NEURAL CONTROL OF BOOST CONVERTERS' INPUT CURRENT

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Abstract. An application of neural networks in the cascade control structure of a boost converter is investigated. Inverse model of process realized using two-layered MLP neural network is used as the input current controller. A Levenberg–Marquardt learning algorithm is employed for off-line adjustment of the network weights and biases. This control structure ensures good performance in all operating regions and compensation of ripples in converter's input current caused by variations of the input voltage. Advantages of the proposed control structure are demonstrated through experimental comparison to the PI controller (with and without manually adjusted feed forward compensator).

Keywords: Power converters, Current control, Harmonics, Neural networks, Boost converters, Inverse control

1. INTRODUCTION

Converters used for supplying consumers with changeable voltage and frequency represent a load for the supply network (ac or dc) with current harmonics, which produce undesired electromagnetic disturbances and additional parasitic effects. Electromagnetic disturbances are particularly undesired in a supply network that is in conductive connection or near devices sensible to disturbances, such as telecommunication and/or signaling safety devices. The typical supply network with high demands on the permitted level of generated disturbances is the railway electric supply network. This is the reason why the International Railways Union regulations (UIC) require that high level requirements should be imposed on converters by means of which the allowed disturbance levels in this supply network are determined [1]. The European railway supply network is specific due to two types (ac and dc) and four levels of supply voltage and has specific additional requirements on converters. One of the important requirements when converter operates on a dc network (1500 V dc or 3000 V dc) is that the input impedance has to be higher than the impedance permitted by UIC regulations in the frequency range from 50 Hz to 100 kHz. The other requirement relating to the case when the converter operates on an ac network (25 kV ac or 50 Hz; 15 kV ac, 16 2/3 Hz) is the power factor greater than 0.95 in the input voltage range between 80 % and 120 % of the rated value.

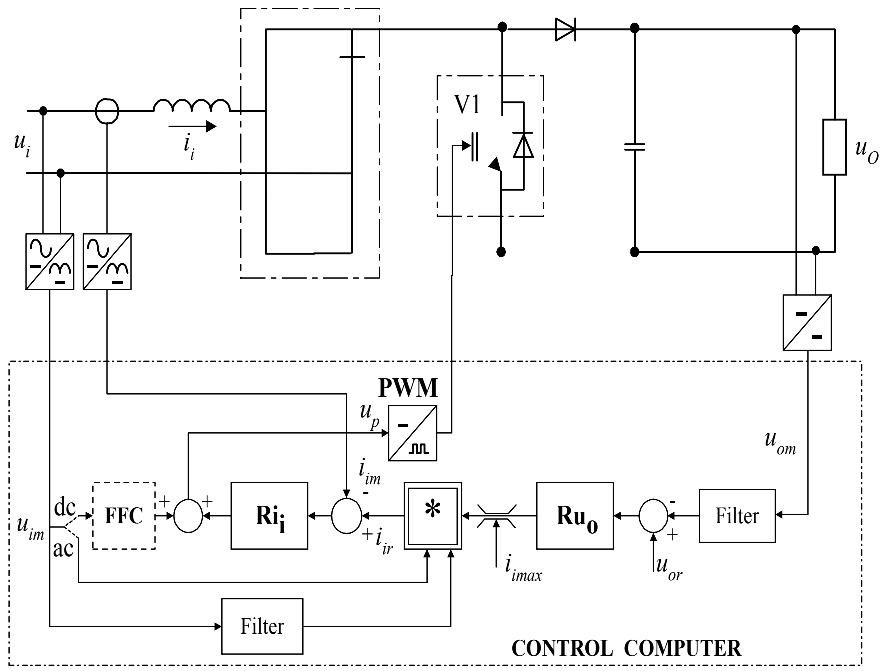
Boost converter is commonly used converter structure in these applications. It serves as an active filter at the input of the four-system converter [2, 3]. To meet above stated high-demanding requirements special attention should be paid to the converter control system.

