Application of the matrix converter to power flow control

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Abstract: Advanced power electronic converters can provide the means to control power flow and ensure proper and secure operation of the future power grid. The small electrical energy sources dispersed in electrical power systems referred to as distributed generation are one of the most significant parts of future grids – Smart Grids. The three-phase, direct matrix converter is an alternative solution to the conventional AC-DC-AC converter for interfacing two AC systems in distributed power generation with different voltage and/or frequency parameters. This paper presents a control analysis of a three-phase matrix converter employed as a power interface of future electrical grids. The proposed system has been successfully tested for bidirectional power flow operation with different grid operating conditions, such as, frequency and voltage variation.

Key words: matrix converter, AC systems, power flow

1. Introduction

Traditional electricity networks were built to transport electrical energy from a relatively small number of large, centralized power generation units to a very large number of distributed loads. Power flows are essentially in one direction – from centralized generator to distributed loads. The smart-grid concept hinges on making energy use more efficient by utilizing the integration of advanced technologies such as information, communication and power electronics technologies, aimed at more effective power delivery and providing increased reliability to the bulk power system [1]. With the adoption of renewable energy, problems concerning the improvement of energy quality and control of power flow need to be solved in novel power systems. Power electronic converters enable changes in voltage levels and frequency, phase shift, inversion and rectification, offering various services which can be successfully applied in smart grids [2-4]. Figure 1a illustrates the most important areas of use of power converters in the power network [2]. In the majority of cases the solutions in AC-AC systems use power electronic converters with a two-stage electric energy conversion AC-DC-AC (Fig. 1b). AC-DC or DC-AC and DC-DC converters are used in the connection of an AC

system with DC parts (DC energy storage, DC-sources), as shown in Figure 1. Thus it seems obvious that DC circuits cannot be eliminated from electric systems. In some cases, a converter with DC energy storage element is recommended.
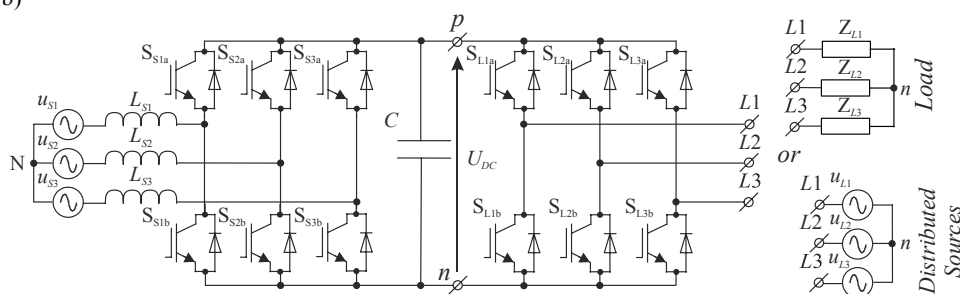
a)
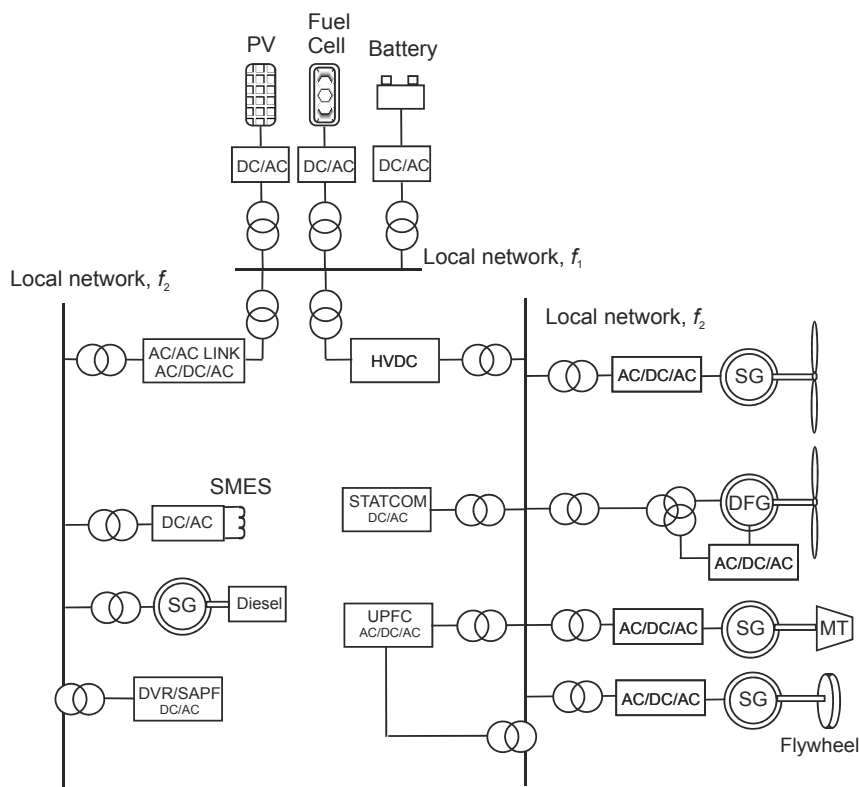
b)

