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Study on Performance of Non-Linear Reactive Power Compensation by Using Active Power Filter under Load Conditions

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***Abstract*—The paper analyses and examines the efficiency of non-linear reactive power compensation when use the active power filter controlled by an algorithm based on the theory of CPC. The developed physical model of 3-phase active filter has been presented and results of its performance in the system so the linear load and nonlinear RL type are discussed. Particular attention was put on its operation in transient conditions. Based on both simulation and investigation results appropriate practical conclusions are formulated.**

***Index Terms*—Active power filter, non-linear reactive power compensation, load conditions.**

I. INTRODUCTION

In modern electric power systems of alternating current there is an urgent need to find ways for optimizing working conditions. One of the most important problems is to reduce the losses associated with transmission of electric energy. The most of loads in practice are of inductive (RL) type. This implies displacement between voltage and current vectors characterized by angle shift φ. Since, the final consumer is interested in obtaining only the active power (which is the useful power) thus, under flow, in feeders, the apparent power value greater than the required the addition power losses are evident. Commonly used indicator of efficiency of transmission is the power factor value (cos φ) defined under the known relationship

$$\cos\varphi = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2}}, \tag{1}$$

where P – active power (useful power), S – apparent power, Q – reactive power. If therefore, S > P, the energy efficiency is less than maximum due to existence of reactive power component.

So striving to improve the efficiency of energy transfer it is required to reduce or eliminate the participation of reactive power.

In electric power systems with sinusoidal waveforms above mentioned problem is solved relatively simply by application of connected in parallel carefully selected capacitive compensators (bank of capacitors, rotating compensators). Change of parameters of current and voltage signals results in variation of the capacity value applied with respective time delay to be introduced by the control system (power factor controller) and time constant of the main circuit.

Already in 1920, it was found that the power factor can be less than one for unbalanced circuits with sinusoidal current and voltage waveforms even if the load is only active [1]. However, it must be noted that structure of the compensator controller is relatively easy to achieve when designed for steady state conditions, and becomes more complex for application under dynamic load changes. Today main problem in electric power systems results from the fact that electric energy is extensively consumed by means of electronics converters. These devices draw deformed currents which can be described by a Fourier series

$$i(t) = I_o + \sum_h \sqrt{2}\, I_h \times \sin\left(\omega_h t + \varphi_h\right), \tag{2}$$

where I_o – dc component, I_h – rms value of “h” harmonic, φ_h – phase shift for “h” harmonic.

In real systems one deals therefore, with stochastic changes of the amplitude of voltages and currents as well as their frequencies. Therefore, in order to simplify considerations under designing we assumed following conditions: balanced 3-phase system, constant amplitude and periodicity of waveforms as for quasi – steady state. However, in practice current waveform can be indicated by high rate of change, up to about a few kA/ms, as it takes place for example in hoist engines applications powered by thyristor converters.

II. THE THEORETICAL BASIS OF REACTIVE POWER COMPENSATION IN SYSTEM WITH DEFORMED VOLTAGE AND CURRENT WAVEFORMS

The complexity of the phenomena in circuits with non-sinusoidal currents and voltages did not allow to work out effective methods of reactive power compensation for more than 90-years despite numerous attempts. Neither power

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theory of Budeanu (1928) nor this of Fryze (1931) gave effective basis for the construction of compensating devices. Publication (in 1981 [2]) of theory of instantaneous power (IPT) was a first major achievement in this field. It allowed for determination of the currents waveforms compensation although neither describes nor explains physical phenomena associated with energy exchange in these circuits. Another important step forward was the theory of the current physical – components (CPC) developed and published in 1984 [3]. This theory is based on the analysis of current and voltage signals in the frequency domain. One phase electric scheme for simplicity of consideration of the CPC theory application is shown in Fig. 1. High harmonics in current and voltage are taken into account with particular attention to active power flow direction caused by signals deformation. Therefore, phase voltage and current as a vector for 3-phase system can be expressed as follows:

$$\begin{cases} u = \begin{bmatrix} u_a \\ u_b \\ u_o \end{bmatrix} = \sqrt{2} R_e \sum_{h \in N} \begin{bmatrix} \underline{U}_{ha} \\ \underline{U}_{hb} \\ \underline{U}_{hc} \end{bmatrix} e^{jh\mu_1 t} = \sqrt{2} R_e \sum_{h \in N} \underline{u}_h e^{jh\mu_1 t}, \\ i = \begin{bmatrix} i_a \\ i_b \\ i_o \end{bmatrix} = \sqrt{2} R_e \sum_{h \in N} \begin{bmatrix} \underline{I}_{ha} \\ \underline{I}_{hb} \\ \underline{I}_{hc} \end{bmatrix} e^{jh\mu_1 t} = \sqrt{2} R_e \sum_{h \in N} \underline{I}_h e^{jh\mu_1 t}. \end{cases} \quad (3)$$