2. CONTROL SYSTEM STRUCTURE

Generally accepted structure of the control system is one of the cascade type, with converter input current control loop as the inner loop and converter output voltage loop as the outer, superimposed control loop (Fig. 1) [4]. The control of input current is realized by means of an input current controller $\mathbf{Ri_i}$, which provides input voltage to the pulse width modulator that control the states of the power electronic switch V1 (Isolated Gate Bipolar Transistor, IGBT). Since it is necessary to stabilize the output voltage of the boost converter at a constant value, while changing load or input voltage, the output voltage controller $\mathbf{Ru_o}$ is superimposed to the input current controller $\mathbf{Ri_i}$, providing the reference value for the input current controller.

In the functional block diagram of boost converter control (Fig. 1.) the dc-ac switch marks the control structure change when the converter works on a dc network or an ac network. The measured instantaneous value of the input voltage u_{im} serves for the compensation of input voltage ripple influence on input current (switch on dc) when boost converter operates on a dc network. Moreover, it serves for generating the input current reference value (switch on ac) when boost converter operates on an ac network. In the presented control structure the measured filtered input voltage perform functions of input current feed-forward control when the converter operated on both a dc and an ac supply network. More detailed description is given in [5].

In order to control the converter-input impedance, when the converter operates on a dc supply network or the input power factor when converter operates on an ac supply network, it is necessary to realize a fast input current control loop. In research of boost converter input current control



Legend:

Ru_o - output voltage controller;
Ri_i - input current controller;
FFC- feedforward compensator;
u_{or} - output voltage reference value;
u_{om} - output voltage measured value;
i_{ir} - input current reference value;
i_{im} - input current measured value;
i_{imax} - input current maximum value;
u_{im} - input voltage measured value;
u_p - input voltage to the PWM block (control signal).

Fig 1. Functional block diagram of boost converter control

algorithms conventional and modern algorithms have been analyzed [4]. The conventional solution is to use a PI controller. Nevertheless, the performance of the input current control loop is not satisfactory in all operating regimes. This is due to nonlinear characteristics of the boost converter. Better results have been obtained using the Generalized Predictive Controller (GPC), because of its robustness to process parameter change [5].

When the converter operates on a dc network the boost converter input voltage contains a high alternating component. The frequency of this alternating component is proportional to the frequency of an ac voltage from that is dc voltage obtained using a power electronic rectifier. Variations of the input voltage cause the high ripples in input current that should be eliminated or reduced as much as possible. Neither PI nor GPC can provide satisfactory reduction of the ripples in the converter-input current, unless an additional feedforward compensator (**FFC**) is applied to the input current control loop [5]. The design of this compensator is not an easy task and should be done carefully. It requires quite considerable manual adjustments, because any amplitude and/or phase shift between the compensation signal and the actual current ripples cause additional ripples.

In order to increase the performances of the input current control loop and to avoid the difficulties of compensator adjustments, we have been investigated the usage of the neural networks in design of the input current controller and of the feedforward compensator. Both, the measured values of the input current and of the input voltage have been introduced into the same neural network so that the current controller and the compensator are incorporated in a single structure.

3. DESIGN OF INPUT CURRENT NEURAL CONTROLLER

The neural controller of converter input current is designed on the basis of input-output data gathered during an identification experiment. Input signals to the process are input voltage to the PWM block u_p (control signal) and measured value of the input voltage u_{im}, while the output signal is measured value of the input current i_{im} (Fig. 1). The process can be modeled by the following nonlinear discrete-time difference equation:

$$i_{im}(k+1) = f[i_{im}(k),\cdots,i_{im}(k-\mathrm{n}1+1); u_p(k),\cdots,u_p(k-\mathrm{n}2+1); u_{im}(k),\cdots,u_{im}(k-\mathrm{n}3+1)], \qquad (1)$$

where is: k - is discrete time step; f - nonlinear map; n1, n2, n3 – number of past values of the corresponding variables.