Fig. 1. Smart grid power systems a) examples of power converter applications in electrical power network as an infrastructure of a smart-grid with commonly used AC/DC/AC, b) topology of AC/DC/AC power converter

The DC energy storage in the conventional indirect frequency converter is a bulky component [3]. In the solution with a voltage source inverter (VSI) the DC-link capacitors are rela-

tively large compared to the size of the rectifier and inverter semiconductor components. Electrolytic capacitors typically occupy from 30% to 50% of the total volume of the converter for power levels greater than a few kW. Furthermore, the application of electrolytic capacitors is a major cause of reduced converter lifetime.

Part of the power conversion in an electric power network is based on AC-AC conversion (wind generators, flywheels energy storage, micro turbines, FACTS, etc.). In these cases, the commonly used AC-DC-AC converters can be substituted by AC-AC converters without DC energy storage element [5]. It is also possible to integrate two systems of different parameters (voltage and frequency) by a power electronic converter without DC energy storage. The most widely known AC-AC power converter is the matrix converter (MC) [5, 6]. In the literature, the various topologies of power converters based on MC are also presented [5, 7, 8]. Generally, the three-phase matrix converter is a single-stage converter with nine bidirectional power switches, able to connect directly three input phases to a three-phase load [5]. For high performance, the MC should have a source filter consisting of a second order LC resonant circuit. The main purpose of the source LC filter is the minimization of the high frequency components in the input current.

The most obvious area for the application of AC-AC converters is in distributed generator systems, in wind installations. Four possible wind solutions with AC-AC converters are presented as follows [2]:

- squirrel cage induction generator (IG) with self-excitation and an AC-AC converter in the main line,
- synchronous generator (SG) with an AC-AC converter in the main line and an AC-DC converter in the exciter circuit,
- permanent magnet synchronous generator (PMSG) and AC-AC converter in main line, double fed wound rotor induction generator (DFIG) with an AC-AC converter in the rotor circuit.

Usually, a frequency converter with voltage source inverter (VSI) is used in order to achieve full control of the active and reactive power. An increasing number of scientific publications, e.g., [3, 9], propose matrix converters as an alternative solution to a system with DC-link. A MC can be used for controlling the active and reactive power independently [6]. Furthermore, a MC is responsible for the quality of the generated power and the grid code requirements. Other types of AC source fed by a MC are microturbine generators (MTG) [10] and flywheel energy storage systems [3].

A second group of potential applications for an AC-AC converter without DC-link are FACTS devices, e.g., unified power flow controllers (UPFC) [11], dynamic voltage restorer (DVR) [12], active power filters (APF) and AC power-electronic network couplers.

A MC can be used for controlling the active and reactive power independently. Different control strategies can be used for the power converter to provide power control requirements [13-15]. One such strategy is based on a synchronous Voltage Oriented Control (VOC) with PI controllers. The analysis of a MC with VOC for power control is the main aim of the paper.

2. Description of analysed circuit

The schematic diagram of the three phase MC that interfaces with two AC systems is shown in Figure 2 [5, 6]. Generally in three phase systems, the MC is a single-stage converter which has an array of nine bi-directional switches that allow any load phase to be connected to any source phase. For good performance, the MC should have a source filter to minimise the high frequency components in the input currents and reduce the impact of the perturbations from the input grid. The MC topology is constructed using bi-directional four-quadrant switches, which are capable of conducting currents and blocking voltages of both polarities.
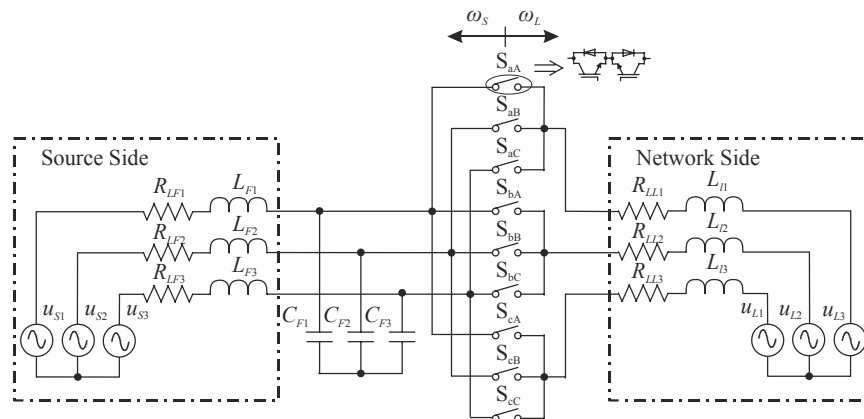

