Modeling of the *AC/HF/DC* converter with power factor correction

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Abstract: In this paper, the power factor correction system consisted of: bridge converter, parallel resonant circuit, high frequency transformer, diode rectifier and $L_F C_F$ filter is presented. This system is controlled by a pulse density modulation method and the principle of its operation is based on the boost technique. The modeling approach is illustrated by an example using *AC/HF/DC* converter. Verification of the derived model is provided, which demonstrated the validity of the proposed approach.

Key words: power factor correction, resonant circuit, high frequency transformer, boost converter

1. Introduction

Power quality control is an important task in the fields of power electronic and power engineering. Total harmonic distortion and input power factor of power supplies have special concern in the power electronics community in last time. Among many converter system solutions the most recommended is the boost converter with mean value of the input current control. The basic its disadvantage is the higher output voltage level than the magnitude of the input voltage. This voltage level is too high for many applications and besides causes the increase transistors switching power losses. Many methods of reduction of the switching power losses is described in the literature [1, 2, 4, 5]. To adopt the output voltage to the desired level, the additional converter or transformer is used. This additional stage of energy conversion causes the power losses increase. The high frequency transformer can be used when the transformed signal has no *DC* component so the elementary configuration boost converter could not be used.

The above mentioned problems do not occur when the discussed converter system configuration shown in Fig. 1 will be used. The converter system consists of the bridge converter, the parallel resonant circuit $L_R C_R$, high frequency transformer T_R, bridge diode rectifier, and output filter $L_F C_F$. The resonant circuit is sourced by a rectangular current wave produced by the input converter. The converter operates in two characteristic modes. The one mode of opera-

tion called a "diagonal" has place when the diagonal pairs transistors T_1T_4 or T_2T_3 conduct simultaneously. The second mode of operation called a "short circuit" has place when T_1T_3 or T_2T_4 simultaneously conduct. During the diagonal mode, the converter v_p voltage (consist of rectified high frequency sinusoidal wave) mean value is higher than the rectifier ($D_5 \div D_8$) output voltage, so the inductance L_i current as the input current i_i decrease. When the input current decreases below its command signal value the second "short current" mode operation appears. The rectifier ($D_5 \div D_8$) output voltage is shorted by inductance L_i and then current i_i increase. The mode operation changes only while the resonant circuit voltage is equal to zero value. The switching moments are determined by the synchronized phase locked loop. The conduction transistors pair chose depends on the resonant circuit voltage sign and control error sign.
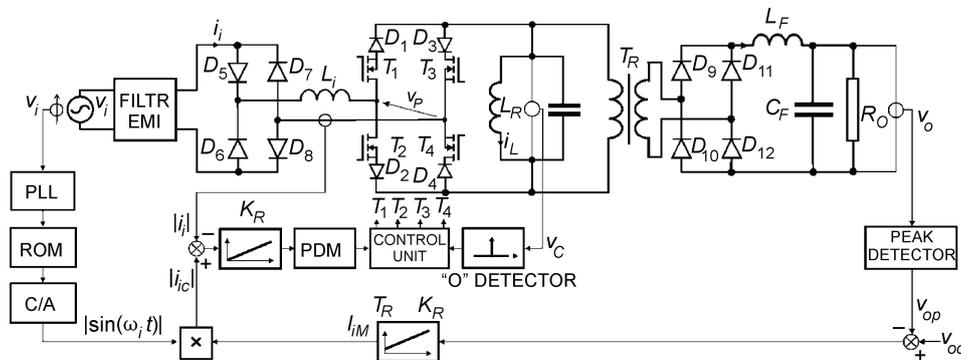

Fig. 1. The converter main circuit and its simplified control schemes

The output filter inductance L_F separates *DC* voltage of the C_F capacitor and high frequency *AC* voltage of the resonant capacitor C_R. This inductance value should be adequate small to ensure the discontinuous current i_F flow, because then the rectifier ($D_9 \div D_{12}$) diodes turn-off power losses are minimized.