From equation (1) the inverse function f^{-1} leading to the derivation of the control signal $u_p(k)$ would require knowledge of the future value of the input current $i_{im}(k+1)$. To overcome this problem the future value of input current $i_{im}(k+1)$ is replaced with its reference value $i_{ir}(k+1)$, which is normally known one step ahead. Thus, the nonlinear input-output relation of the plant inverse is:

$$u_p(k) = f^{-1}[i_{im}(k),\cdots,i_{im}(k-\mathrm{n}1+1), i_{ir}(k+1); u_p(k-1),\cdots,u_p(k-\mathrm{n}2+1); u_{im}(k),\cdots,u_{im}(k-\mathrm{n}3+1)]. \qquad (2)$$

The nonlinear mapping f^{-1} can be approximated by a neural network f_N^{-1}:

$$\hat{u}_p(k) = f_N^{-1}[i_{im}(k),\cdots,i_{im}(k-\mathrm{n}1+1), i_{ir}(k+1); \\ u_p(k-1),\cdots,u_p(k-\mathrm{n}2+1); u_{im}(k),\cdots,u_{im}(k-\mathrm{n}3+1); \boldsymbol{\Theta}], \quad (3)$$

where $\boldsymbol{\Theta}$ is the vector of network parameters. As a measure of the approximation quality following performance index was used:

$$\Im(\Theta) = \sum_{i=1}^{N} (u_p(i) - \hat{u}_p(i), \Theta)^2 \;, \quad (4)$$

where N is the length of input-output data set used for network training. We have used multiplayer perceptrons (MLP) network [6] to build inverse controller of input current. The parameters of the neural network controller (3) are adjusted off-line using an efficient Newton-type training algorithm [7], which minimizes the performance index (4).

4. EXPERIMENTAL RESULTS

Experimental investigations of the performances of the neural controller were done on a laboratory model of boost converter (power 2.5 kW) with IGBT switch. The control system has been implemented using MATLAB/SIMULINK® program package and its Real-Time Workshop. The experiments were conducted separately for dc and for ac supply networks.

Boost converter supplied from the dc network

The analysis of input current control loop, when the converter operates on a dc network has been carried out on a boost converter physical model with input inductance of 84 mH and with output capacitance of 3.75 mF. The boost converter is supplied by variable voltage obtained from autotransformer connected to the single-phase network of 220 V, 50 Hz. With regard to full-wave rectified network voltage, the boost converter input voltage contains a high alternating component with a frequency of 100 Hz.

The first experiment was conducted without any controller and responses of the boost converter input current i_{im} to the step changes of control signal u_p are shown in Fig 2. High overshoots (about 100%) and high ripples (amplitude about 1.8 A peak to peak) appear in the input current responses.

Next step was conducting the identification experiment. Process had been excited with the Band Limited White Noise (BLWN) signal u_p and $2N$ values of u_p and i_{im} had been collected during the experiment and these signals are shown in Fig. 3.

Then the neural controller (3) was trained on the first half of data, while the second half of data were used for the regularization and validation purposes [8]. The MLP network with one hidden layer with 8 neurons (tansig activation functions) was used. Input vector to the neural controller was $[i_{im}(k), i_{im}(k\text{-}1), i_{ir}(k\text{+}1), u_p(k), u_p(k\text{-}1)]$. This controller will be called NC1 controller. Responses of the boost converter input current i_{im} to step changes of its reference value i_{ir} obtained with NC1 controller are shown in Fig. 4. A more detailed view of a step response from Fig. 4 is given in Fig. 5.

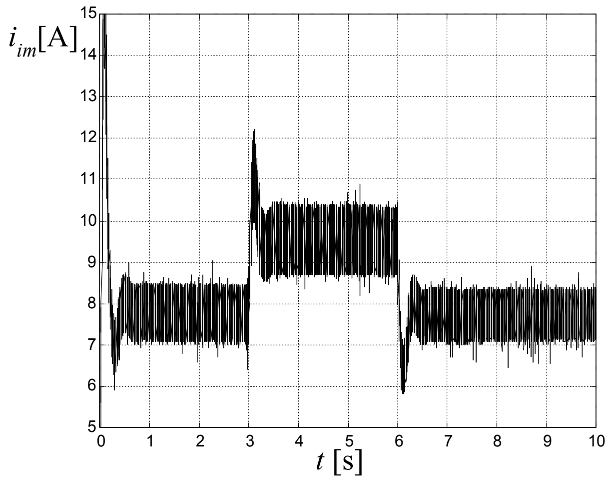


Fig. 2. Responses of the boost converter input current i_{im} to step changes of the control signal u_p