Fig. 2. Schematic representation of two AC systems interfaced by a MC

The MC has several modulation strategies which can be applied [16]. The most frequently used modulation strategy for MCs is the Space Vector Modulation (SVM) [16]. The SVM modulation for MCs is able to synthesize the reference output voltage vector and it is also able to control the source current displacement angle. The SVM technique is based on the instantaneous space vector representation of load voltages and source currents in the MC. For the SVM of the MC it is convenient to define the following space vectors for each switch configuration [16]:

$$\underline{u}_{OL} = \frac{2}{3}\left(u_{ab} + \underline{a}u_{bc} + \underline{a}^2 u_{ca}\right) = u_{OL}(t)e^{j\alpha_{OL}(t)}, \tag{1}$$

$$\underline{i}_S = \frac{2}{3}\left(i_A + \underline{a}i_B + \underline{a}^2 i_C\right) = i_S(t)e^{j\beta_I(t)}, \tag{2}$$

where $\underline{u}_{OL}$ is the space-vector representation for the output line-to-line voltage, $\underline{i}_S$ is the space-vector representation for the input phase current and $a = e^{-2\pi/3}$. The allowed switching configuration of matrix connected switches in the SVM algorithm are shown in Figure 3 and may be categorized as one of three groups of "zero", "active" and "synchronous" configurations, which correspond to the "zero", "active" and "synchronous" vectors. Active vectors are pre-

sented in Figure 4a, b. The reference output voltage and source current space-vectors are constructed by selecting four nonzero configurations (with pulse duty factor δ_I, δ_{II}, δ_{III}, δ_{IV}), applied for suitable time intervals within the switching sequence period T_{Seq}, while zero configurations are applied to complete time T_{Seq}, (Fig. 4c, d).
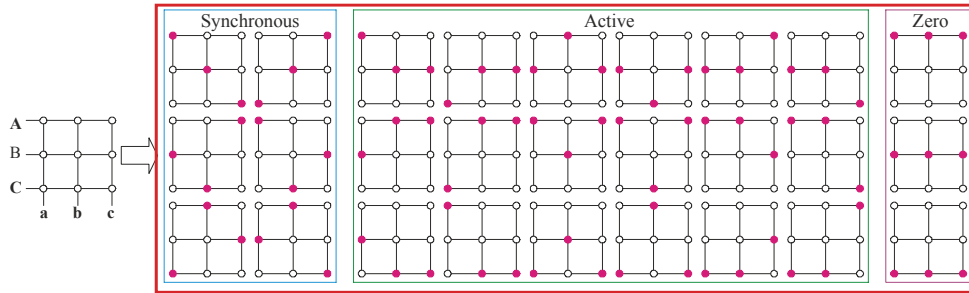

Fig. 3. Allowed switch combinations in a MC

The required modulation duty cycles for four selected switching configurations I, II, III, IV in actual sequence period T_{Seq} are given by equations (3)-(6) [16]:

$$d_I = (-1)^{S_0 + S_i + 1} \frac{2}{\sqrt{3}} q \frac{\cos(\alpha_0 - \pi/3)\cos(\beta_i - \pi/3)}{\cos\varphi_i},$$ (3)

$$d_{II} = (-1)^{S_0 + S_i} \frac{2}{\sqrt{3}} q \frac{\cos(\alpha_0 - \pi/3)\cos(\beta_i + \pi/3)}{\cos\varphi_i},$$ (4)

$$d_{III} = (-1)^{S_0 + S_i} \frac{2}{\sqrt{3}} q \frac{\cos(\alpha_0 + \pi/3)\cos(\beta_i - \pi/3)}{\cos\varphi_i},$$ (5)

$$d_{IV} = (-1)^{S_0 + S_i + 1} \frac{2}{\sqrt{3}} q \frac{\cos(\alpha_0 + \pi/3)\cos(\beta_i + \pi/3)}{\cos\varphi_i},$$ (6)

where S_0 is the output voltage sectors as shown in Figure 4a, S_i is the input current sectors as shown in Figure 4b, q is MCs voltage gain ($0 < q \le 0.866$), φ_i is the input phase displacement angle, α_0 and β_i are the angles of the output voltage and input current vectors measured from the bisecting line of the corresponding sectors (each sector is change every $60°$), and which are limited as follows:

$$-\pi/6 < \alpha_0 < \pi/6, \quad -\pi/6 < \beta_i < \pi/6.$$ (7)

