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Control Methods for PWM ac-to-dc Converters Applied in Active line-conditioning

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Abstract

The paper investigates the performances of a PWM AC - to - DC converter operating with the help of new control strategies, implemented so that the conditioning of the utilities may become possible. It is discussed the idea to use the PWM DC converters as power conditioner equipments too. Appropriate control strategies are introduced with the purpose to apply the active line conditioning. Corresponding MATLAB/SIMULINK structures are developed. The results of the simulations, depicted in the paper proves the line-conditioning capabilities of the studied converter.

Keywords: *PWM AC - to - DC converter, active line-conditioning, power conditioner.*

Introduction

The continuous development of industrial and private, electric and electronic equipments creates some problems to be solved in the near future. These equipments are usually based on nonlinear power electronic devices. Therefore they produce, due to their operating principle, disturbances in the AC mains. In order to preserve the quality of the power delivered by the AC mains and also to ensure its stability and sustainable development, the producers, the operators of the network and the high majority of the users must respect a lot of rules, recommendations and standards. As a consequence a new class of power converters provided with power factor control, PFC, was developed. These power electronic equipments operate line-friendly from the point of view of the mains but are not able to reduce the negative effect of other consumers that disturb the public power distribution network. In addition, it is important to observe that even the PWM AC – to – DC converters are able to act as power conditioning equipments, POCON [1].

The latest researches in the field of new power relations, their definition and application, [2], [3], offers the possibility to determine the actual state of the mains at a point of common coupling, PCC. As a result we anticipate that in the following ten-year periods, the operators of the public utilities will inject in the network a special signal to inform the users about the necessity to run in capacitive or inductive operation mode. With the help of this signal, more advanced control strategies in order to control the power factor could be implemented.

This paper investigates how a PWM AC - to - DC converter, can be provided with active line-conditioning control strategy with the purpose to act as a series-connected power conditioning converter too.

Line-conditioning with the help of the DC converters

Taking into account the possibilities of the PWM AC – to – DC converters associated with the knowledge of the actual state of the mains, there are possible to identify more situations when this power electronic converters could overtake line-conditioning tasks. Beside the main electronic function of the converter, that consists in the DC energy generation, now appears the line-conditioning as a secondary, new electronic function, [4], [5].

With the purpose to introduce the conditioning principles of the public network, we assume a point of common coupling, PCC, where only two consumers are connected: an AC - to - DC converter which supplies a DC load and a conventional inductive load. From now on we consider a sinusoidal waveform of the line voltage.

If we take into account the situation when the AC – to – DC converter is operating as a “unity power factor rectifier”, we can represent the following phasor diagram:

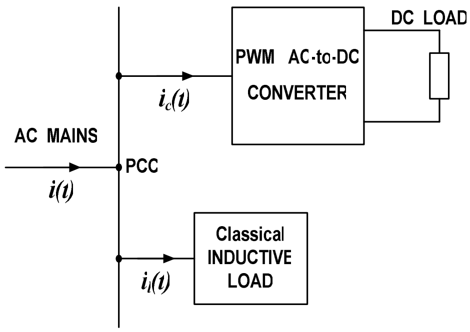

Fig.1. Simplified AC mains model.

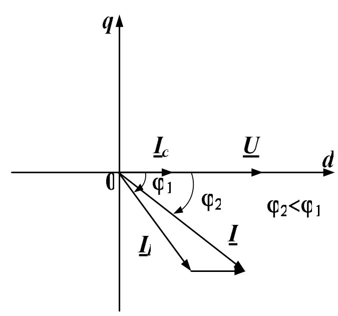

Fig.2. Phasor diagram for simple-line conditioning of AC Line

Due to the operating principle of the PWM AC – to – DC converter, it’s current phasor, $\underline{I}_c$, and the line-voltage phasor have the same direction. The conventional inductive load has a current phasor of magnitude I_l , and phase shift φ_1 in respect to the voltage phasor.

Therefore, at the PCC, the phasor of the input current will have the magnitude I, and the phase shift φ_2 ($\varphi_{2<}$ φ_1) in respect to the same voltage phasor.

In consequence this PWM AC – to – DC converter improves the general situation, but it can’t assure a unity power factor at the PCC of the AC Line.

