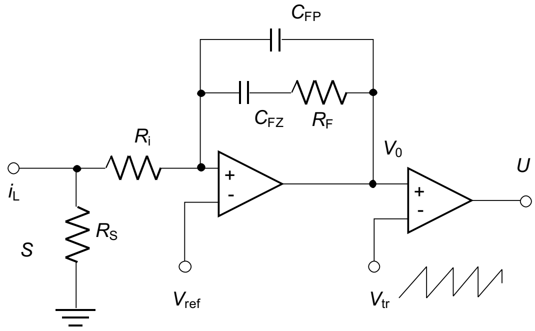

Fig. 4. ACMC implementation.

Thus, when analyzing the system, the source generator is modeled as an ideal current source.

2.2. Filter topology

The line filter reduces the high frequency harmonic content of the line current caused by the switched operation of the VSI.

Usually, the line filter consists of filter inductors but other combinations of capacitors and inductors such as LC- or LCL-filters can be used.

The L-filter is a first-order filter. Its attenuation is 20 dB/decade over the whole range of frequency. Using this filter, the switching frequency of the converter has to be high to obtain sufficient attenuation of the harmonics caused by the PWM converter.

The LC-filter is investigated especially in systems using UPS where the loads are resistors in most cases [8]. However, when connecting systems with this filter to a public grid, the resonance frequency varies over time like the inductance value of the grid. For the reason above, the LC-filter is not investigated in this paper.

Using LCL-filter, seen in Fig. 2, the resonance frequency, given by equation (1), depends only to values of the filter components.

$$f\text{res} = \frac{1}{2\pi}\sqrt{\frac{L_1 + L_2}{L_1 L_2 C}} \tag{1}$$

The most advantages of LCL-filter are:

a) low grid current distortion and reactive power production,
b) attenuation of 60 dB/decade for frequencies over the resonance frequency,
c) possibility of using a relatively low switching frequency.

The frequency responses of L- and LCL-filters [1, 5] are given in Fig. 3.

It is shown that the two filters have the same attenuation below the resonance frequency. For this range of frequencies, the LCL-filter can be regarded as an L-filter with an inductance of $L_1 + L_2$. However, the difference in the attenuation indicates that the sum $L_1 + L_2$ is smaller than the L-filter inductance L. Consequently, the voltage drop across the LCL-filter, caused by the injected current harmonics, is lower compared to the L-filter case.

2.3 Filter design

The passive filter design depends on the attenuation needed in order to reduce the high frequency component of the line current. Standards, such as IEC 1000-3-4 regulation on current harmonic emissions into the power grid, must be used to rate this attenuation. The IEC 1000-3-4 regulation states that current harmonics above the 33$^{\text{rd}}$ should be less than 0.6 % of the nominal current.

The transfer function of the LCL-filter defined by the output voltage to the input current is:

$$G^{\alpha\beta}(s) = \frac{\frac{1}{L_1 \cdot L_2 \cdot C}}{s\left(s^2 + \frac{L_1 + L_2}{L_1 L_2 C}\right)} \tag{2}$$

where the series resistance of inductors are neglected for simplicity. The corresponding Fourier transform gain

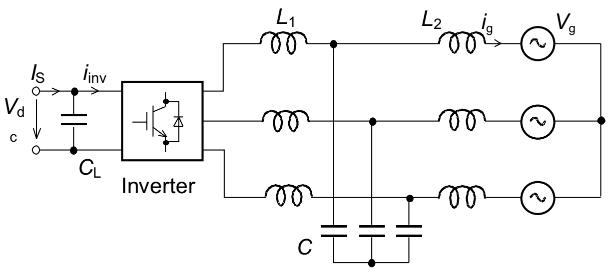

Fig. 5. System to be controlled: the VSI side inductors are equal, the same for the grid side inductors and capacitors.