Figure 4c clearly shows that the reference output voltage $\underline{u}_O$ is resolved into the components $\underline{u}'_O$ and $\underline{u}''_O$ along the two adjacent vector directions [16]. The vector of source currents $\underline{i}_S$ is also resolved into components along the two adjacent current directions (Fig. 4d). The $\underline{u}'_O$ component can be synthesised using two voltage vectors having the same direction of u_O, whereas the $\underline{u}''_O$ component can be synthesised using two voltage vectors having the opposite direction, as follows:

$$\underline{u}'_O = d_I \underline{u}_I + d_{II} \underline{u}_{II} \quad \underline{u}''_O = d_{III} \underline{u}_{III} + d_{IV} \underline{u}_{IV}. \tag{8}$$
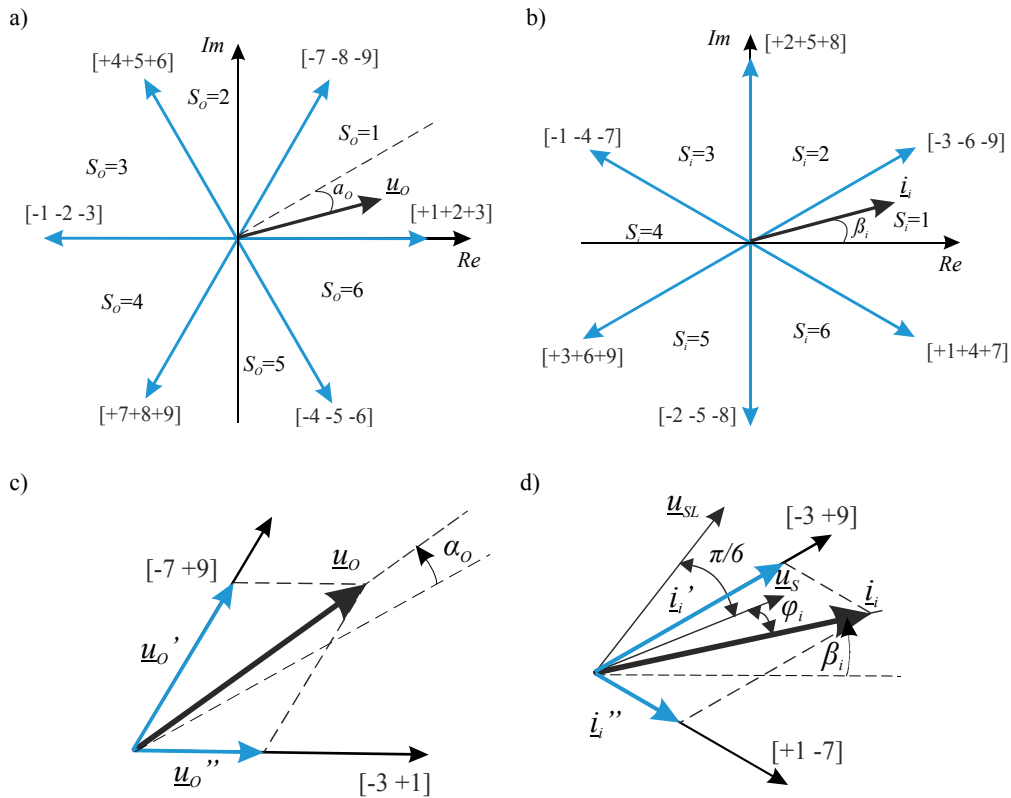

Fig. 4. Available MC vectors for SVM: a) sectors and direction of the output voltage vectors, b) sectors and directions of the input line current vectors, c) synthesis of reference output voltage vector, d) synthesis of reference input current vector

3. Matrix converter interfaces for two three-phase AC systems

A MC can be used for controlling the active and reactive power independently. Furthermore, a MC is responsible for the quality of the generated power and the grid code requirements. Different control strategies can be used for the power converter to provide these specified requirements [13, 14]. One of them is based on synchronous Voltage Oriented Control (VOC) with PI controllers, which was first adopted to DC-AC and is shown in Figure 5a [14]. This control strategy is based on the coordinate transformation between the stationary α-β and the synchronous d-q reference frames (Fig. 5b). It provides fast transient response and high static performance due to the internal current control loops.
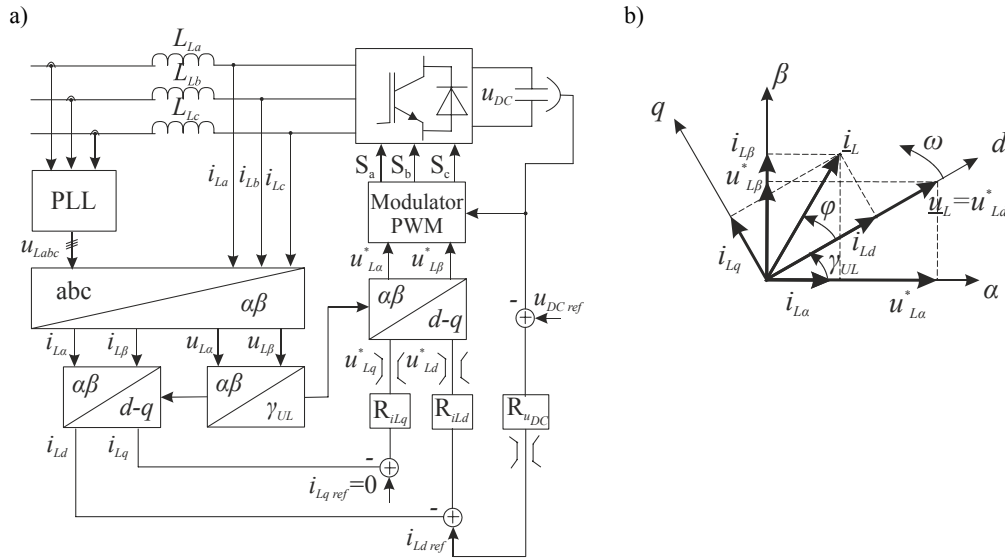
Fig. 5. Voltage Oriented Control method for DC/AC inverter (VOC): a) block diagram,
b) phasor diagram