This operating mode of the converter was called **simple line-conditioning** of the AC mains, [6]**.**

In order to further support the AC network, we provided the AC – to – DC converter with a special control strategy for line conditioning, that gives the advantage that the input current phasor can be positioned as required, in respect with the line voltage phasor.

Supposing that the delivered DC power is less then its rated value, the PWM AC – to – DC converter will be controlled at his rated apparent power. As a result the input current will take its rated value and simultaneously will be shifted in respect to the line-voltage. A non-active component of the input current phasor will appear.

The situation is presented in Figure 3 for capacitive operation mode of the converter.

In the above mentioned figure, due to this special operation mode of the converter, the current phasor, $\underline{I}_c$, has a magnitude $I_c = I_N$ and is shifted with an angle φ in respect to the voltage phasor. The active component of this current, oriented along the “d” axis, is the same as in Figure 2. The conventional inductive load is also assumed the same. It is important to observe that the input current phasor at the PCC will have a changed position so that its phase difference φ_3 in respect to the voltage phasor becomes less as in the previous situation, $\varphi_{3<}$ φ_2. The advantage of this procedure is that using an appropriate number of loads, and an adequate control strategy it can be achieved even unity power factor at PCC.

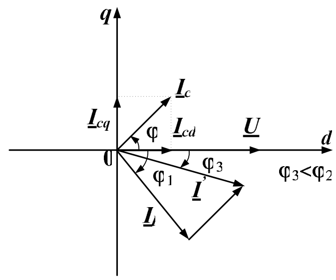

Fig.3. Phasor diagram for active-line conditioning of AC Line

This operating mode of the converter was called **active line-conditioning** of AC mains**.**

New control strategies of the converter must be developed with the purpose to implement the active line-conditioning. This paper offers two possible solutions.

In the case of distorted line-voltages the conditioning of the mains implies other control principles, defined as **complex line-conditioning**, [4], [6]. This situation is not taken into account in this paper.

The investigated converter

The paper will analyze the problems in the case of a single-phase PWM AC - to - DC converter. The converter, provided with simple line conditioning was in detail investigated in previous published papers, [7], [8].

Figure 4 presents the block-diagram of the investigated converter, associated with the control circuitry adequate for active-line conditioning.

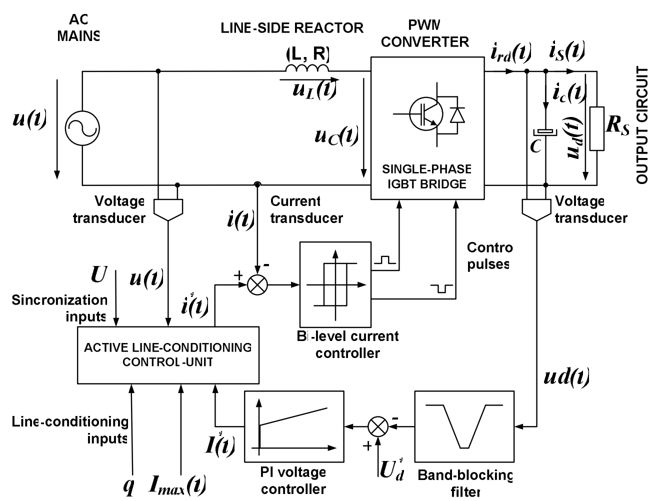

Fig.4. The investigated PWM AC-to-DC converter

The power electronics is based on a current-controlled voltage inverter in rectifier operation mode. A PI controller controls the output DC voltage level and the input, line-current shaping is performed with the help of the bi-level current controller. The active line-conditioning is achieved in the specific unit. The modeling of the converter is based on the following equations system, written in a fixed system of coordinates, [8], [9]:

$$u(t) = \hat{U} \cdot \sin(\omega \cdot t) \tag{1}$$

$$L \cdot \frac{di(t)}{dt} = u(t) - u_c(t) - R \cdot i(t) \tag{2}$$

$$i_{rd}(t) = \frac{u_c(t)}{u_d(t)} \cdot i(t) \tag{3}$$

$$i_c(t) = C \cdot \frac{du_d(t)}{dt} = i_{rd}(t) - i_s(t) \tag{4}$$

$$u_c(t) = \begin{cases} +u_d(t), \Delta i(t) \geq +\dfrac{\Delta h}{2} \\ -u_d(t), \Delta i(t) \leq -\dfrac{\Delta h}{2} \end{cases} \tag{5}$$