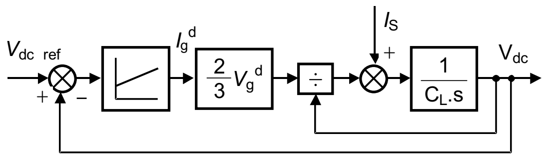

Fig. 6. DC-link voltage regulation.

function for each harmonic component (n) is:

$$\left|G^{\alpha\beta}(jn\omega)\right| = \frac{\frac{1}{L_1 \cdot L_2 \cdot C}}{\left|n\omega\left(-n^2\omega^2 + \frac{L_1+L_2}{L_1 \cdot L_2 \cdot C}\right)\right|}\,. \tag{3}$$

With this equation and other statements, like resonance frequency and low ripple current in the inner inductor, inductors values are determined. In addition the capacitor value is rated with the accepted reactive power production in the level of the capacitor. In fact, from reference [1], additional requirements are given by:

$$L_1 = 2 \cdot L_2 \qquad C = 0.05C_{\text{base}} \tag{4}$$

where C_{base} is the base value of capacitance in the p.u system.

Substituting (4) into (3) and solving for the outer inductor L_2 finally gives a design expression for the LCL-filter:

$$L_2 = \max_n\Big(\frac{3}{4Cn^2\omega^2} + \sqrt{\big(\frac{3}{4Cn^2\omega^2}\big)^2 + \frac{V_{g,rms}}{n\omega I_n}}\Big)\,. \tag{5}$$

The same procedure used above can be applied to design the L-filter.

3 AVERAGE CURRENT MODE CONTROL

A wide range of power conversion applications use the current control technique. This technique controls the peak inductor current to regulate the converter output.

The most drawbacks of current control are a poor noise immunity and instability at duty ratios exceeding 0.5. The Average Current Mode Control (ACMC) is a control technique that overcomes problems listed above. ACMC is a two-loop technique that uses an integrator in the inner loop to average the sensed current. ACMC description and its standard design are presented in [2].

A circuit scheme that could be used to implement ACMC is shown in Fig. 4.

The current to be controlled is sensed through R_S and averaged. The voltage reference V_{ref} is delivered by the outer loop. The integrator output is compared to a triangular waveform, the switch control is then generated.

The transfer function of the integrator circuit [4] is described by equation (6).

$$V_0 = V_{\text{ref}} + (V_{\text{ref}} - V_i)\frac{sR_F C_{FZ} + 1}{sR_i \cdot (sR_F \cdot C_{FP} \cdot{}_{FZ} + C_{FP} + C_{FZ})} \tag{6}$$

where $V_i = R_S \cdot i_L$.

4 CONTROL SYSTEM

The system to be controlled is a three phase VSI connecting a source generator to the grid. An L- or LCL-filter is applied to eliminate harmonics generated in VSI. The basic scheme with an LCL-filter is shown in Fig. 5.

The main goal of the control is to transfer all source generator produced energy to the grid.

The proposed system control is a two loop based. The outer loop is the DC-link voltage. The inner one is around ACMC compensators and controls inductors currents.

4.1 DC-link voltage regulator

To design the DC-link voltage regulator, the following assumptions are considered:

- The grid voltage amplitude is constant;
- Using rotary axes d–q, the grid voltage v_g coincides with d-axis;
- The unity power factor is required, then the displacement between the grid voltage and current is zero. Their q-axis components are also zeros.

The grid power is expressed as follows [7]:

$$P_{\text{grid}} = 3 \cdot V_g \cdot I_g = \frac{3}{2}V_g^d I_g^d\,. \tag{7}$$

The generated power and the link capacitor power are expressed by equations (8) and (9) respectively

$$P_{\text{source}} = V_{\text{dc}} \cdot I_S\,, \tag{8}$$

$$P_{\text{capacitor}} = C_L \cdot V_{\text{dc}} \cdot \frac{\mathrm{d}V_{dc}}{\mathrm{d}t}\,. \tag{9}$$

The VSI losses is assumed to be omitted, the following relationship is verified:

$$P_{\text{grid}} = P_{\text{source}} \cdot P_{\text{capacitor}}\,. \tag{10}$$

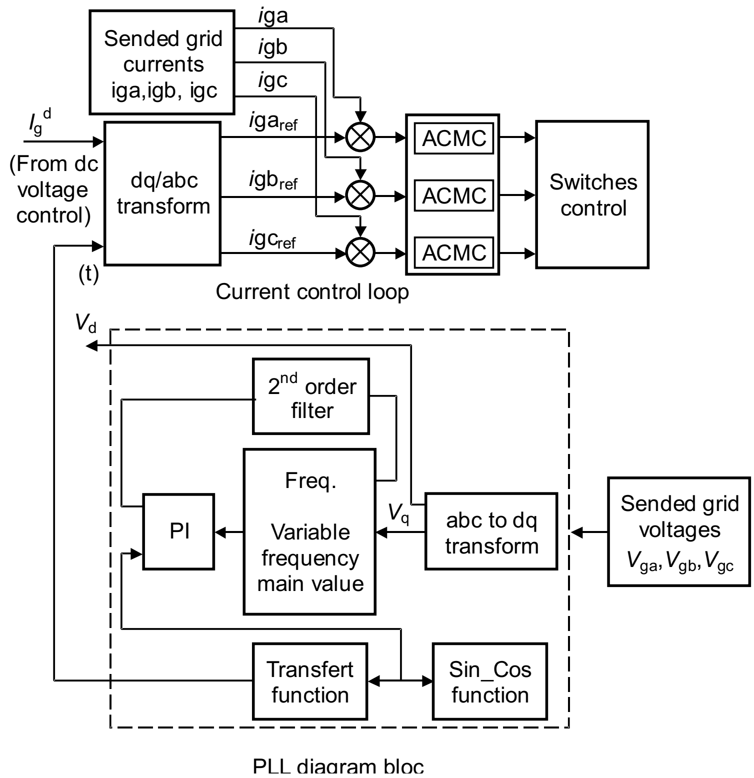

Fig. 7. Average Current Mode Control scheme.

Following equations (7) to (10), the relation between DC-link voltage and the grid current expressed in rotary axis is obtained:

$$V_{\mathrm{dc}} = \frac{1}{C_L \cdot s}\left(I_s - \frac{3}{2}\frac{V_g^d}{V_{\mathrm{dc}}} \cdot I_g^d\right). \tag{11}$$

A PI regulator must be designed to hold a constant DC-link voltage [3].

The DC-link voltage control loop is presented in Fig. 6.

4.2 Current control

As mentioned above, the current control is based on the Average Current Mode Control (ACMC). The proposed model scheme is shown in Fig. 7.

The grid currents are sensed and compared with references currents. The errors are integrated by ACMC compensators. The outputs are compared with a saw tooth waveform and switch controls are then generated.

I_g^d is the output of PI control in DC-link voltage regulator. $\theta(t)$ is obtained from a Phase-Looked Loop (PLL) which is required to perform the synchronization. In fact, since the reference currents are generated using the $dq0$ to abc transformation, a sine wave and cosine wave needed to be generated must be synchronized to the utility grid voltage. Figure 7 shows also a block diagram of the improved PLL. The compensator used is based on the PI regulator which must drive the component value of the utility grid voltage in the d-axis (V_d) to zero performing then the desired value of $\theta(t)$.

5 SIMULATION RESULTS

The rated power, AC voltage level, filters parameters and frequencies switching used in this simulation are listed below.

Rated power:	1 KW
Voltage (RMS):	220 V
L-filter:	
Inductance (L, r):	10 mH, 1 Ω
Frequency switching:	10 KHz
LCL-filter:	
Converter side inductance ($L1$, $r1$):	2 mH, 0.2 Ω
Grid side inductance ($L2$, $r2$):	1 mH, 0.1 Ω
Capacitor (C, rd):	5 μF, 5 Ω
Frequency switching:	2.5 KHz

5.1. DC-link Voltage regulation

Figure 8 shows the DC-link voltage result. It is regulated and reaches closely the voltage reference after a small rise time compared to the grid period. Furthermore, in actual case, the DC-link capacitor should be charged before starting the system.

5.2. VSI and Grid currents

The grid current is generated using two filter cells mentioned earlier (L and LCL ones), Figs. 9 and 10(b). It can be seen that the result are enhanced using an LCL-filter.