The VOC control was subsequently adapted to MC control [17]. A simplified block diagram of the VOC control with PI controllers and MC interfaces for two three-phase AC systems is shown in Figure 6. In voltage oriented d-q coordinates, the AC line current vector i_L is split into two rectangular components i_{Ld} and i_{Lq}. The component i_{Lq} determinates reactive power, whereas i_{Ld} decides on active power flow. Thus, the reactive and the active power can be controlled independently. As current controller, the PI-type with anti-windup can be used (Fig. 7) [18]. The output signals from PI controllers after $dq/\alpha\beta$ transformation are used for switching signals generation by a Space Vector Modulator [17].

4. Simulation analysis

To validate the accuracy of the developed MC controls, a study of the system in Figure 6 is considered. Figure 6 shows schematic representation of a matrix converter that interfaces with two AC systems with nominal frequencies of f_S = 60 Hz and f_L = 50 Hz [6]. To verify the validity of the proposed scheme, two simulations are carried out in Matlab/Simulink. In the first one, energy control from the network side to source side is considered; in the second there is a reversal of the energy flow – from source to network side.

Some studies have been done using the following parameters: source voltage 230 V/60 Hz, network voltage 133 V/50 Hz, input filter inductance L_F = 1 mH / 0.05 Ω, input filter capacitance C_F = 20 μF, load inductance L_L = 5 mH/0.05 Ω, switching frequency f_{Seq} = 10 kHz and simulation step T_p = 1 μs. The parameters for current PI controllers are: K_P = 17.54, K_I = 0.58 and T_I = 0.1 ms.
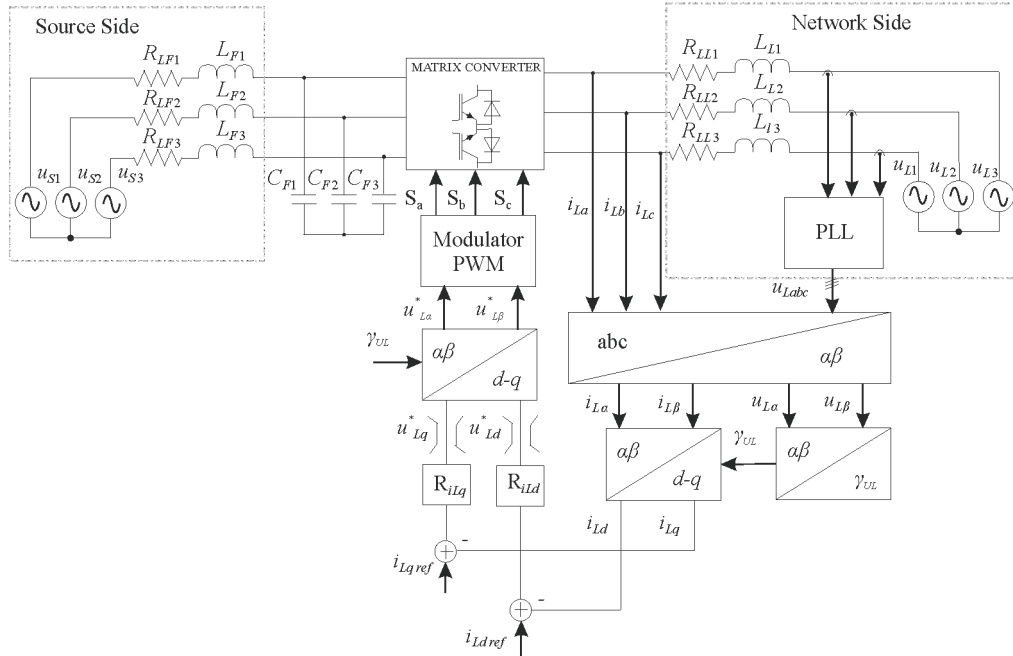
Fig. 6. Control block diagram for a matrix converter interface of two three-phase AC systems
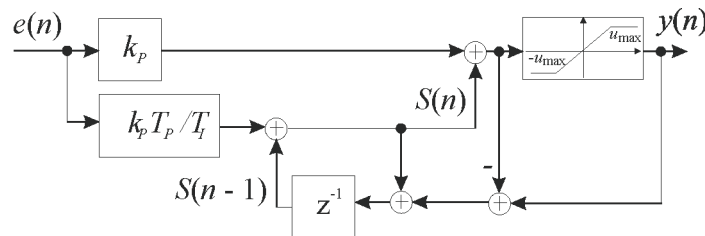