A simulation model, in detail described in [8], [9], was created in MATLAB /SIMULINK and a converter with the following parameters: U_N = 48V, P_N = 250W, $\cos\varphi_N$ = 1, f = 50Hz, U_{dN} = 100V, I_N = 5.2083A, L = 1.76mH, R_B = 0.3318Ω, C = 1650μF was carefully investigated in steady-state and dynamic behaviour.

Appropiate control strategies for active line conditioning

With the purpose to investigate the performances of the converter in active line-conditioning operation mode, two control strategies were developed.

Active line-conditioning based on predictive control of the line current phasor

The control strategy for active line-conditioning was developed supposing that in the AC network is injected a so called *“ line-conditioning signal”*, *q*. Based on the block diagram from Figure 4 and on the presented mathematical model, on the AC-side of the converter is valid the phasor diagram from Figure 5.

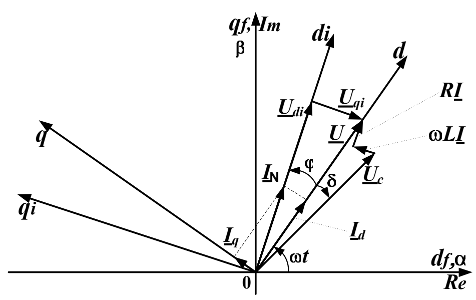

Fig.5. Phasor diagram for the capacitive operation mode of the converter with active line conditioning

According to the “active line-conditioning” principle, if the AC mains needs inductive or capacitive consumers, the “active line-conditioning signal”, q =-1 or +1 will appear. As a result, the line-current phasor, I, will be shifted with a phase difference φ with respect to the line-voltage phasor, U. This phase difference depends on the line conditioning capabilities of the electronic consumer, the installed apparent power of the consumer and the DC power delivered at the output. In Figure 5 is depicted this situation, taking into account capacitive operation mode, corresponding to q = +1. It is necessary to determine the phase difference φ, so that the amplitude of the line-current phasor becomes $I = I_N$, according to the operation with rated apparent power. The line-current phasor is no more oriented across the line-voltage phasor. In d-q, line-voltage oriented system of coordinates, the active current Id will have the same value and orientation as in the case of the simple line-conditioning, and also nonactive-current, Iq, will appear. Now the components of the converter-voltage phasor are:

$$U_{Cd} = U - RI_N \cos\varphi + \omega LI_N \sin\varphi \quad (6)$$

and:

$$U_{Cq} = \omega LI_N \cos\varphi + RI_N \sin\varphi \quad (7)$$

Computing of the phase angle φ, based on Equations (6) and (7) is not very easy. As a result, the analyse in line-current oriented $d_i - q_i$ system of coordinates is indicated. Now the components of the converter-voltage phasor are:

$$U_{Cdi} = U_{di} - RI_N \quad (8)$$

and:

$$U_{Cqi} = U_{qi} + \omega LI_N \quad (9)$$

Supposing an ideal converter, without losses, results the following equation that gives the phase angle φ:

$$\cos\varphi = \frac{P_d + RI_N^2}{U I_N} \quad (10)$$

where, P_d, is the actual value of the DC power delivered at the output.

With the purpose to analyze the performances of the PWM AC - to - DC converter provided with predictive active line-conditioning an adequate control unit was developed, Figure 6.