Next the complex power $\underline{S}_h$ for h order of high harmonic can be calculated

$$\underline{S}_h = P_h + jQ_h, \quad (4)$$

and resultant set N of all harmonics can be divided into two subsets N_A and N_B depending on sign of active power of particular harmonics P_h. Thus, if $P_h \geq 0$ ($h \in N_A$) load is passive, whereas for $P_h < 0$ ($h \in N_B$), due to nonlinear load the voltage source of the system is treated as passive load; *i.e.* the active power P_h is reversely transferred to the source. As a result the CPC theory introduces the distribution of the load current into 5 components, *i.e*:

– i_a – active current related to the transmission of active power to the receiver,

– i_r – reactive current component due to receiver susceptance,

– i_h – current of high harmonics associated with non-linearity of the receiver (load),

– i_n – unbalanced component, the current related to the voltage unbalance source,

– i_{sc} – scattering current associated with high harmonics in the voltage source and presence of load impedance value z_L dependent on frequency.

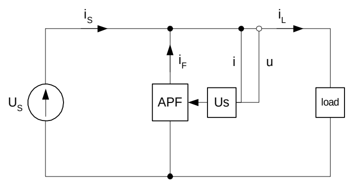
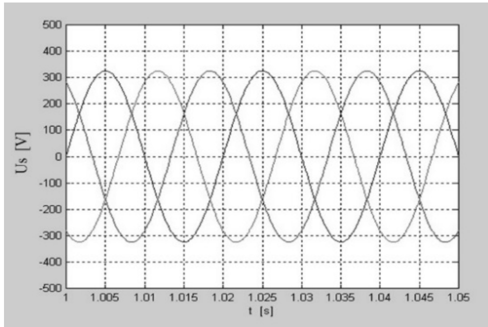


Fig. 1. Simplified scheme of circuit with active power compensation applied; z_L – load (receiver) impedance, APF – active power filter, US – control unit, i_L – load current , i_F – additional (compensation) current, U_S, i_S – network voltage and current respectively.



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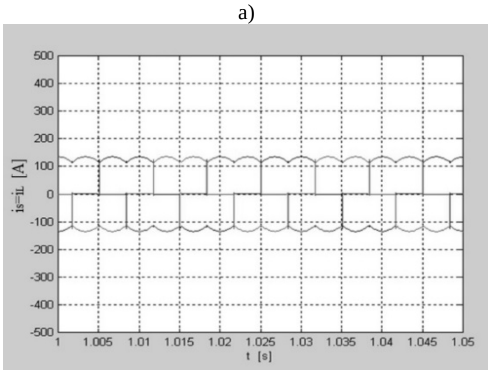

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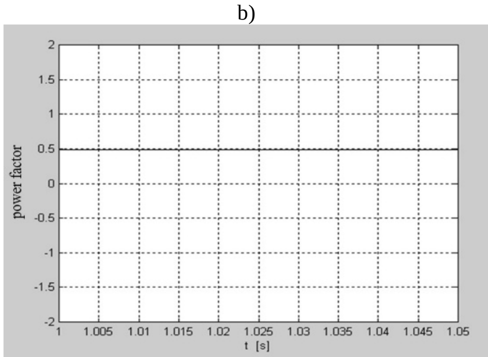

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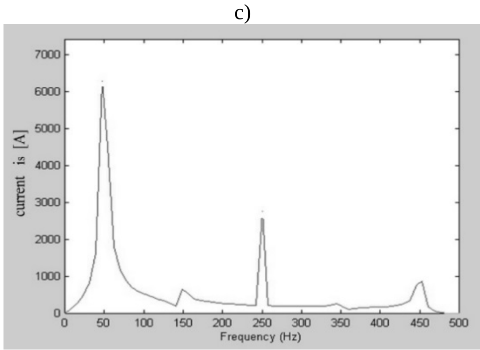

