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A Static Synchronous Compensator for Displacement Power Factor Correction under Distorted Mains Voltage Conditions

R. Cimbals, O. Krievs, L. Ribickis
Faculty of Power and Electrical Engineering, Riga Technical University,
Kronvalda bulv. l, LV-1010,Riga, Latvia, e-mails: r.cimbals@gmail.com, oskars@eef.rtu.lv

Introduction

The improvement of electrical energy transmission efficiency has long been realized using passive power factor compensators containing shunt capacitors. Shunt capacitors are relatively inexpensive to install and maintain. Installing shunt capacitors in the load area or at the point where compensation is necessary increases the voltage stability. However, shunt capacitors have the problem of poor dynamics, poor voltage regulation and, beyond a certain level of compensation, a stable operating point is unattainable. Furthermore, the reactive power delivered by the shunt capacitor is proportional to the square of the terminal voltage; during low voltage conditions reactive power support drops, thus compounding the problem [1]. In addition, shunt capacitor compensators may suffer from resonances with distributed inductances of the utility grid.

Nevertheless, in practice shunt capacitors have proven to be sufficiently effective, provided that the line voltage is sinusoidal. However due to proliferation of different power electronic converters amongst industrial and household equipment, which often draw explicitly non-sinusoidal current, in some cases the grid voltage quality is affected considerably. This being the case, the application of passive capacitive power factor compensators becomes problematic, since capacitor’s reactance is decreased for higher voltage harmonic components leading to excessively increased capacitor currents. A typical industry solution for this problem is the application of tuned filter reactors in series with each compensation capacitor bank [2]. This solution, however, significally increases the required capacitance and rated voltage of the capacitors, as well as the cost of the whole compensator. This justifies application of more advanced techniques like SCR based dynamic power factor compensators or STACOM (Static Synchronous Compensator) converters, which can cope with all the problems mentioned above.

Static Synchronous Compensator (STATCOM)

By definition, STATCOM is a static converter operated as a parallel connection static reactive power compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage [3], [8].

In addition to system voltage control, which typically is the main task of the STATCOM, it may also be employed for additional tasks such as damping of power system oscillations, which results in improvement of the transmission capability.

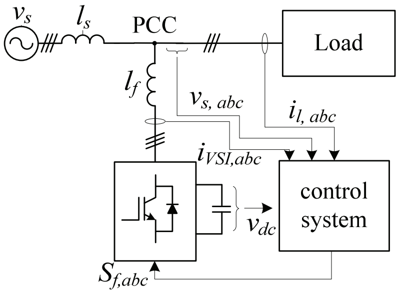

Fig. 1. Basic structure of a STATCOM system

Structurally STATCOM is a voltage-source inverter (VSI) based device (Fig. 1), which converts a DC input voltage into an AC output voltage in order to compensate the reactive power and improve power factor in the system. In case the system voltage drops sufficiently to force the STATCOM output to its ceiling, still its reactive power output is not affected by the grid voltage magnitude. Therefore, it exhibits constant current characteristics when the voltage is low. STATCOM can provide instantaneous and continuously variable reactive power in response to grid voltage transients, enhancing the grid voltage stability. The STATCOM operates according to voltage source principles, which together with unique PWM (Pulsed Width Modulation) switching of power switches gives it unequalled performance in terms of effective rating and response speed [4]. This performance can be dedicated to active harmonic filtering [6] and voltage flicker mitigation, but it also allows providing displacement power factor compensation of the load, thus improving the power factor.

Developed STATCOM Control System

According to the "*p-q*" theory the instantaneous power can be decomposed into three different instantaneous powers – instantaneous zero-sequence power *p*0, instantaneous active power *p* and instantaneous reactive power *q* [5]. In case of three-phase three wire systems where no zero-sequence currents, can be present, the instantaneous power can be defined using Clark's coordinate transformation in orthogonal αβ reference frame as follows

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}, \tag{1}$$

where $v_{\alpha\beta}$ and $i_{\alpha\beta}$ are the voltage and current of the three phase system in Clark's reference frame.