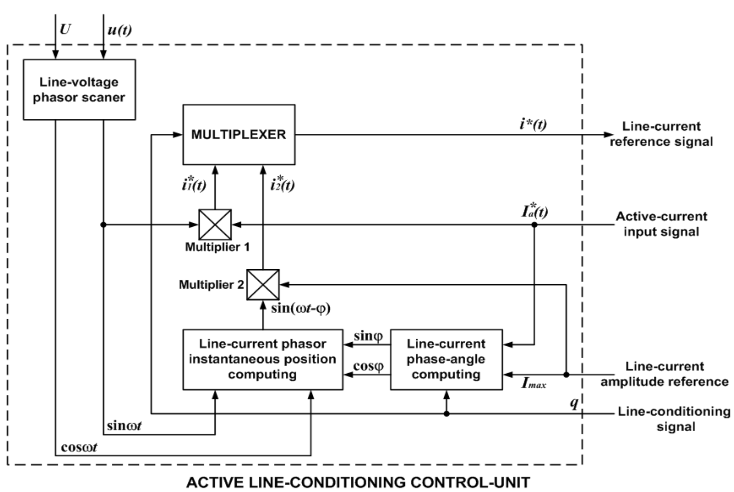

Fig.6. Block-diagram of the active line-conditioning control-unit.

The most important element of the control structure is the three-way multiplexer, which selects, according to the value of the signal *q*, between the intermediate current references, $i_1^*(t)$ and $i_2^*(t)$, and generates at his output the final line-current reference signal, $i^*(t)$, corresponding to the active line conditioning mode required by the mains.

With the purpose to study the new active line-conditioning concept, the program developed in fixed system of coordinates, [9], was completed, with an appropriate control-unit. This control-unit operates according to the strategy depicted in Figure 6. The final model of the PWM AC – to – DC converter associated with active line-conditioning strategy is indicated in Figure 7.

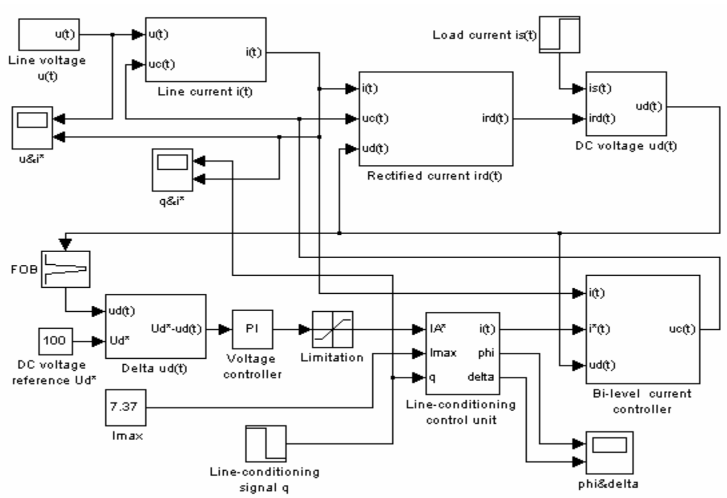

Fig.7. The model of the PWM AC-to-DC converter associated with active line-conditioning strategy.

Active line conditioning based on the control of the R.M.S. value of the line current

The proposed approach is based on a new strategy for active line conditioning. In order to operate at rated apparent power, it will be used the control the R.M.S. value of the input line current to its rated value, I_N. Then the phase difference of the line-current phasor in respect to the line voltage phasor is generated similar to the first presented method.

The figure depicted below presents the basic structure for the active line conditioning based on this control principle:

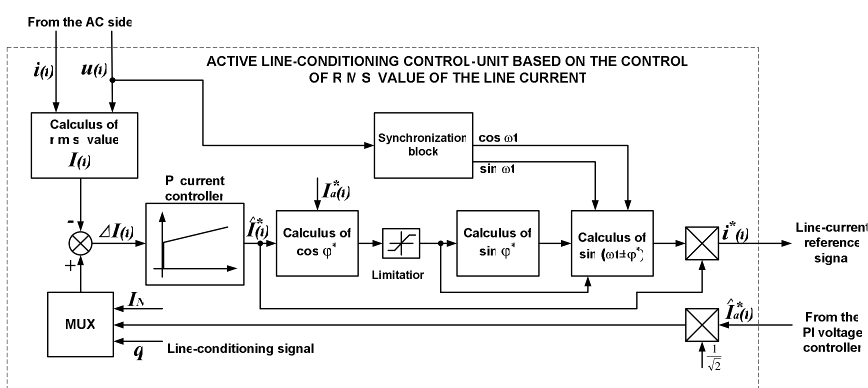

Fig.8. Block-diagram for the active line-conditioning unit based on the control of R.M.S. value of the line current.