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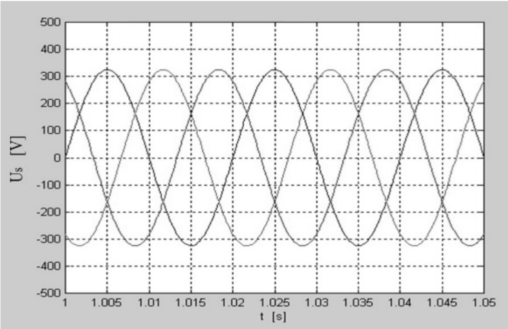
Fig. 2. Waveforms of network voltage U_s (a), network current $i_s = i_l$ (b), power factor - cosφ (c) and network current high harmonics spectrum (d) when supply 3-phase non-linear RL load (2 Ω, 10 mH) via 6-pulses controlled rectifier at ignition angle $\alpha = 60°$ without active compensation (3 × 400 V, 50 Hz).

Each of these components specified is responsible, in a structural way, for energy phenomenon occurring in the circuit. Both CPC and IPT theory allow for effective reactive power compensation in electric circuits with distorted waveforms [4]. It is obvious that the minimization of power losses in the transmission system is related not only with elimination of reactive current component i_r but also with elimination of undesirable other currents i_u, i_s, i_h. Only such an approach enables efficient minimization of active power losses amount in unbalanced circuits and/or in circuits with non-sinusoidal current and voltage waveforms.

The essence of the compensation is therefore, based on generation, by the so-called active power filter APF (compensator keying), such additional current component i_F that, when injected into the network, allows for existence only active current responsible for the transmission of active power from the source to the receiver (Fig. 1).



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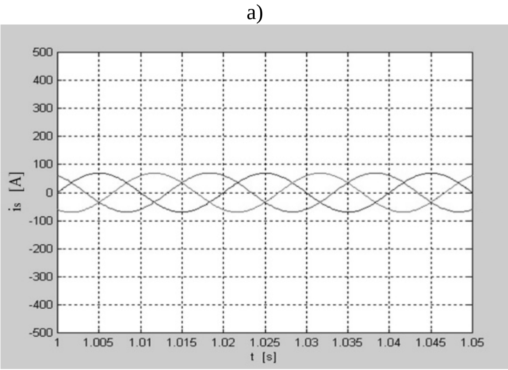

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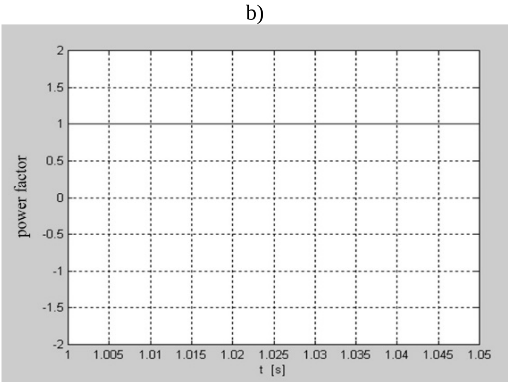

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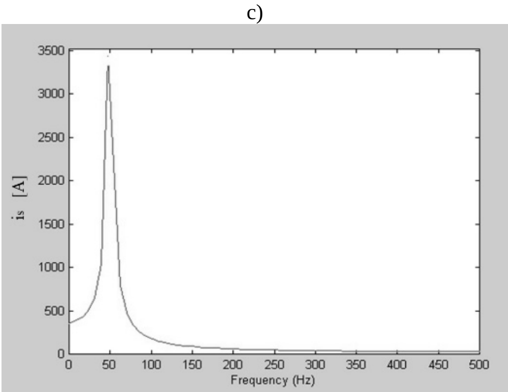

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Fig. 3. Waveforms of voltage U_s (a) and network current i_s (b) as well as power factor value (c) and i_s current harmonics spectrum (d) for non-linear load as in Fig. 2 but with APF applied.

Before construction of a physical model a mathematical representation of APF has been developed to carry out appropriate simulation studies. The compensation effectiveness investigations carried out for 3-phase resistive and/or resistive-inductive load such balanced and unbalanced at sinusoidal voltage supply of 3 V × 400 V, 50 Hz. The non-linear load modelled using controlled rectifier. Results of simulation studies confirming the aptness of concept were published, inter alia, in [5]. For example in Fig. 2 are shown selected simulation results for balanced non-linear RL load controlled by 6-pulse thyristor bridge (at ignition angle α = 60°) without active compensation whereas, in Fig. 3 – with APF applied respectively. One can see the positive impact of the active power filter (APF) manifested in sinusoidal waveshape of currents drown from the network (Fig. 3(b)), the total compensation of reactive power (Fig. 3(c)) and full suppressing of the current harmonics (Fig. 3(d)). Advanced technical measures nowadays, allow for execution of high-speed control systems responsible both for the reliable spectral analysis of the current and voltage waveforms, derivation of reference current (desired) for the network and for generation (in high current part of the circuit) of such additional (compensation) current component i_F to fulfil requirement