Considering that the Park's transformation is power invariant and choosing a reference frame so that v_{sq}=0, the active and reactive power of the load under consideration in Park's reference frame can be given by

$$\begin{bmatrix} p_l \\ q_l \end{bmatrix} = v_{sd} \begin{bmatrix} i_{ld} \\ i_{lq} \end{bmatrix}, \tag{2}$$

where v_{sd}, v_{sq} and i_{ld}, i_{ld} are the voltage and current in synchronous reference frame obtained by Park's transformation (Fig. 2):

$$\begin{cases} \mathbf{v}_{sdq} = \mathbf{D}\mathbf{v}_{s\alpha\beta} \\ \mathbf{i}_{sdq} = \mathbf{D}\mathbf{i}_{s\alpha\beta} \end{cases}, \quad \mathbf{D} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}, \tag{3}$$

$$\theta = \arctan\frac{v_{s\alpha}}{v_{s\beta}}. \tag{4}$$

Under non-sinusoidal and/or unbalanced conditions the equation (2) can be decomposed in average and oscillatory terms as follows:

$$\begin{bmatrix} \bar{p}_l \\ \bar{q}_l \end{bmatrix} + \begin{bmatrix} \tilde{p}_l \\ \tilde{q}_l \end{bmatrix} = \left(\bar{v}_{sd} + \tilde{v}_{sd}\right)\left(\begin{bmatrix} \bar{i}_{ld} \\ \bar{i}_{lq} \end{bmatrix} + \begin{bmatrix} \tilde{i}_{ld} \\ \tilde{i}_{lq} \end{bmatrix}\right), \tag{5}$$

where $\bar{v}_{dq}$ and $\tilde{v}_{dq}$ are the average and the oscillatory terms of the power grid voltage and, $\bar{i}_{ldq}$ and $\tilde{i}_{ldq}$ are the average and the oscillatory terms of the load current.

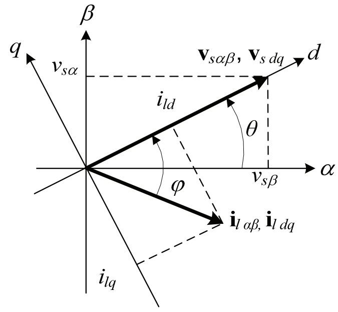

Fig. 2. Load current and grid voltage phasors in Clark's and Park's reference frames

In accordance with the "*p-q*" theory, the instantaneous active power describes the energy flow in the system from source to load and its average value corresponds to active power in classical interpretation, while the average value of instantaneous reactive power corresponds to the reactive power in classical interpretation. The average terms of the grid voltage and load current represent the first harmonic components of positive sequence, but the oscillatory terms represent the harmonic voltages (currents) as well as the unbalanced condition of the grid.

In order to compensate the displacement power factor of the load under consideration, the STATCOM converter must ensure the total average reactive power to be zero. Provided that the grid voltage is balanced and the harmonic distortion, if present, is eliminated in the grid voltage measurement signal, the compensation according to (4) can be achieved by generating compensation current along *q* axis, which is equal to the average load reactive current component $\bar{i}_{lq}$.

Fig. 3 demonstrates the configuration of the developed STATCOM control system consisting of two regulating loops - control loop of the DC link voltage and control loop of the VSI current.

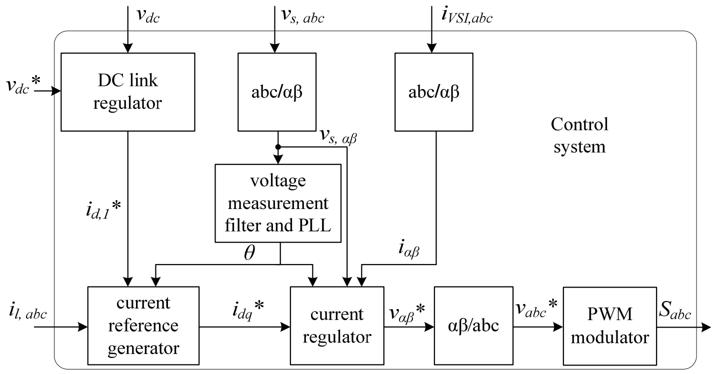

Fig. 3. The block scheme of the control system

The task of the two control loops is to perform regulation of the VSI current as well as the DC link voltage v_{dc} in order to keep it constant and higher than the amplitude of the grid line voltage, if the inverter is to be able to generate the desired compensation current.