Similar to the classical solutions, the manipulated variable for the active current magnitude is computed by a PI voltage controller:

The reference for the current magnitude on the ac – side of the converter is determined also by a

$$I_a^*(t) = K_P \cdot \Delta u_d(t) + K_I \cdot \int \Delta u_d(t) \cdot dt \tag{11}$$

PI current controller:
The input of this controller is selected according to the conditioning signal q:

$$I^*(t) = K_{Pi} \cdot \Delta I(t) + K_{Ii} \cdot \int \Delta I(t) \cdot dt \tag{12}$$

$$\Delta I(t) = I_N - I(t) \text{ for active line conditioning, q = ± 1} \tag{13}$$

$$\Delta I(t) = \frac{I_a^*(t)}{\sqrt{2}} - I(t) \text{ for simple line conditioning, q =0.} \tag{14}$$

The phase angle of the line-current results based on the active-current input signal, $I_a^*(t)$, and the line-current amplitude reference, $I^*(t)$:

$$\cos\varphi^* = \frac{I_a^*(t)}{I^*(t)} \tag{15}$$

$$\sin\varphi^* = \sqrt{1-\cos\varphi^*} \tag{16}$$

The synchronization of the converter takes place based on the relations:

where U and u(t) are, respectively, the amplitude of the line-voltage and its instantaneous value.

$$\sin\omega t = \frac{u(t)}{U} \tag{17}$$

$$\cos\omega t = \sqrt{1 - \sin^2 \omega t} \tag{18}$$

As a result, the following equation gives us the line-current reference:

$$i^*(t) = I^*(t) \cdot \sin(\omega \cdot t \pm \varphi^*) \tag{19}$$

This current-reference must be taken into account when the AC-line support becomes necessary.

With the purpose to study the new active line-conditioning concept, was developed the program depicted in Figure 9. The novelty of this program is represented by the new configuration of the active line conditioning unit. Simulated results concerning the proposed control methods

The introduced control strategies for the active line-conditioning of the mains with the help of a PWM AC – to – DC converter are satisfactorily in steady-state operation mode for all the range of the DC load connected at the output.

Based on the developed models for the converter a careful analysis of the dynamical behaviour becomes necessary. In the case of the line-current prediction, Figure 10 presents the general performances of the converter.

At the beginning of the simulations from Figure 10, the freewheeling of the PWM AC – to – DC converter, with simple line conditioning is taken into account. The line current is practically equal to zero and the power factor takes his maximal value of 1. An output current step of 1.2 A is applied at the moment of 0.12 s. As a result, the line current rises, without changements in the power factor range. At t = 0.20 s, when the active line-conditioning becomes necessary, the signal q becomes q = -1, the line-current rises again to his rated value and the power factor decreases to 0.7.

Similar to the previous simulation, Figure 11 presents the dynamic behaviour of the converter provided with active line-conditioning based on the control of R.M.S. value of the line current.

Due the delay in R.M.S. computation some little changements in the perturbation moments were necessary.

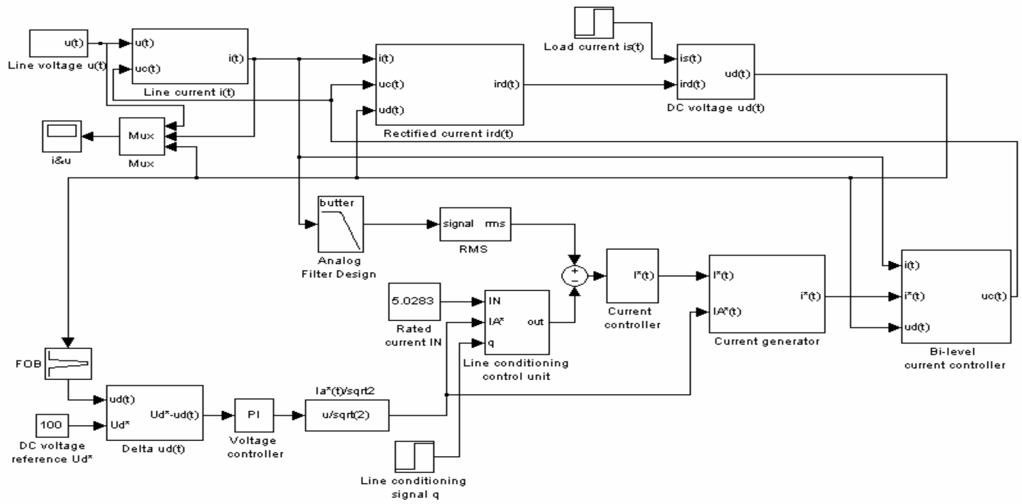

Fig.9. The model of the PWM AC-to-DC converter associated with active line-conditioning strategy based on the control of R.M.S. value of the line current .