2. Control strategy

To improve the proposed converter advantages the closed control loop should be introduced in the converter control system. It ensures the output voltage adequate control range, damps disturbances and provides the energy supporting resonant circuit oscillations. It is difficult to introduce the accurate dynamic model of the converter system as it includes a nonlinear components. Therefore the linearized models are used to description of the system dynamic properties. The standard criterions to system dynamic properties assessment as: a control time and overregulation are applied. In this paper the analytical way of the controller parameters selection will be taken into consideration. In discussed *AC/HF/DC* control system (showed in Fig. 2) a duty-cycle coefficient δ is the controlled variable. It is defined as ratio of "short circuit mode" operation time to period of the control frequency $\delta = t_p/T$.
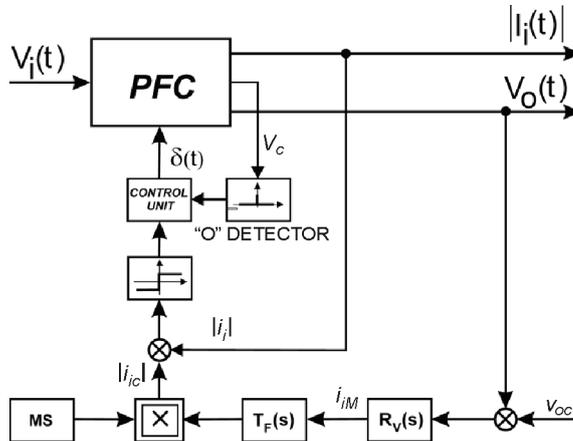
Fig.2. Block scheme of the control system
AC/HF/DC converter

3. Design example

A. Initial specifications

input voltage	$V_i = 110$ V ($V_{im} = 155$ V)
line frequency	$f_i = 50$ Hz
input power	$P_i = 1$ kW
transformer turns ratio	$k_T = 1$
output voltage	$V_O = 250$ V
resonant circuit frequency	$f_R = 50$ kHz
input current relative fluctuations	$\delta_{i\,max} = 0.1$
maximal resonant voltage magnitude	$V_{m_{R\max}} = 500$ V
maximal resonant capacitor current magnitude	$J_{C_{R\max}} \approx 2 \cdot J_{im} \approx 25$ A

B. Calculated parameters:

output resistance	$R_O \approx V_O^2 / P_i = 62.5\,\Omega$
filter inductance [2]:	$L_F = 17.5$ mH
input inductance [2]	$L_i = 1.2$ mH
resonant circuit parameters [2]	$L_R = 60$ µH, $C_R = 16$ µH

4. Synthesis of the voltage and current controllers of *AC/HF/DC* converter controlled by *PDM* method

In this chapter, the current controller and output voltage controller parameters are discussed. The block scheme of the current control loop and the output voltage control loop are shown in Fig. 2. The transistor converter using current feedback loop is controlled by a pulse density modulation with frequency equal to resonance frequency of the resonant circuit. The

equivalent circuit would have a time constant equal to half of the period of the resonant circuit [6, 9, 10]. Delay time of the current control subsystem could be approximated with a first order inertial block which time constant is $T_H/2$. The converter output current is flow to filter loaded by a resistive load. The system transmission of voltage control loop is described by the following equation:

$$T_O(s) = D' \frac{1}{sT_F + 1} \frac{1}{s\frac{T_H}{2} + 1} \frac{R_O}{sC_F R_O + 1} = D' \frac{1}{sT_\Sigma + 1} \frac{R_O}{sT_O + 1},$$ (1)

where: $T_O(s)$ – voltage control loop transfer function, D' – steady state of complementary duty-cycle, T_F – time constant of voltage controller filter, T_H – period of resonance circuit, T_Σ – sum of small time constant, $T_O = C_F R_O$ – time constant of output filter.