The DC link voltage control loop (Fig. 4) compensates the active losses of the VSI and maintains a suitable level of the DC voltage. This loop contains an anti-windup PI regulator with the error of DC link voltage regulation at the input, but the output signal i_d is supplied to the current reference generator, where it contributes to the compensation current along *d* axis regulating the active power of the STATCOM.

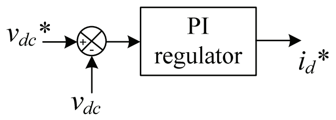

Fig. 4. PI Controller for voltage loop

The input of the reference generator, in accordance with the scheme given in Fig. 5., is the load current measurement signal $i_{l,abc}$ and output signal of the DC link voltage control loop i_d*.

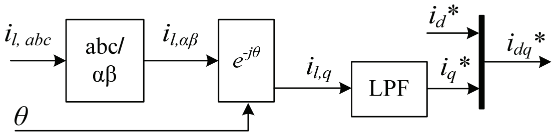

Fig. 5. Current reference generator

The reference current contains fundamental harmonic components in dq axes for the control of the DC voltage and compensation of the displacement power factor of the load. The reference is found from the load current measurements filtering out the oscillating terms in the synchronous dq reference frame with a LPF filter.

The current regulator (Fig. 6) contains a second PI regulator with feed-forward of filtered grid voltage measurement in dq reference frame, which controls the current of the STATCOM according to the given reference, performing regulation of the fundamental component of the current reference in dq reference frame. The output is transferred to αβ reference frame by inverse Park's transformation.

The extraction of a correct current reference as well as the operation of the whole control system of the STATCOM converter is strongly dependant on a precise estimation of the phase of the fundamental positive sequence phasor θ of the grid voltage. The harmonic distortion, if present in the grid voltage, affects the whole current control loop, because the phase signal used for the Park's reference frame transformations is distorted. A phase-locked-loop (PLL) system described in [7] is used here for a smooth estimation of the position of the grid voltage phasor containing simple software PLL applied to the fundamental component of the grid voltage measurement.

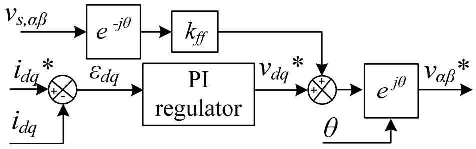

Fig. 6. Current regulator for the current loop

Simulation results of the STATCOM System

In order to investigate the developed STATCOM system a computer model in MATLAB/SIMULINK environment has been elaborated (Fig. 7). The control system described above is realized by means of C language embedded systems function, having several advantages – this approach allows applying the same control code for the simulation and experimental investigations using MATLAB RTI. Triggering of the control system is realized synchronously with PWM triangle-form carrier signal „Carrier".

In the power system model (Fig. 8) the VSI of the STATCOM is connected in parallel with two identical 3-phase active-inductive loads (P=10kW, Q=3kVAr) - one of the loads is enabled after a time delay of 500ms (signal "full_load" is activated) to simulate a dynamic change in load power.

Simulation results in Fig. 9 illustrate the operation of the control system during the whole simulation time ($t = 0$ ... 0,8s). At the instant $t_1 = 50ms$ the soft start of the VSI DC-link capacitor is finished. At the instant $t_2 = 60ms$ the execution of the control algorithm starts – the sequence of the supply voltage is detected and after two mains cycles PLL starts its operation, determining the phase of the supply voltage vector. After one more mains cycle the operation of PLL is stabilized and PWM control is actuated, which charges the DC-link up to the reference voltage ($v_{dc}^* = 700V$). At time instant $t_3 = 300ms$ the compensation of the load reactive power is started.