Fig. 7. Anti-windup PI controller structure

Figure 8 shows the energy flow from network side to source side. This case is typical in generator mode. The direct-axis reference and measurement network side current are shown in Figure 8a, whereas, the time waveforms of network current and voltage are indicated in Figure 8b. In the case of $i_{Ld\,ref}$ it was subjected to a step change from 15 A to 100 A in time intervals every 0.1 s. The input voltage and current of the matrix converter are shown in Figure 8c. The phase shift of source current and voltage is almost equal 180°, whereas the network side voltage and current are the same phase shift. Then only active energy is reversed to the source, as is visible in Figure 8d. The active power has minus polarity, which means, that the energy is delivered back to the source. The dynamics of the system are very good. The duration time of step response is short, but the overshoot is visible. A detailed analysis of PI regulator parameters is required [17].
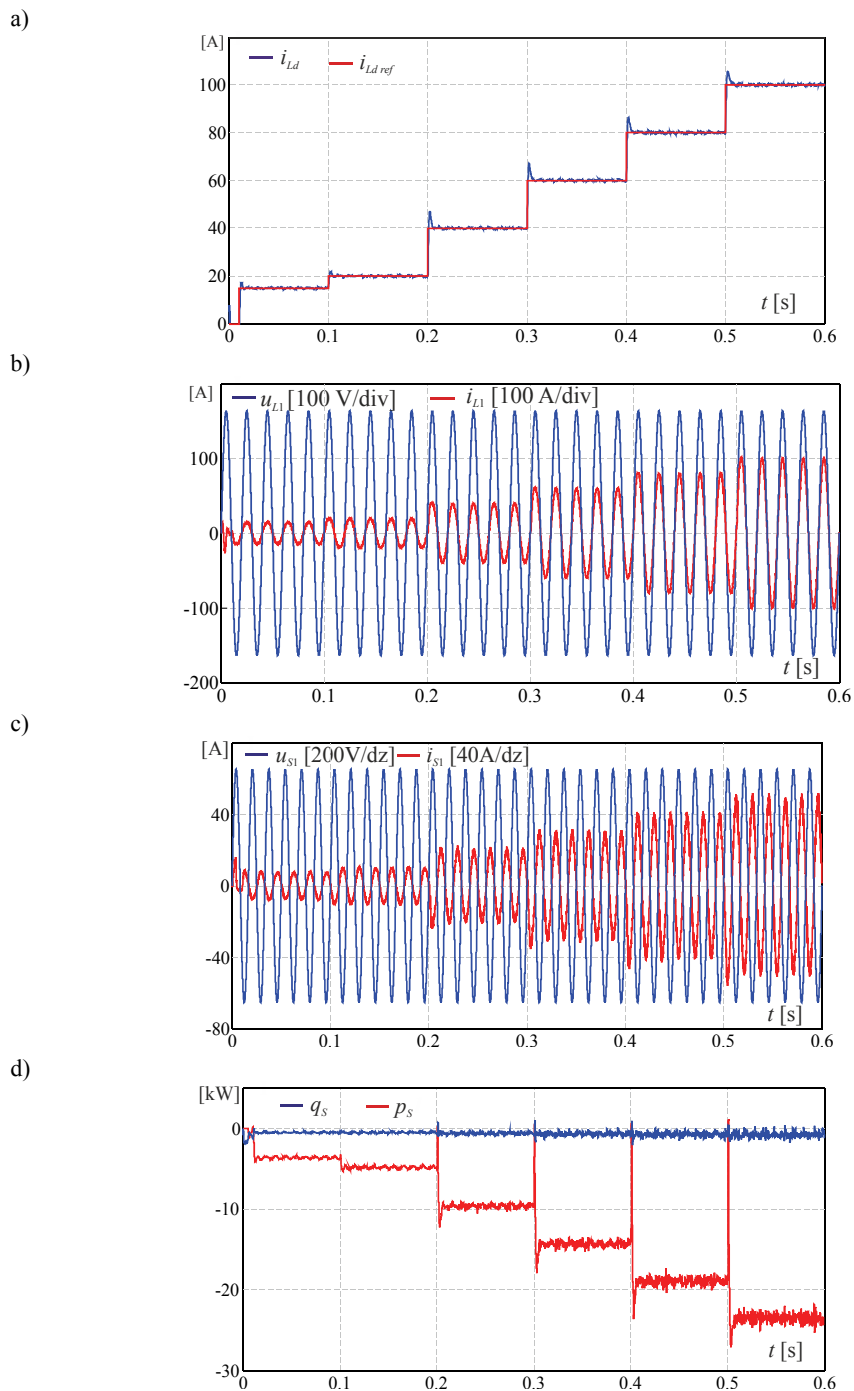
a)

b)

c)

d)