Parameter D' is a steady state complementary duty cycle. It takes into account, that during "short circuit" mode operation input current does not flow to load [2, 7, 8]. The remaining blocks present in the voltage control loop are the *PI* controller and the filter in order to damp undesired output current oscillations [9]. The time constant T_F of this filter is chosen somewhat arbitrarily is equal to $T_F = 2.5$ ms [6, 9]. It minimize change of the input current amplitude when the instantaneous input power is small [2]. We chose a *PI* controller because it is known as a good, stable static and dynamic system. The block diagram of the *AC/HF/DC* converter control loop is shown in Fig. 3.
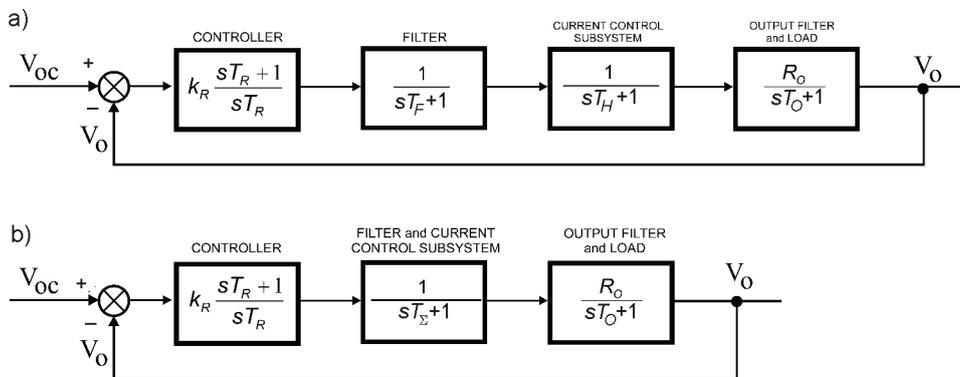

Fig. 3. Block diagram of *AC/HF/DC* converter controlled by pulse density modulation

Next, as the aim of control was assumed that the voltage control time and the voltage overshoot should be minimized. Based on the module criteria, we selected voltage controller parameters and analysis of voltage control loop Bode diagram. The following assumption has been made.

For the preliminary estimation of the voltage controller parameters we applied module criteria which allow to obtain small overshoot and relatively short setting time. Exact controller parameters were selected based on step voltage response performed with *SIMULINK*. Our simulation results showed that the optimal time constant of voltage controller should be equal

to $0.5 \div 0.3 \ T_O$ range whereas the controller gain should not exceed 0.2. The voltage controller gain, could reach even one, but because of the fluctuations of the instantaneous power and the resonant circuit voltage we limited this value to 0.2. The voltage fluctuations occurs, because the resonant circuit voltage amplitude and the converter output voltage are controlled on the basis of the converter input current. The time constant of the output filter is higher that time constant of resonant circuit. Because the circuits with the longer time constants are located after the resonant circuit, very fast change the input power (converter input current) could cause undesired overshoot condition of the resonant circuit. The Bode characteristics of the converter voltage control system are shown in Fig. 4. On the basis of the Bode diagram we can notice that the phase margin is equal to $71°$, while gain margin is equal to infinity.
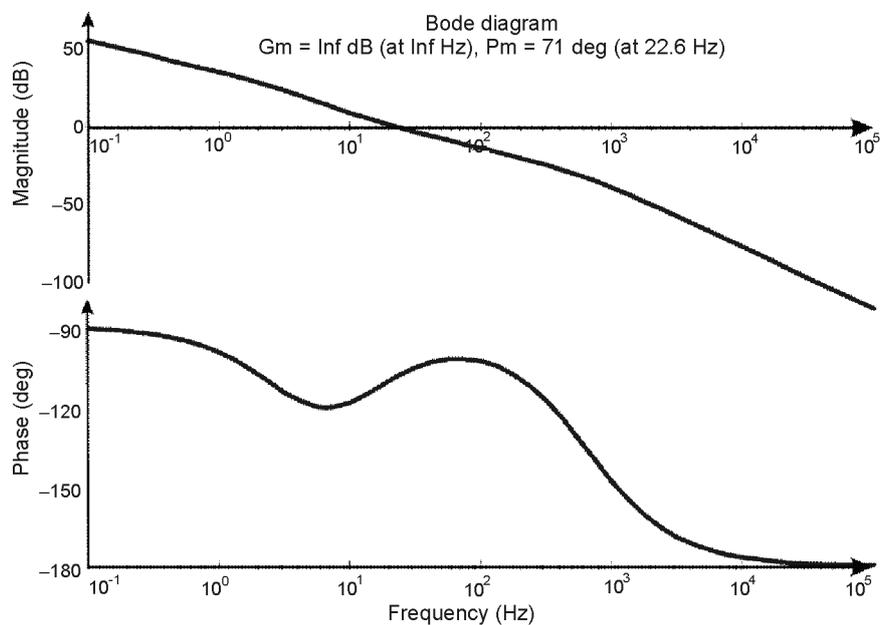