$$i_L + i_F = i_S = i_a. \quad (5)$$

III. Laboratory Studies of the Performance and Dynamics of the Active Compensation System

A. Testing System and Measurement Method

Studies of the efficiency and dynamics of operation of the active power compensator (APF) were performed on physical laboratory model of 10 kVA (as illustrated in Fig. 4 and Fig. 5) developed of the compensator controlled by means of an algorithm employed the CPC theory [5]–[8]. A block diagram of the developed APF physical model is shown in Fig. 6. In order to determine the APF suitability the laboratory tests were performed in system as in Fig. 7 for a different so linear and non-linear balanced and unbalanced 3-phase loads. Time of signal processing of distorted voltage and current waveforms in the control system was valuated to be about 297 µs. Full results of laboratory test under various operating conditions can be found in [9] and [10]. They confirmed the usefulness of this APF model both for non-linear reactive power compensation, high harmonics elimination from waveforms of network currents and supply load balancing.

Fig. 4. View of the active power filter (APF) developed.

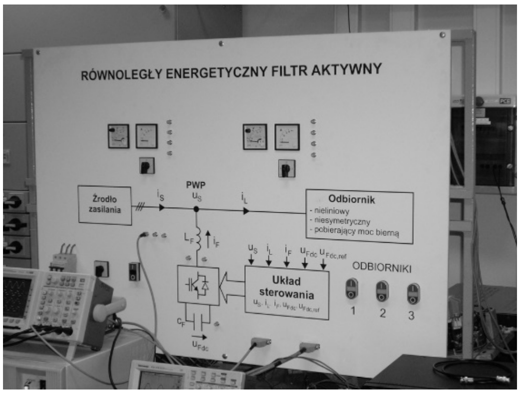


Fig. 5. Overview of laboratory installation under testing.

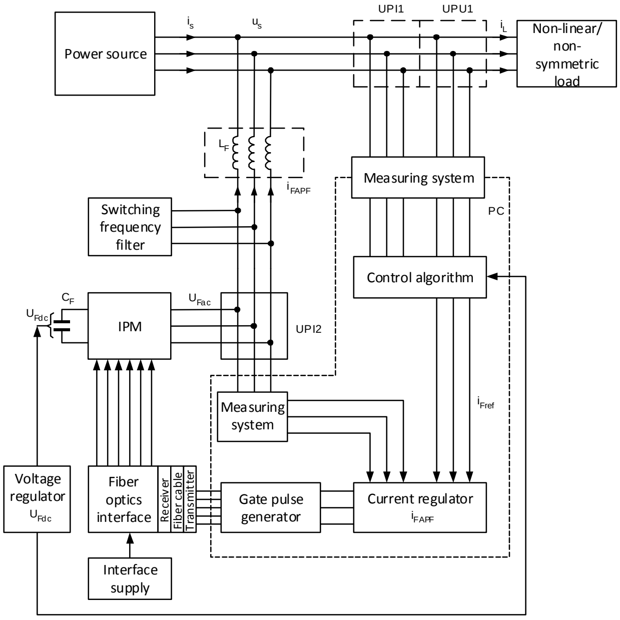


Fig. 6. Block diagram of the developed APF physical model. IPM-intelligent power module, C_F-DC capacitor, L_F-coupling reactor, PC-microcomputer, i_s-supply network current, i_L-load current, u_s-network voltage, i_{Fref}-reference current of the active filter, i_{FAPF}-active filter current, U_{Fdc}-voltage of the capacity, U_{Fac}-AC voltage at output of power module, U_{PI1}, U_{PI2}-current measuring systems, U_{PU1}-voltage measuring system.

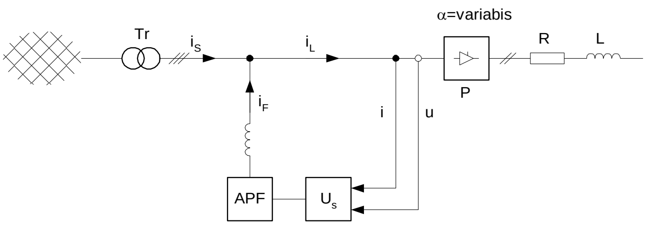


Fig. 7. Schematic testing system of the effectiveness of the active compensator under dynamic load, APF – active power filter, U_S – control system, R, L – different load, P – controlled rectifier (α – specified angle of delayed conduction), i_S – network current, i_F - additional (compensation) current, i_L – load current.