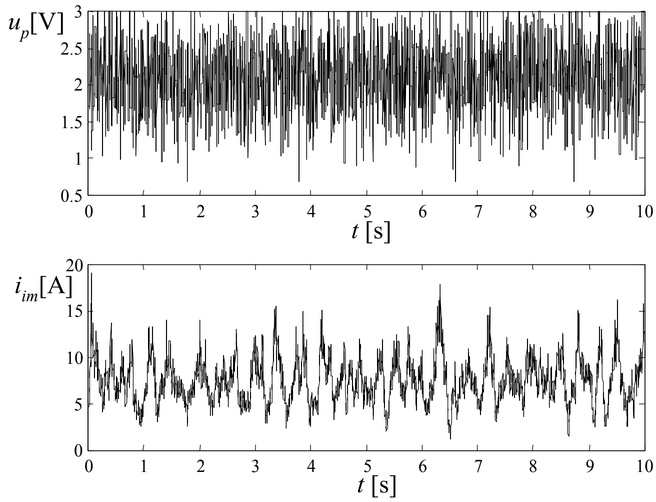


Fig. 3. Control signal u_p and input current i_{im} collected during an identification experiment

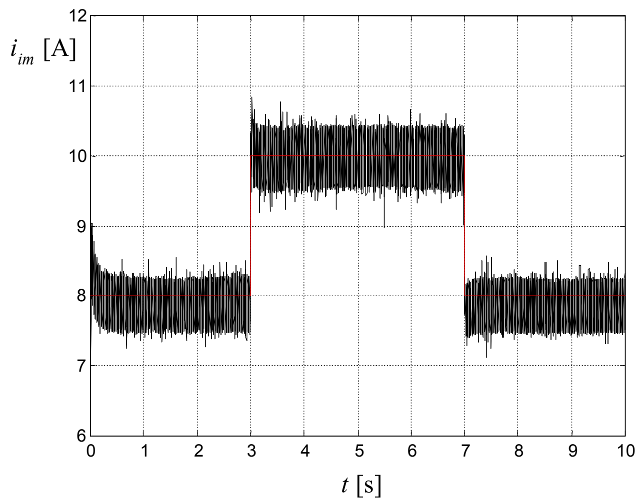


Fig. 4. Responses of the boost converter input current i_{im} to step changes of its reference value i_{ir} obtained with NC1 controller

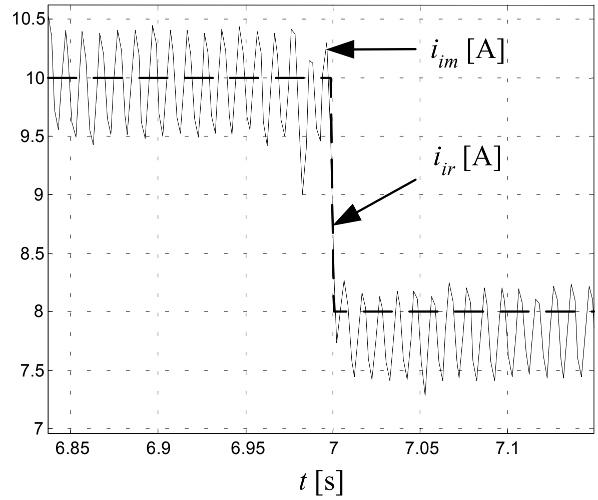


Fig. 5. A more detailed view of a step response from Fig. 4.

From Figs. 4 and 5 it can be seen that the overshoots of the input current responses to the step changes of its reference value are completely eliminated and that the settling time is shorter than 10 ms. However, the satisfactory attenuation of the ripples in input current response is not ensured using this control structure. The amplitude of these ripples is about 0.9 A peak to peak. The ripples appear because the control signal u_p is not in counter-phase with the full wave rectified input voltage u_{im} (Fig. 6).