Fig. 4. Bode diagram of voltage control loop of AC/HF/DC converter

5. Simulation results of *AC/HF/DC* converter with PDM regulator

The simulation of the *AC/HF/DC* converter with closed current control loop dynamic properties were obtained in *SIMULINK* package. Characteristic the converter currents responses after command signal step V_{OC} is shown in the Fig. 5. After the command signal step V_{OC} the converter output voltage has small overshoot (Fig. 6). The converter output voltage (with small not removal fluctuations) is equal to its reference value. It takes approximately two periods of line voltage to reach a steady state mode of operation. It was observed, that obtained control time of the output voltage is three times shorter that obtained after setting

a voltage controller time constant according to module criterion. In a steady state the converter control system converter input current is exactly a sinusoidal wave (Fig. 7 and Fig. 8).
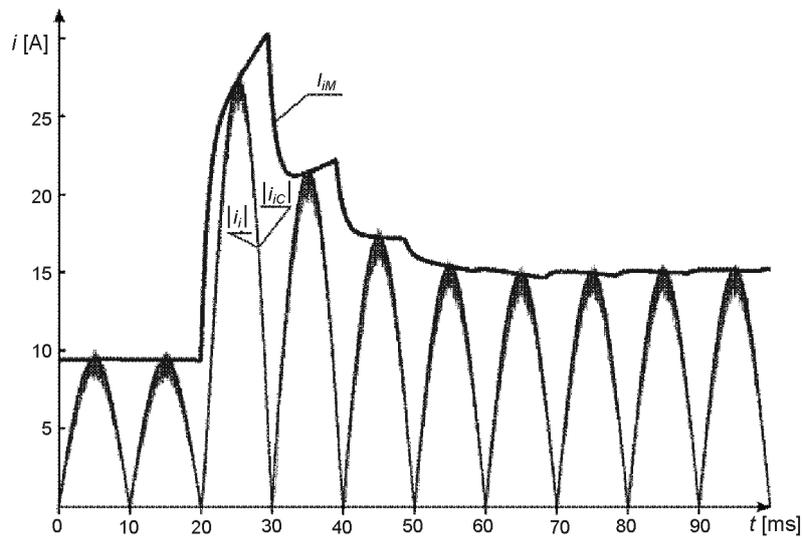
Fig. 5. The transient state waveforms after step changes of the output voltage command signal (i_i – input current, i_{ic} – input current command signal, i_{iM} – amplitude of the input current command signal); $R_O = 62.5\ \Omega$
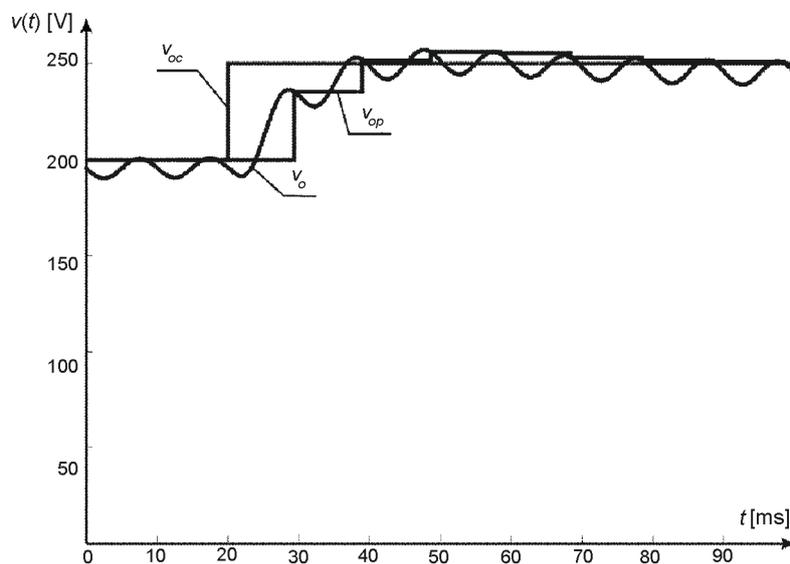