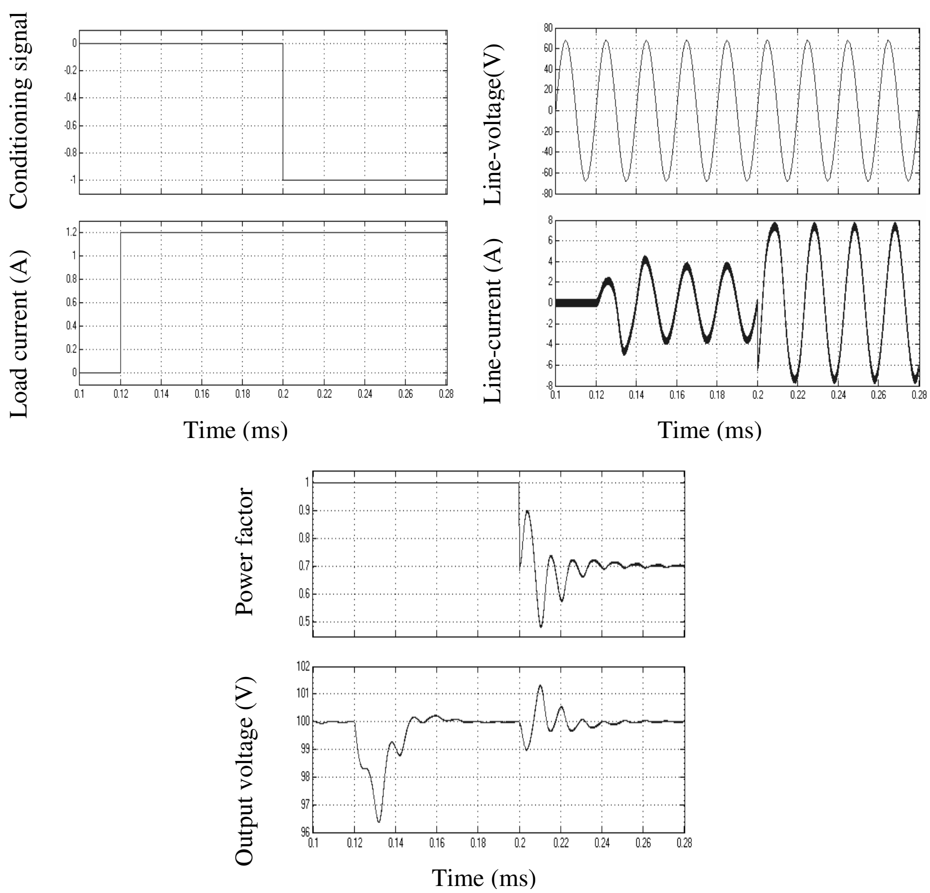

Fig.10. Simulated results corresponding to the operation-mode of the converter with the active line-conditioning strategy based on predictive control of the line current phasor.