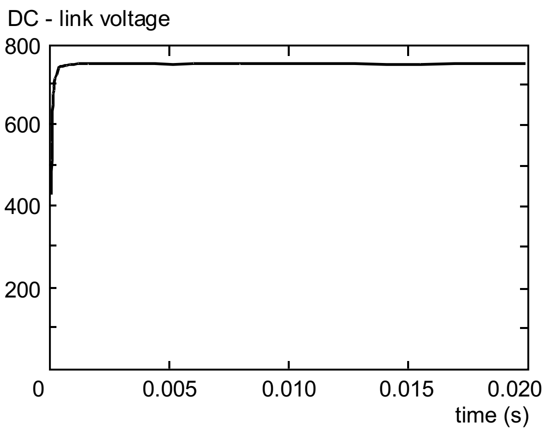

Fig. 8. DC-link voltage.

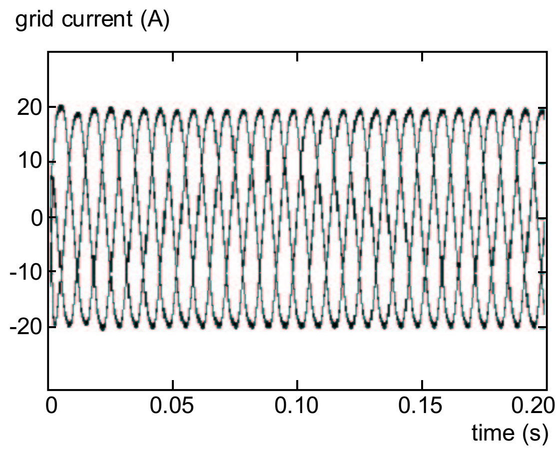

Fig. 9. Grid currents: L-filter case.

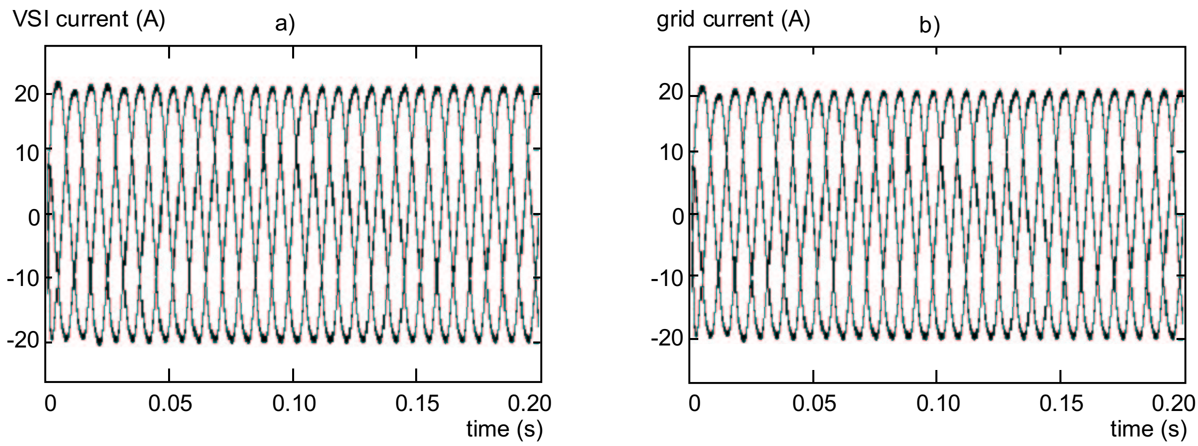

Fig. 10. Generated current: a):before and b):after filtering with LCL-filter case.

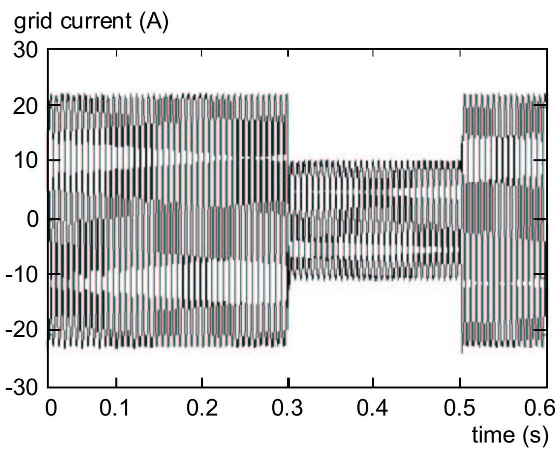

Fig. 11. Transient response: effect in step change (lower and upper) in source current.