Fig. 6. The transient state waveforms after step changes of the output voltage command signal. (V_{oc} – voltage control signal, V_{op} – output voltage peak detector signal, V_o – output voltage); $R_O = 62.5\ \Omega$
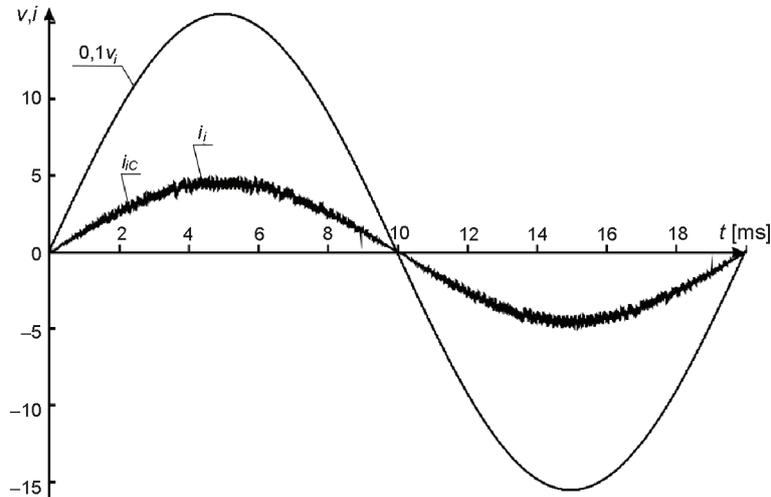
Fig. 7. Characteristic waveform during the steady state operation (v_i – input voltage, i_i – input current, i_{iC} – input current signal); $V_O = 250$ V and $R_O = 3R_{ON} = 187.5$ Ω
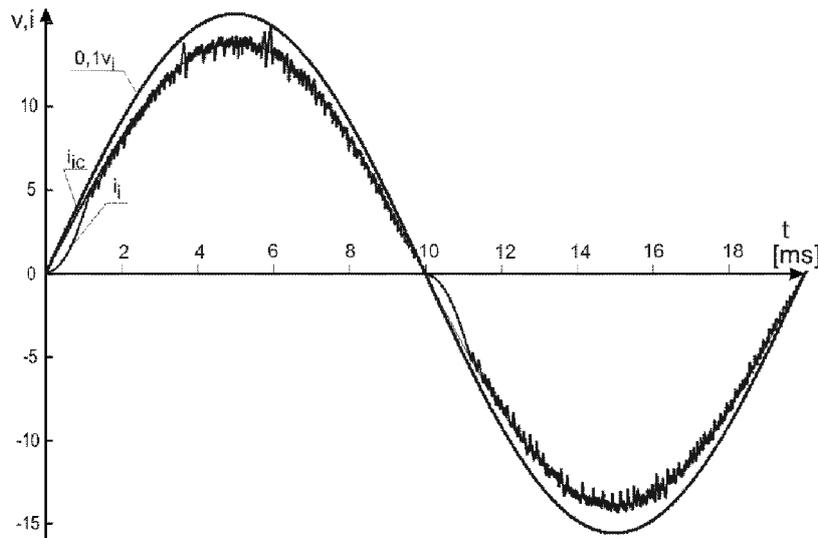

Fig. 8. Characteristic waveform during the steady state operation (v_i – input voltage, i_i – input current, i_{iC} – input current signal); $V_O = 250$ V and $R_O = R_{ON} = 62.5$Ω

The transient input current waveform is worth noticing. Rapid decrease of the input current signal i_{iC} causes the input current to be smaller than the output filter current i_F and dampening oscillations in the resonant circuit. That is more, the inductance L_F in Fig. 1 also draw energy from resonant circuit. In order to avoid damping oscillations, the controller enters into a "diagonal" mode of operation. As the result the input current is not controlled until the amplitude of the resonant circuit is smaller than 50 V. This phenomenon does not concern the steady

state operation, it takes place during transient mode operation, when amplitude of the input current command signal I_{iM} decreases.