However, the signal processing (in the control systems and in APF) is very fast, but introduces unavoidable time delay value under generation of compensation current component i_F with respect to the needs to be related to instantaneous load current i_L value and its waveform. Therefore, it is of great importance to examine and explain also the influence of this time delay on efficiency of compensation especially in the case of high dynamics of the i_L load current. Therefore the controlled rectifier was loaded by RL receiver of following parameters: R = 18.2 Ω, L = 14.7 mH. During the tests the ignition α angle was changed in a step way in the range of 0° to 50° (by means of the control voltage regulation) and performance of the active compensation system was observed and recorded.

B. Investigated Results under Transient States

Waveforms of network voltage, network current, load current and the compensation current (APF) were measured and recorded as a response to the change of the α angle of the rectifier. Variation of the control voltage signal with time to change the rectifier angle value from α = 0° to α = 50° is shown in Fig. 8.The delay time of this process is around 4 ms.

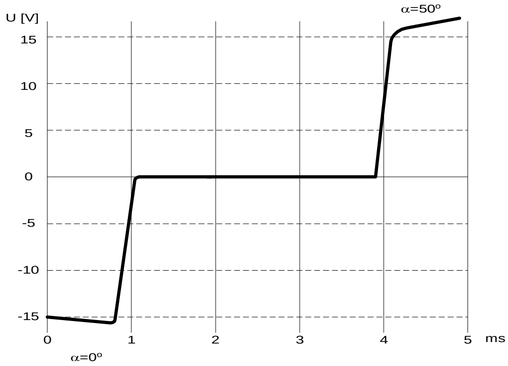
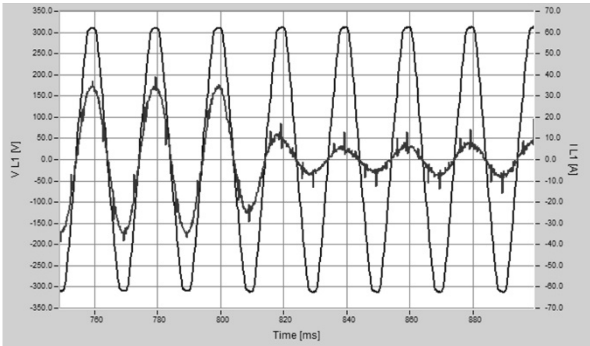


Fig. 8. Voltage waveform of controlling signal of rectifier to change value of its conduction angle α from 0° to 50°.



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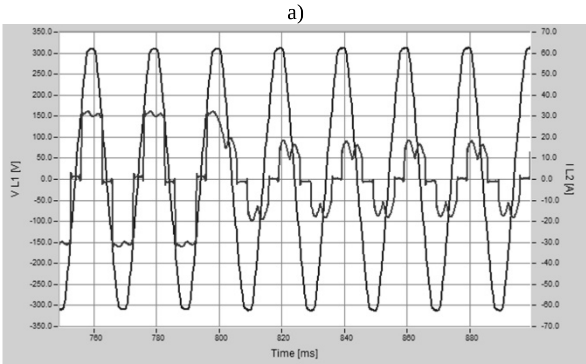

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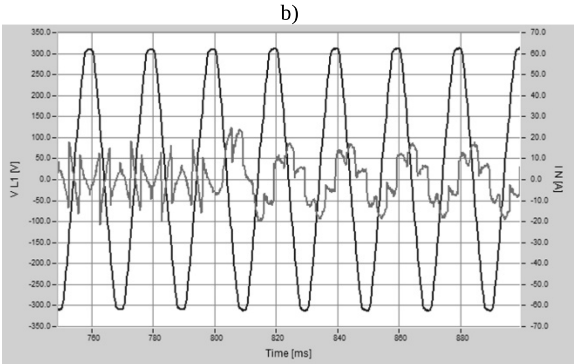