The simulation results of active and reactive power of phase a of the STATCOM system show that until around 100ms while the control of the STATCOM is not operational yet, the active power of one phase is around 3.3 kW and the reactive power 1 kVAr in stationary mode, but after the control system fully operates, DC link voltage increases till 700V (reference voltage) and the reactive power is compensated approximately to zero. After 500ms when the second load is enabled, the active power increases twice, but the reactive power is still kept to zero.

Fig. 10 demonstrates the operation of the current regulator in steady-state mode - the regulation error hardly exceeds ± 1A even under distorted grid voltage (7% 5th and 5% 7th harmonic components are introduced in the grid voltage which results in THD of around 8% as illustrated in Fig. 11).

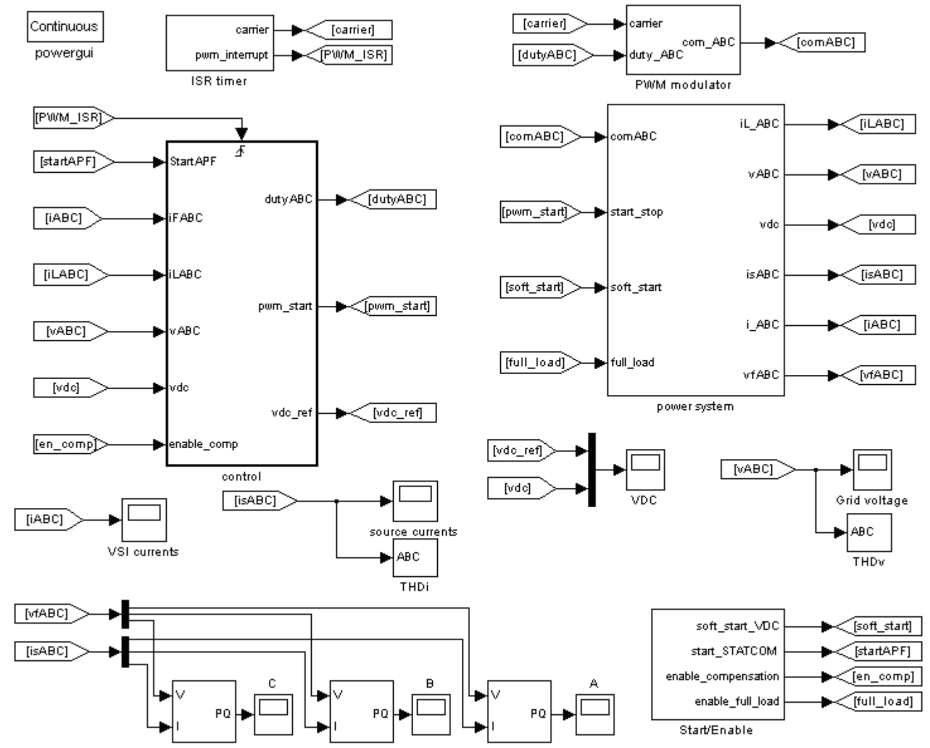

Fig. 7. MATLAB/SIMULINK model of the STATCOM system

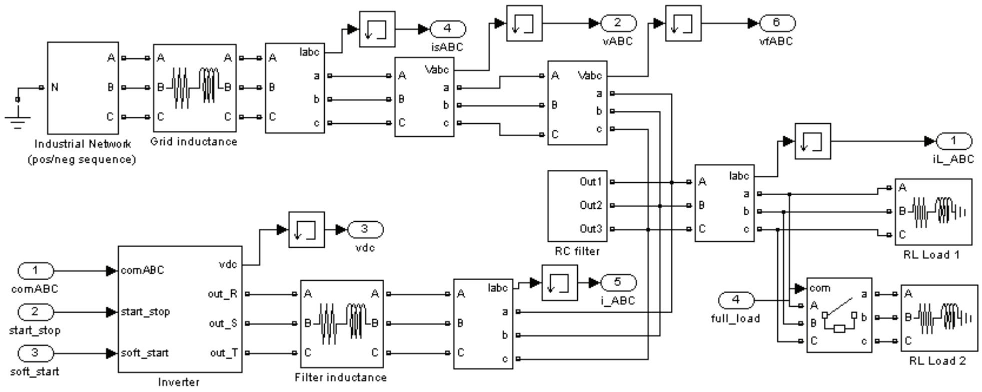

Fig. 8. MATALAB/SIMULINK model of the STATCOM power system

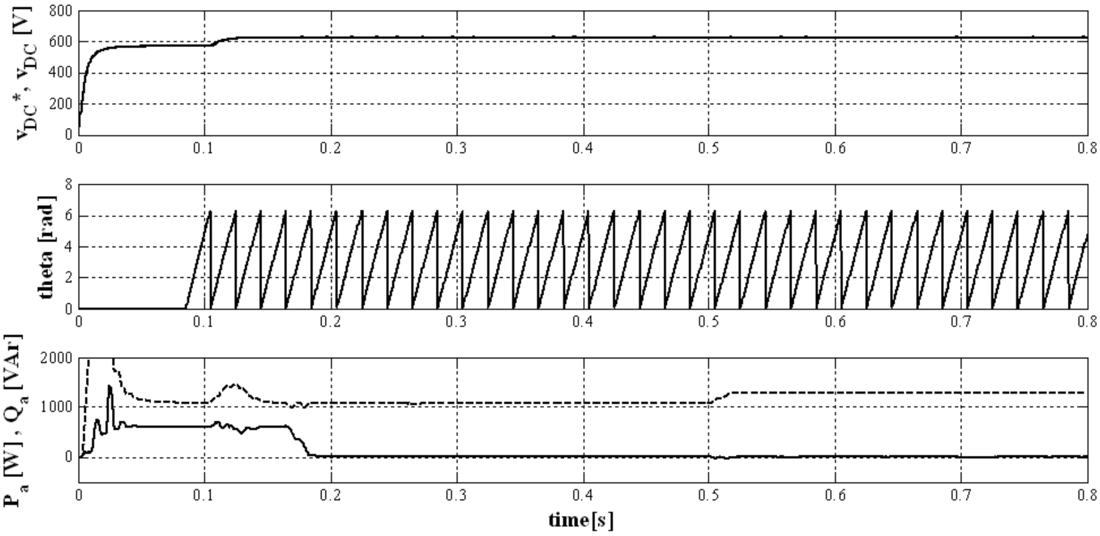

Fig. 9. Simulation results of the STATCOM system: DC-link voltage reference v_{DC}*and actual value v_{DC}; instantaneous phase angle θ of the grid voltage; active power P (dashed) and reactive power Q (solid) of phase A

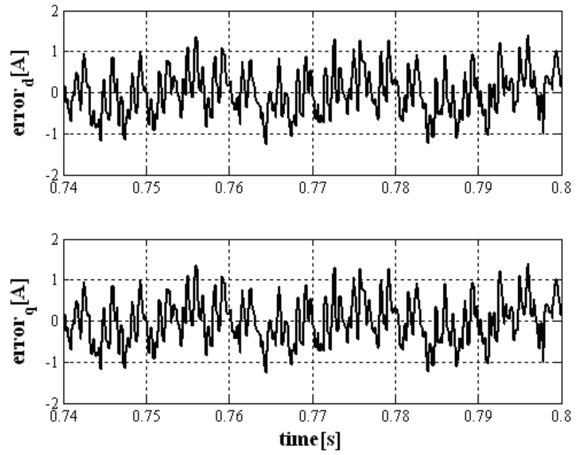

Fig. 10. Simulation results of the STATCOM power system: current regulation error in dq axes