Characteristic converter responses after output load steps are shown in the Fig. 9. We can notice that converter output voltage takes smaller values for short period of time. After that, the voltage controller increases the value of the reference current. After two periods of line voltage, the converter enters a steady state with voltage control error equal to zero.
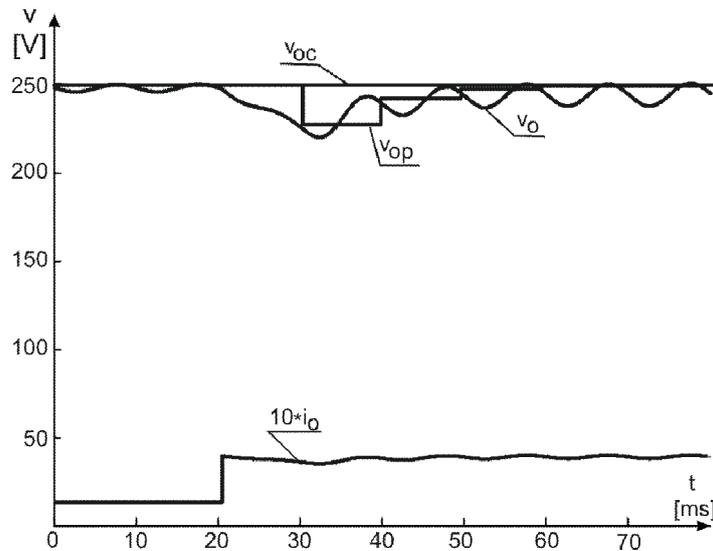

Fig. 9. The transient state waveforms after step changes of the load.(V_{oc} – voltage control signal, v_{op} – output voltage peak detector signal, v_o – output voltage)

Our simulation results confirmed good dynamic characteristics of the presented system. A discrete implementation of the converter, as opposed to one using an integrated circuit, lends itself to systems with higher power dissipation (order of the kW) and limited switching frequencies. The input current harmonic content and value of the *THD* coefficient satisfy international standards and requirements. This system is highly efficient. Hence, it lends itself to electronic design and electric power applications.

6. Predictive controller

Up to now we analyzed dynamic characteristics of the converter without taking into account effects of inductances L_i and L_F on circuit performance. First of all, we add effect of a delay caused by an inductance L_i and take it into consideration in the equation expressing transmittance as follows [3, 7]:

$$G_o(s) = \frac{k_o e^{-s\tau}}{1 + sT},$$ (3)

where: k_o – amplification coefficient, T – time constant and τ – time delay of object.

This transmittance formula has been validated in our application. Initially, after the step changes of the command voltage signal, the converter enters a "short circuit" mode which is necessary to allow current increase. At this time the filter capacitor provides charge to the load while maintaining almost constant voltage. After reaching a desired current, the controller enters a "diagonal" mode of operation. The converter is now powered from the mains through the resonant circuit and output filter. Voltage on its terminals changes exponentially with a time constant $T_O = C_F R_O$. It describes a delay during energy transfer to the output. Value of delay depends on the instantaneous value of the input voltage corresponding to a current step. To derive a mean delay we could use an equivalent model of converter [7, 11]. Let us assume the converter steady state conditions as follows: mean output voltage V_O, output current I_O, DC equivalent input voltage V_{iRMS}, current I_{iRMS} and complementary duty-cycle D' (average value over one line voltage period). In a steady state, if we neglect converter internal losses, the input and output power are equal. This fact allows substitution of the analyzed converter with an equivalent scheme shown in Fig. 10
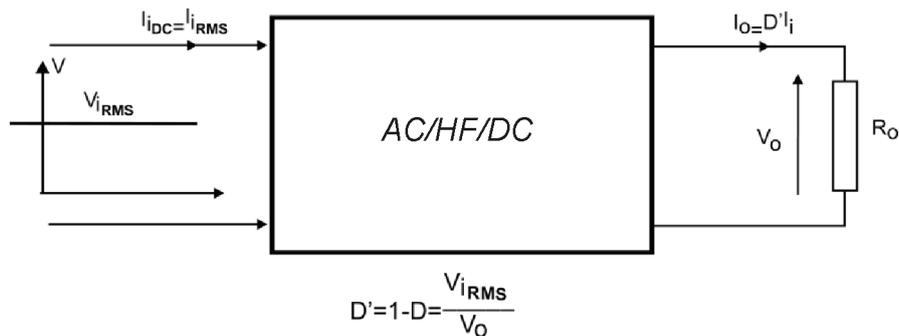