Fig. 8. Energy transfer from network side to source side: a) reference and measurement network side current in direct axis; b) time waveforms of network side current i_{L1} and voltage u_{L1}; c) time waveforms of source current i_{S1} and voltage u_{S1}; d) instantaneous value of input active and reactive power
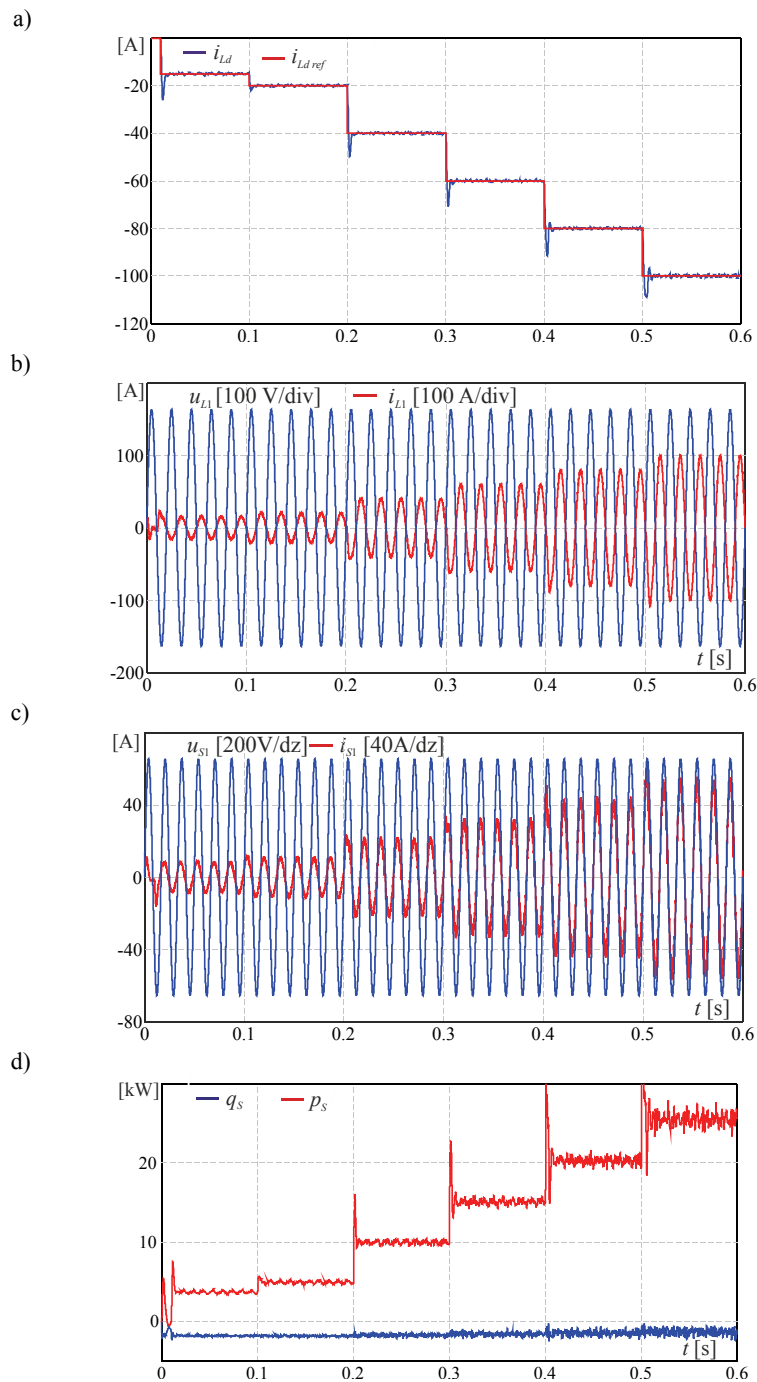
a)

b)

c)

d)

Fig. 9. Energy transfer from source side to network side: a) reference and measurement network side current in direct axis; b) time waveforms of network current i_{L1} and voltage u_{L1}; c) time waveforms of source current i_{S1} and voltage u_{S1}; d) instantaneous value of input active and reactive power

Figure 9 presents energy transfer in the opposite direction with similar waveforms as the latter case. This case is typical for motor mode. The active power has positive polarity, which means that the energy is transferred from the source to network side. The phase shift between network side current and voltage equals 180°. The dynamics of the system also produce very good performance.