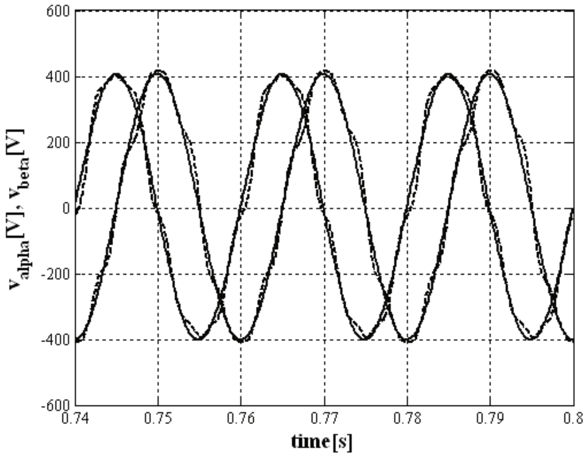

Fig. 11. Simulation results of the STATCOM system: dashed - grid voltage in αβ axes; solid – filtered grid voltage in αβ axes

Experimental testing of the STATCOM System

Experimental verification of the proposed STATCOM control scheme was carried out as well. The same C language embedded control code was used as in simulation. As an interface between SIMULINK environment and DSPACE platform which performs the generation of the command signals for the inverter transistor drivers and acquisition of the process variable measurement signals serve the MATLAB RTI (Real Time Interface) libraries. The libraries perform the compiling of the control program into machine code and loading it into the master processor of the DSPACE platform.

Experimental results are shown on Fig. 12. to Fig. 15. The measurements were carried out using Fluke 435 power quality analyzer with 0.5sec recording step. In order to obtain distorted supply voltage conditions, a 25kVA supply transformer loaded with 10kVA non-linear load was utilized, resulting in considerable supply voltage distortion (7,5% THD – see Fig. 12.).

Fig.13. illustrates the active, reactive, and full three-phase power of system during the whole experiment. At instant around 30 s a three phase RL load is turned on (S = 3,6kVA, P = 3,1kW and Q = 2kVAr) and short before 60s the compensation of the displacement power factor is enabled staying on until approximately 110s. At around 80s a dynamic change in load power is introduced by turning on a second RL load (according to the topology shown in Fig. 8) producing total three-phase full power S = 5,3kVA, active power P = 3,5kW and Q = 4kVAr.

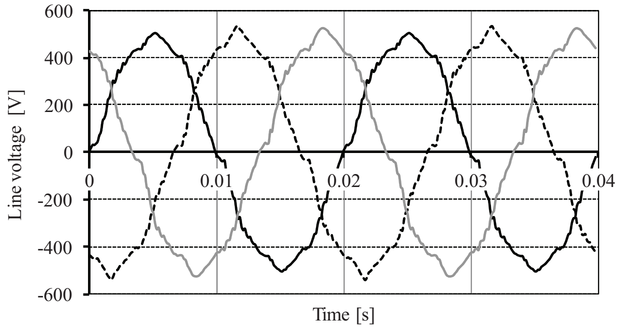

Fig. 12. Experimental results: Waveforms of line voltages under distorted conditions

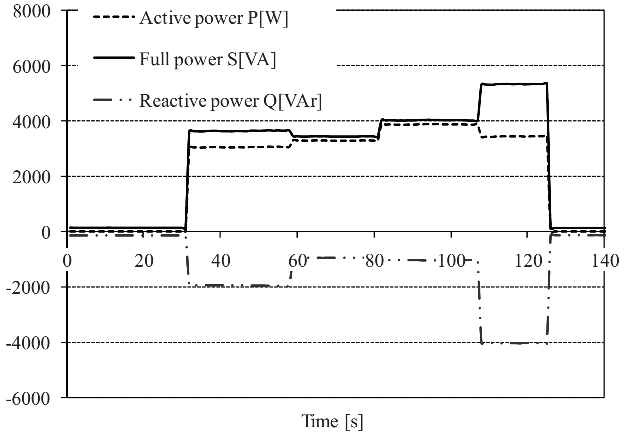

Fig. 13. Experimental results: active, reactive and full power of the STATCOM system

Fig. 14 illustrates the total power factor of the system during the whole experiment. As can be seen, the power factor, which is composed of displacement and distortion power factors, during compensation is stable (PF = 0,97) even after a dynamic change in load power is introduced at 80s.