Fig. 10. Adequate model of *AC/HF/DC* converter

Assuming that a voltage source is equal to the effective input voltage of the converter, the following relationships will be true:

$$V_i = V_{iRMS} \Rightarrow V_O = \frac{V_{iRMS}}{1-D} \Rightarrow D' = \frac{V_{iRMS}}{V_O} \quad P_{we} = P_O \Rightarrow V_{iRMS} I_{iRMS} = V_O I_O =$$

$$= \frac{V_{iRMS}}{1-D} I_O \Rightarrow I_O = I_{iRMS} D'. \tag{4}$$

Estimation of a coefficient D' allows determinate of an amplification coefficient k_o is given by:

$$k_o = D' R_O \eta. \tag{5}$$

The coefficient η takes into account circuit efficiency.

The required delay for the input current to reach its desired value, assuming the converter is powered from a reasonable source of adequate *DC* power, is equal:

$$\frac{I_{iRMS}}{\tau} = \frac{V_{iRMS}}{L_i} \Rightarrow \tau = \frac{I_{iRMS}}{V_{iRMS}} L_i. \tag{6}$$

Equations (5) and (6) allow us to derive parameters present in the transmittance formula (3). To control output voltage is most beneficial the use of a predictive controller because for high delay values prediction is more effective than differentiation [3]. Transmittance of a closed loop of *AC/HF/DC* converter with a predictive regulator can be expressed as:

$$G_o(s) = \frac{k_o e^{-s\tau}}{1 + s\lambda T}. \tag{7}$$

Parameter λ in the formula (7) above can be varied in a wide range typically $\lambda \in (0.5, 5)$ [3]. Value of this parameter determines dynamic characteristics of a closed loop step response. For $\lambda = 1$ time constant of the closed loop is equal to the time constant of open loop. For $\lambda < 1$ closed loop response is faster than open loop and for $\lambda > 1$ slower respectively. Regulator, for which a closed loop transmittance has the desired characteristics, can be described as follows:

$$G_R(s) = \frac{1}{k_o} \frac{1 + sT}{1 + s\lambda T - e^{-s\tau}}. \tag{8}$$

Assuming $\lambda = 1$ and $T = T_O$, we can write the following equation:

$$I_{iM}(s) = k_R \varepsilon(s) + \frac{e^{-s\tau}}{1 + sT_O} I_{iM}(s), \tag{9}$$
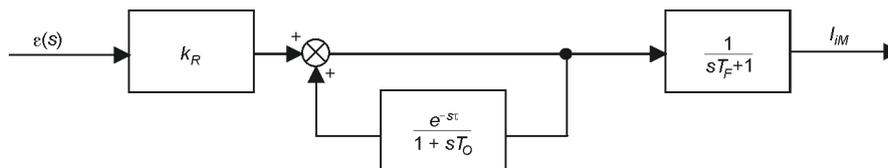
where $k_R = 1/k_O$.