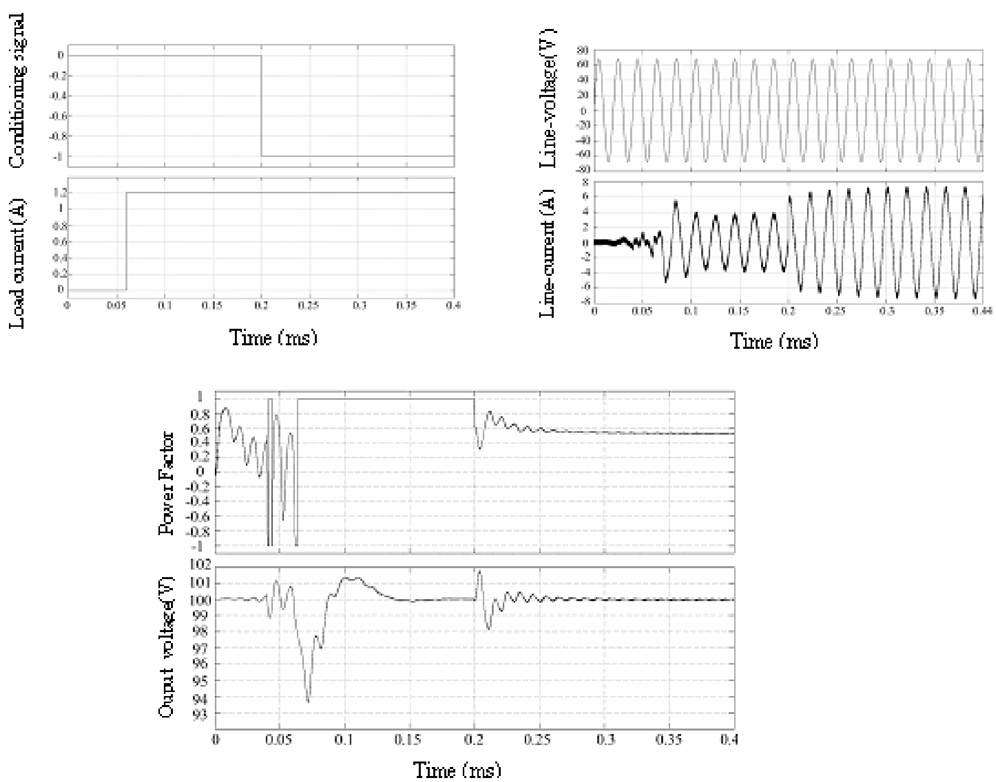

Fig.11. Simulated results corresponding to the operation-mode of the converter with active line-conditioning strategy based on the control of R.M.S. value of the line current .

At the beginning of the simulations from Figure 11 the PWM AC – to – DC converter, is acting as a simple-line conditioning equipment, the signal q being equal to zero. The line current is practically equal to zero. Due the filtering of the DC voltage and to the principle of the current control, in the first moments the power factor doesn't take his maximal value of 1. Fortunately this transient process is not a disadvantage due to the little value of the line – current. An output current step of 1.2 A is applied at the moment of 0.06 s. As a result, the line current rises exactly to half of its rated value, and the power factor riches the value of 1. At t = 0.20 s, when the active line-conditioning becomes necessary, the signal q becomes q = -1, the line-current rises again to its rated value and the power factor decreases to 0.7. Obviously, the operation conditions at the output remain unchanged.

All the other virtual experiments carried-out for other combinations between the DC-load steps and the line-conditioning demands confirm the same performances.

Conclusions

The analyze proves that both control methods are satisfactorily in steady-state operating mode and presents good dynamic behaviour. Therefore this control strategies are recommended for line-conditioning with PWM AC – to – DC converters.

The careful comparison between the two proposed methods shows that the predictive control of the line current phasor has some advantages, reported to the operation of the converter provided with active line-conditioning based on the control of the R.M.S. value of the line current. The main drawback of the second control principle consists in the one period delay in the RMS value computation. As a result a very accurate tuning of the PI current controller becomes necessary in new investigations.

The above presented results justify the necessity of detailed experimental researches, including the corresponding line-conditioning signal generation at PCC and its accurate transmission to the PWM DC-converters.

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Metode de control ale convertoarelor de c.a./c.c. cu comandă PWM aplicate în condiționarea activă a rețelei de curent alternativ

Rezumat

Această lucrare investighează performanţele unui convertor de c.a./c.c cu comandă PWM. care operează cu ajutorul unor noi strategii de control, implementate pentru ca condiţionarea reţelelor de curent alternativ să devină posibilă.. Este propusă de asemenea ideea de a utiliza convertoarele de curent continuu cu comandă PWM ca echipamente de condiţionare. Sunt introduse, cu scopul de a aplica principiul de condiţionare activă, strategii de control corespunzătoare. Sunt dezvoltate structuri MATLAB/SIMULINK. Rezultatele simulărilor, prezentate în lucrare dovedesc că convertorul studiat presupune capacităţi în condiţionarea reţelei.