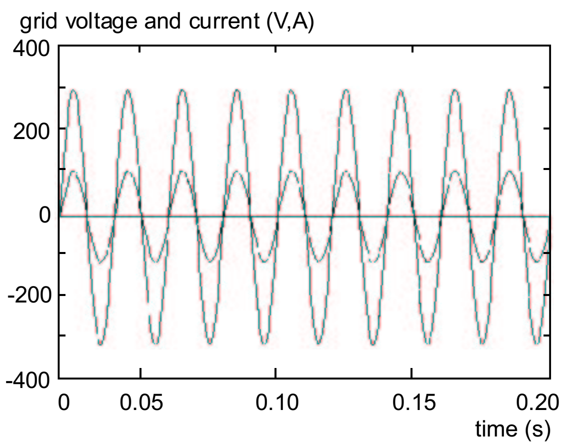

Fig. 12. Phase displacement between grid voltage and current (current is multiplied by a factor of 5). LCL-filter case.

5.3 Transient Response

A 50 % step (lower and upper) change in the source current s simulated. Figure 11 shows that the grid current follows this change with a fast time.

5.4 Power factor

Figure 12 shows one phase displacement (the same for other phases) between the grid voltage and current. A near unity power factor can be reached as required.

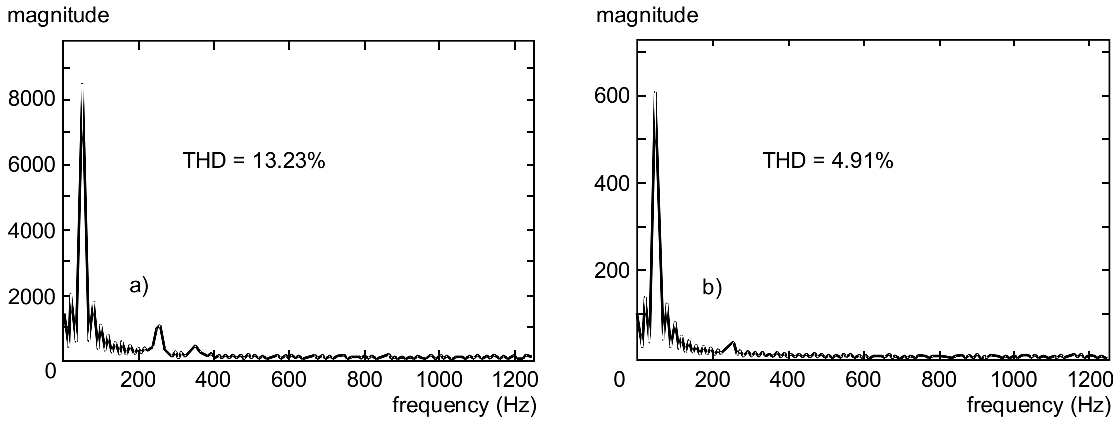

Fig. 13. The frequency response and the value of the THD for L-filter (a) and LCL-filter (b).

5.5 Total harmonic distortion

The effectiveness of each configuration, corresponding to a type of the filter cell inserted between the VSI and the utility grid, in term of harmonic rejection, was quantitatively determined by calculating the total Harmonic Distortion (THD) of the resulting supply current.

An expression for THD is given in equation (12) bellow, where $I_{n(rms)}$ is the root-mean-square current of the n^{th} harmonic.

$$THD = \frac{\sqrt{\sum_2^\infty I_{n(rms)}^2}}{I_{l(rms)}} \times 100\,\% \tag{12}$$

Figure 13 shows the frequency response and the value of the THD for each type of filter cell.

6 CONCLUSION

This paper presents the Average Current Mode Control (ACMC) technique applied to a three phase full-bridge inverter inserted between an arbitrary renewable power source (fuel cell, photovoltaic cell, wind turbine, etc) and the utility-grid. This method, based on a compensator circuit used as an integrating filter, produces a user-defined current waveform.

By using the Concordia (alpha, beta) transformation, we reduce the compensator blocks to two circuits.

In the future, most investigations will be done in the object to control the currents in the mains by using minimum sensors.

Another interesting point presented in this paper concerns the choice of the filter type inserted between the inverter and the grid in order to lower the transmitted high frequency current ripple. The comparison done between two filter configurations shows the effectiveness of the LCL-filter in terms of harmonic rejection versus the most common L-filter.

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