Fig. 11. Block diagram of a predictive controller

Step characteristics of *AC/HF/DC* converter with a predictive controller are illustrated in the figures below. Characteristic of the converter output voltage responses after command signal step V_{OC} is shown in the Fig. 12. After the command signal change the converter quickly establishes a new output voltage value V_{OC} with small overshoot and the output voltage (with small, not to remove pulsations) is equal to its set value. Characteristic the converter currents responses after command signal step V_{OC} are shown the Fig. 13. Amplitude of the input current command signal I_{iM} is smaller in the system with predictive controller than in the system with classic *PI* controller, for compared time of control. In the steady state the control system reproduces a sinusoidal converter input current like (Fig. 7 and Fig. 8).
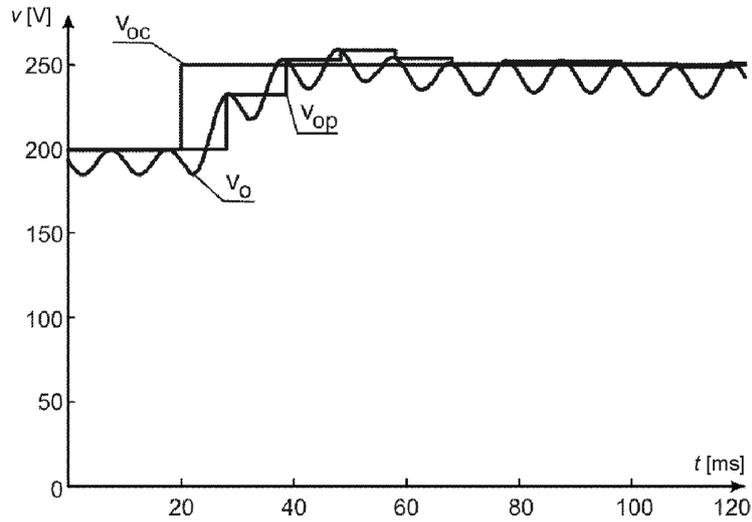
Fig. 12. The transient state waveforms after step changes of the output voltage command signal
(V_{oc} – voltage control signal, v_{op} – output voltage peak detector signal, v_o – output voltage); $R_O = 62.5$ Ω
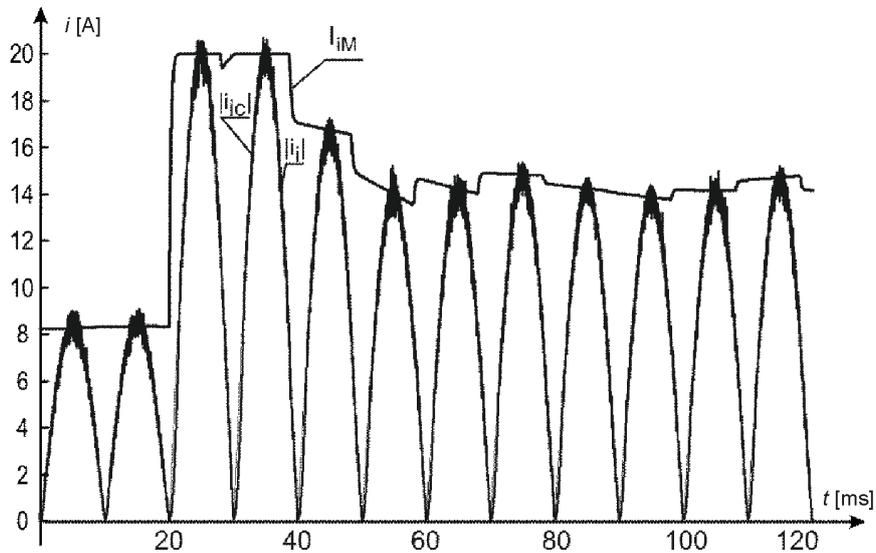

Fig. 13. The transient state waveforms after step changes of the output voltage command signal
(i_i – input current, i_{ic} – input current command signal, I_{iM} – amplitude of the input current command
signal); $R_O = 62.5$ Ω

7. Conclusions

Analysis of the power factor correction (*PFC*) converter dynamic properties is presented in article. The *PFC* converter consists of: bridge inverter, resonant circuit, high frequency trans-

former, rectifier and filter. The bridge inverter is controlled with pulse density modulation method in the system like as the boost converter. The resonant circuit voltage oscillation make possible the converter transistors switching with zero voltage conditions it reduce the transistor power losses. The converter model was introduced which is correct for the frequencies below half of the switching frequency. This model is useful to the controllers parameters selection, particularly for the controllers of input current and the output voltage of *AC/HF/DC* converters. Presented in article algorithm was verified by simulations with *SIMULINK* package use. The system steady-state simulations confirm the unity value of the input power factor. The current absorbed by the system has near sinusoidal waveform with a small distortion. The input current harmonic content and value of the input power factor satisfy the international standards requirements (*THD* coefficient is smaller than value acceptable by standards EN-61000-3-2).

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