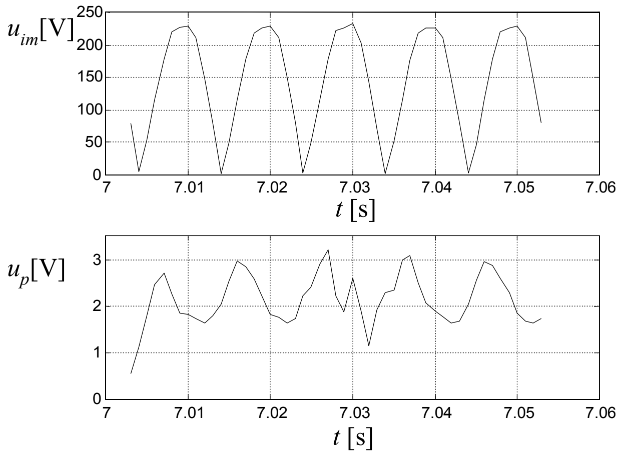


Fig. 6. Full wave rectified input voltage u_{im} and output signal from the NC1 controller u_p

The ripples in the input current can be reduced if the past values of the input voltage u_{im} are introduced as an additional input vector to the neural network used in the previous experiment. The input vector to the neural controller was therefore [$i_{im}(k)$, $i_{im}(k\text{-}1)$, $i_{ir}(k+1)$, $u_p(k)$, $u_p(k\text{-}1)$, $u_{im}(k)$, $u_{im}(k\text{-}1)$]. This controller will be called NC2 controller. Again, neural network parameters have been adjusted off-line, using Levenberg-Marquardt algorithm. Responses of the boost converter input current i_{im} to step changes of its reference value i_{ir} obtained with NC2 controller are shown in Fig. 7. A more detailed view of a step response from Fig. 7 is given in Fig. 8. It can be seen that the overshoots of the input current response to the step changes of its reference value are completely eliminated and that the settling time is about 10 ms. But, NC2 controller provides much better attenuation of the ripples in the input current than NC1 controller. The amplitude of the ripples is about 0.3 A peak to peak. This strong attenuation of the ripples is the consequence of fact that the control signal u_p is much closer to be in counter-phase with the full wave rectified input voltage u_{im} (Fig. 9).

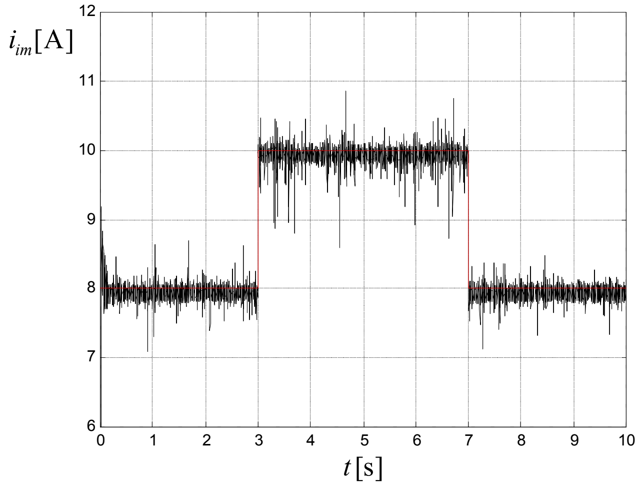


Fig. 7. Responses of the boost converter input current i_{im} to step changes of its reference value i_{ir} obtained with NC2 controller

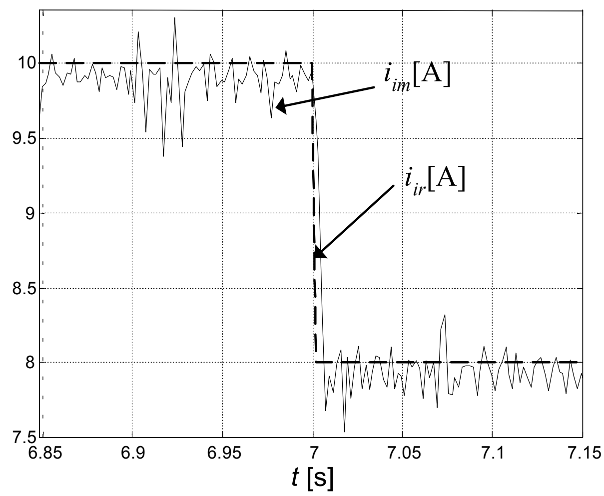


Fig. 8. A more detailed view of a step response from Fig.7.