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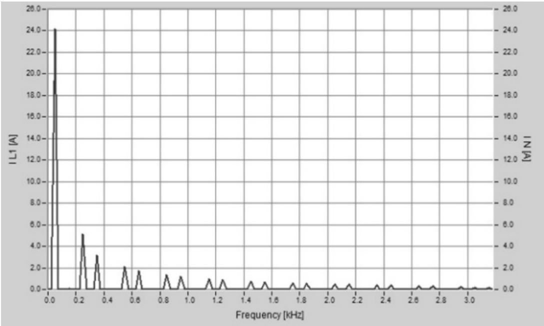

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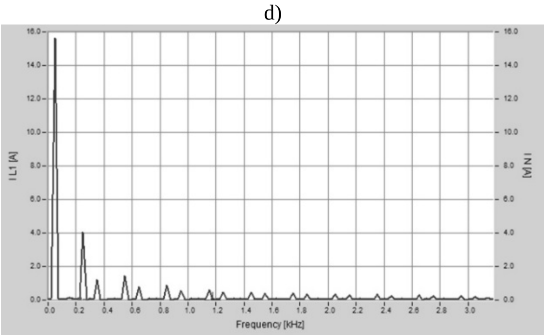
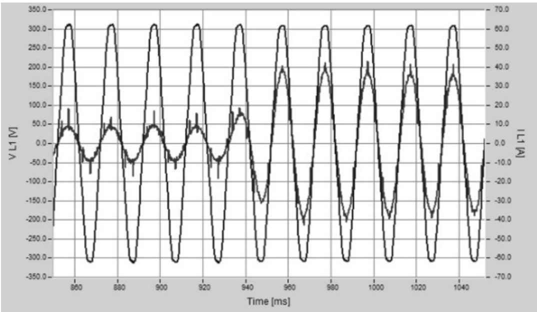


e)

Fig. 9. Variation of voltage and current (in network) waveforms (a), rectifier current (b), APF current (c), and harmonics spectrum of network current in transient d), e) as a response for rapid change of the angle α value from 0° to 50°.



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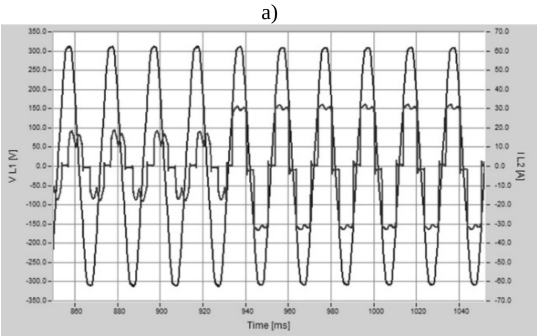

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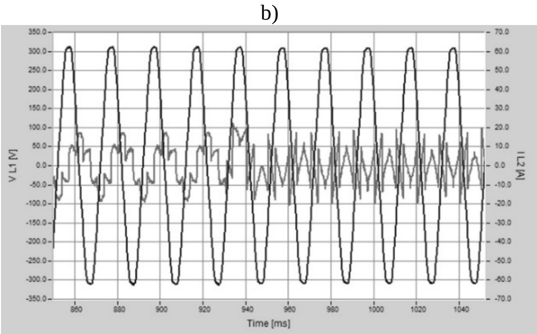

c)

Fig. 10. Variation of voltage and current in network (a), rectifier current- (b), APF current (c), in transient as a response for change of the angle α value from 50° to 0°.

Performance of the active compensation unit in transient under rapid change of the conduction angle was found to be satisfactory for application in electric power networks characterized by implemented inertia due to electromagnetic systems applied. The response of the APF for stimulated variation of the non-linear load is within 15 ms and results in fast stabilization of instantaneous load current value, load balancing as well as in acceptable sine wave shape of both current and voltages in the network. Selected investigated results under rapid change of the conduction angle (from 0° to 50° and reverse) of the non-linear load are presented for example in Fig. 9 and Fig. 10 respectively.

IV. Conclusions

The developed active compensation system using active compensation control algorithm based on CPC theory and employed the active filter (APF) operating at frequency of the 6.4 kHz (PWM modulation) was found to perform properly under both quasi steady states and rapid variation of the non-liner load parameters. Particular attention paid on performance in transient showed that after step way changes of the ignition angle value of the controlled rectifier the compensated value of the network current is quickly stabilized within the time less than one period of basic harmonic (around 15 ms). For most non-linear loads such speed and dynamic of performance is satisfactory in practice. In general simulation study and laboratory tests confirmed the reliable operation and full usefulness of this type of active compensation devices in electric power networks (of both low and middle voltage) characterized by sufficient inertia due to electromagnetic systems cooperation.

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