The zoomed part of time waveforms of selected source and load current are presented in Figure 10. The MC is able to control simultaneously the source current and output voltages. By controlling the output voltage on load inductance i_{L1}, i_{L2}, i_{L3}, the system has the possibility of load current control. The obtained source and load currents have a good quality. The frequency spectrum of such currents are also presented in Figure 10. The total harmonic distortion factors (THD) for such currents are: THDi_{S1} = 4.3%, THDi_{L1} = 1.1%.
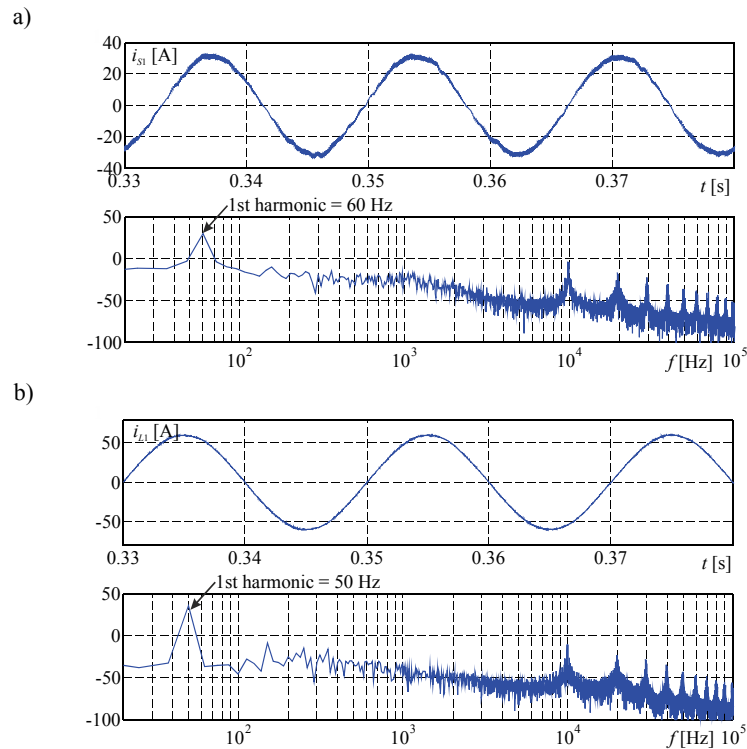

Fig. 10. Zoomed part of time waveforms of source and load current and its spectrum;
a) source current (THD = 4.3%), b) load current (THD = 1.1%)

5. Advantages of MC

The classical AC/DC/AC converter (Fig. 1b) is limited with respect to a minimum DC-link voltage [19]. For proper operation of the rectifier, a minimum DC-link voltage is needed to

obtain undistorted current waveforms and operate with a unity power factor (in both directions of energy flow). Theoretically for a diode rectifier, the maximum DC output voltage is the peak value of line-to-line RMS voltage (Fig. 11) [19]:

$$U_{DC\min} = \sqrt{2}\sqrt{3}U_S = \sqrt{2}U_{S1-l}. \tag{9}$$

This limitation is introduced by freewheeling diodes in a voltage source rectifier (VSR) which operates as a diode rectifier. In practice the DC-link voltage is about 15-20% more than $U_{DC\min}$ [19]. For low levels of the generated voltages (from distributed sources) there is a need to increase the DC-link voltage.
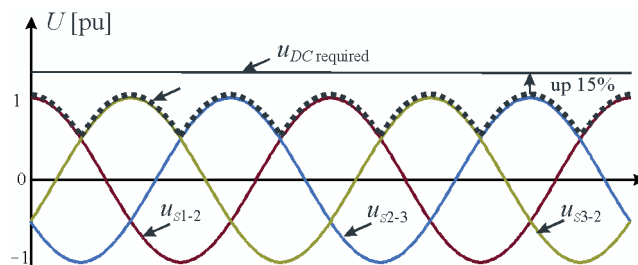

Fig. 11. DC-link voltage condition in AC/DC/AC converter

In the solution with a MC there is no need to increase the generated voltage, because the MC does not have a DC-link and freewheeling diodes in VSR. The energy with a unity power factor fed back to the grid, in the system as shown in Figure 2, is possible even at low levels of the generated voltages [6, 17]. Theoretically the generated voltage should be higher than the voltage drop in the power electronic components (transistors and diodes) and passive elements. This is the main advantage of a power electronic interface solution with matrix converter compared to a two stage AC/DC/AC converter.

6. Conclusions

Power electronic converters are an integral part of the energy power network in such applications as power interfaces of distributed sources, network couplers, devices for improving energy quality, compensation of non-active power and control power flow in the power system. In the majority of cases of power converters implemented in AC power systems, power electronic converters with a DC energy storage element is used. This element is often the least reliable part in the whole power converter. DC circuits cannot be eliminated from power systems, but in some applications the commonly used converters can be replaced by converters without a DC energy storage element. The AC-AC converter offers many potential benefits to power converter applications. This converter will not be the best solution for all applications, but it offers significant advantages for some.

The working principle of the MC used to interface with two AC system controls has been presented. The system has been tested with the step change in reference to a direct-axis network side current $i_{Ld\,ref}$. The dynamics of the system have produced very good performance, but a detailed analysis of PI regulator parameters and system parameters is required. In the power electronic interface solution with MC, the energy fed back to the grid with a unity power factor is possible even at low levels of generated voltages.

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