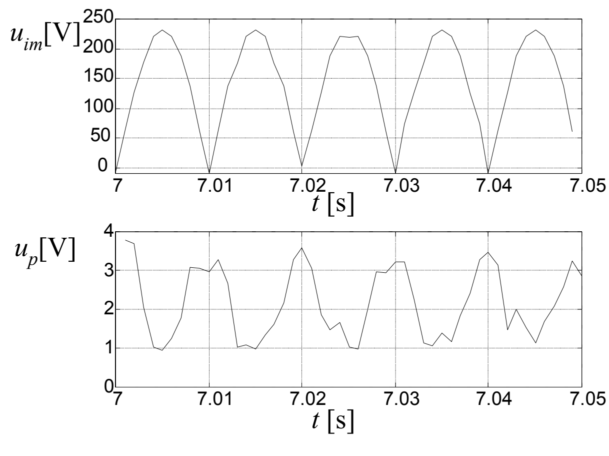


Fig. 9. Full wave rectified input voltage u_{im} and output signal from the NC2 controller u_p

For the sake of comparison, the results obtained with the PI controller and feedforward compensator is given below [5]. Transfer functions of the PI controller and compensator are:

$$G_R(z) = \frac{U_p(z)}{I_{ir}(z) - I_{im}(z)} = 16 \cdot \frac{64z - 54}{54z - 54}, \quad (5)$$

$$G_c(z) = \frac{U_p(z)}{U_{im}(z)} = \frac{1}{61} \cdot \frac{2.54z^3 - 6.72z^2 + 5.84z - 1.66}{6.08z^3 - 16.57z^2 + 16.01z - 5.5}. \quad (6)$$

Responses of the boost converter input current i_{im} to step changes of its reference value i_{ir} obtained with PI controller and feedforward compensator are shown in Fig. 10. A more detailed view of a step response from Fig. 10 is given in Fig. 11.

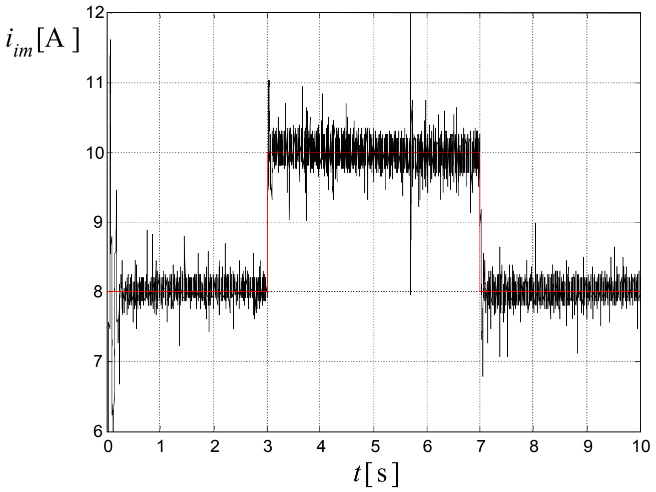


Fig. 10. Responses of the boost converter input current i_{im} to step changes of its reference value i_{ir} obtained with PI controller and feedforward compensator

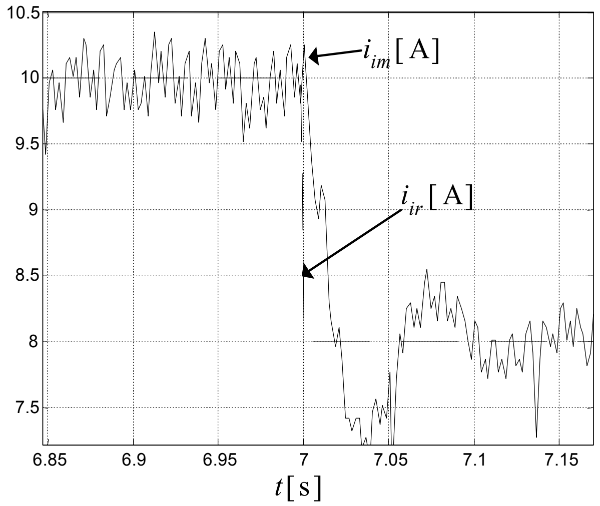


Fig. 11. A more detailed view of a step response from Fig.10.