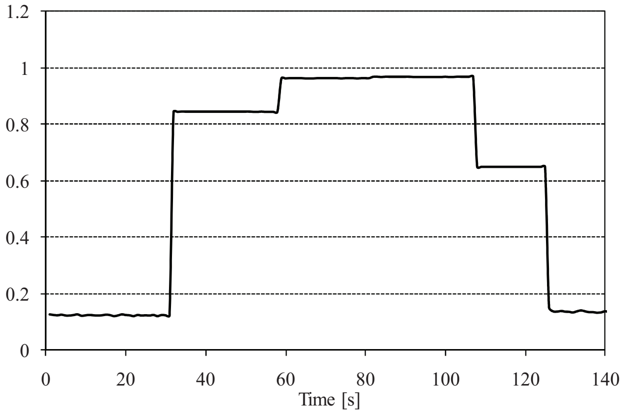

Fig. 14. Experimental results: total power factor of the STATCOM system

Fig. 15 shows the RMS value of load line current during the whole experiment.

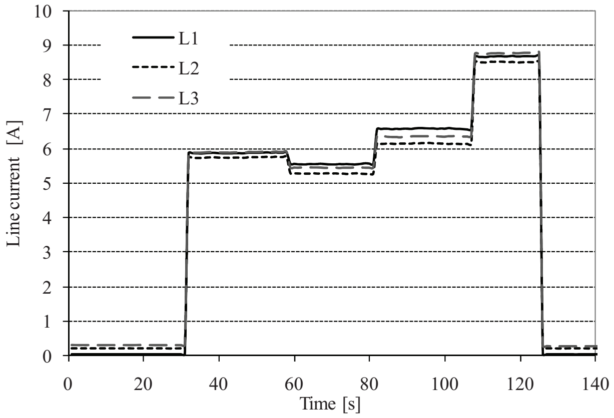

Fig. 15. Experimental results: RMS value of line currents

Conclusions

STATCOM system can be used for reactive power compensation and power factor correction in the industrial network grid and under distorted mains voltage conditions, it is more reliable than shunt capacitor reactive power compensator. Both the shunt capacitors and STATCOM increase the static voltage stability margin and power transfer capability, however STATCOM provides better performance in terms of dynamic load changes, grid voltage fluctuations and harmonic distortion. The STACOMs are relatively expensive, but taking into account that under distorted mains voltage conditions separate filter inductors have to be installed in series with each shunt capacitor battery, to ensure its rated current is not exceeded, the implementation of STATCOM systems is justified.

The simulation and experimental results of the developed STATCOM system presented in the paper indicate that the developed STATCOM control system performs well – DC-link regulation is very smooth, current loop regulation error is relatively small too and the power factor correction exhibits good transient and steady state performance. The results indicate, that developed STATCOM converter can provide dynamically stable load displacement power factor correction even under significally distorted (THD = 7,5%) grid voltage conditions.

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A STATCOM system is presented in this paper applied for compensation of displacement power factor under distorted mains voltage conditions. The developed STATCOM control system consists of two regulating loops - DC link voltage control loop with anti-windup PI controller and the current control loop with a feed-forward PI controller. The simulation results indicate that the developed control system performs well, ensuring displacement power factor compensation with good transient and steady state performance even under significantly distorted grid voltage conditions. Ill. 15, bibl. 8 (in English; abstracts in English and Lithuanian).

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Aprašoma statinių sinchroninių kompensatorių (STATCOM) sistema, skirta galios korekcijai, kai maitinimo įtampa yra nestabili. Sukurta STATCOM valdymo sistema sudaryta iš dviejų reguliavimo grandinių. Sumodeliavus siūlomą sistemą nustatyta, kad tokia valdymo sistema veikia gerai ir užtikrina poslinkio galios koeficiento kompensaciją ir esant dideliems maitinimo įtampos svyravimams. Il. 15, bibl. 8 (anglų kalba; santraukos anglų ir lietuvių k.).