From Figs. 10 and 11 it can be seen that the overshoots of the input current responses to the step changes of its reference value are about 35 % and that the settling time is about 150 ms. The amplitude of the ripples in input current is about 0.6 A peak to peak.

Obviously, NC2 controller provides much better responses of the input current than PI controller: 15 times shorter settling time, 2 times better ripples attenuation and responses without overshoots in opposite to 35% overshoots. Besides, PI controller requires separate feedforward compensator, which needs considerable manual adjustments. However, a small steady state error occurs in the step response obtained with NC2 controller and it doesn't occur in the step response obtained with PI controller. This error doesn't have any effect on the overall control system performance, because the output voltage controller $\mathbf{Ru_o}$ is superimposed to the input current controller $\mathbf{Ri_i}$ (Fig. 1).

Boost converter supplied from the ac network

When boost converter operates on a ac network it is important to provide as high power factor as possible. In order to provide high power factor, it is necessary to ensure phase angle between input voltage and input current as close to zero as possible. Results obtained with NC2 controller and with PI controller in this operating mode are shown in Fig. 12 and Fig. 13, respectively.

It can be concluded that NC2 controller provides better tracking performance than PI controller. This is because the control structure has faster dynamics with NC2 controller than with PI controller. Better tracking is particularly obvious near abrupt changes of reference signal i_{ir} (zero value of reference signal), where PI controller reacts much slower than NC2 controller. However, in the input current response obtained with NC2 controller there is a small steady state error (similarly as in dc operating mode). But, as it was said above, this error will not have any effect on the overall control system performance.

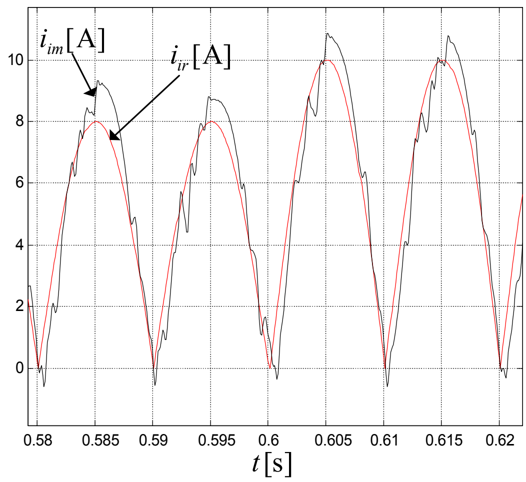


Fig. 12. Responses of the boost converter input current i_{im} in ac operating mode obtained with NC2 controller

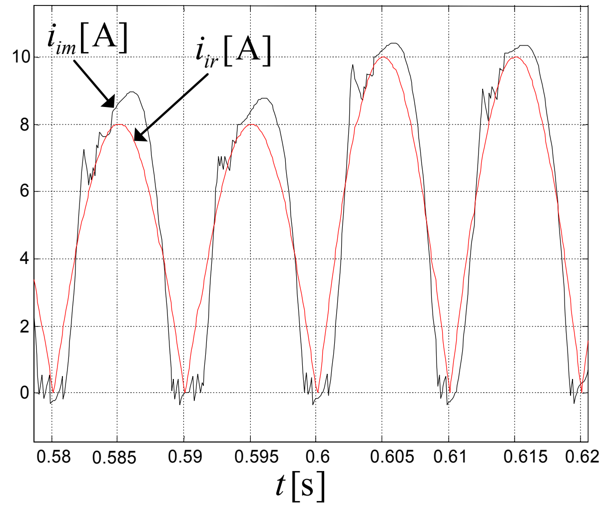


Fig. 13. Responses of the boost converter input current i_{im} in ac operating mode obtained with PI controller

5. CONCLUSION

The use of neural networks for control of the input current of boost converter has been investigated. The investigation of the control system has been carried out for the cases when the converter is supplied from a dc network and from an ac network. The obtained results are very satisfactory in both cases and much better than results obtained with a PI controller complemented with a feedforward compensator. Besides, it is much easier to adjust neural network controller then the PI controller.

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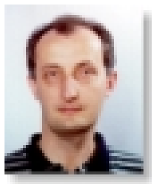

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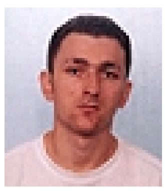

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