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POWER CONDITIONING SYSTEM WITH SMES – A WAY TO PROVIDE HIGH POWER QUALITY

Summary. Power quality is nowadays one of the most important issue in energy conversion and power distribution systems. Industry processes especially controlled by power electronics elements and devices are in one hand sources of reactive power and higher current harmonics in other hand need ensure continuity of supplying voltage. Power conditioning system (PCS) with superconducting magnetic energy system (SMES) is one of possible way to ensure high power quality. Description of whole system, possible operation conditions and applications are described in the paper. Proper designing of PCS is provided by simulation and experimental results presented in the paper.

KONDYCJONER MOCY Z CEWKĄ NADPRZEWODZĄCĄ – SPOSÓB POPRAWY JAKOŚCI ENERGII ELEKTRYCZNEJ

Streszczenie. Jakość energii elektrycznej jest jednym z najważniejszych zagadnień analizowanych współcześnie w procesie produkcji i dystrybucji energii elektrycznej. Procesy przemysłowe, szczególnie sterowane przez układy energoelektroniczne, pogarszają parametry jakości energii elektrycznej poprzez generację mocy biernej i wyższe harmoniczne w prądach sieciowych. Z drugiej strony – wymagają one zapewnienia pewności i ciągłości zasilania, gdyż nawet krótkie przerwy w zasilaniu mogą spowodować znaczne straty finansowe. Jednym z rozwiązań pozwalających na poprawę jakości energii elektrycznej jest zastosowanie układu kondycjonera mocy (PCS – power conditioning system) z zasobnikiem energii w postaci cewki nadprzewodzącej (SMES - superconducting magnetic energy storage). W artykule opisano układ proponowanego kondycjonera mocy oraz omówiono możliwe warunki pracy i zastosowania. Przedstawione w artykule wybrane wyniki badań symulacyjnych i eksperymentalnych potwierdzają poprawność działania zaprojektowanego układu kondycjonera mocy.

1. INTRODUCTION

In recent years the amount of nonlinear loads connected to the mains is still increasing. These loads – i.e. thyristor bridge rectifiers have to be supplied not only with active but also with reactive power and generate higher harmonics in the power system. A reactive power decreases a total power which can be delivered from the mains and high harmonics can cause improper operation of power systems elements (i.e. transformers). On the other hand electrical equipment has much higher requirements about continuous of supplying than in the past. Some of industry processes especially controlled by computers and microcontrollers are very sensitive for every voltage sags or dips and short innteruptions in supplying. This increases costs of production. Additionally some power loads have pulsating character, which means that the power of them is changing rapidly in time in normal operation condition. These changes can cause flickering effects that can be very annoying for personnel or even cause power system instabilities for very high power loads.

Described above parameters like high current harmonics, voltage dips or flickering effects characterises power quality. There is no power quality definition but there exists European standards about limits of parameters describing power quality [1]. Power quality can be analysed from two points of view. On one hand power quality can be analysed as an influence of industry process (group of loads) on the mains (power system). On the other hand power quality can be analysed as an influence of power system on load - possibility of ensures voltage continuity and supplying reliability. Good power quality in both aspects can be provided separately or simultaneously by different power electronic systems:

- APF - active power filters [2],
- FACTS, STATCOM [3],
- UPS - uninterruptible power supplies [4],
- PCS with SMES [5-10].

Power conditioning systems are power electronic systems connecting DC energy storage like SMES to the mains. They are mainly used to ensure continuity of supplying voltage for separated group of relatively high power loads in voltage sag condition for short period of time or for power system stabilisation [10]. In opposition to uninterruptible power supplies that are solution for low power loads for time longer than 1 minute the PCS with SMES can supply high power loads only for short period of time (for example hundred of kW to a few of MW for time shorted than few seconds). Analyses of disturbances in the mains provide that short interrupts in supplying voltage are most common.

Proposed Power Conditioning System can be used to increase power quality in different operation conditions. Main task for it is prevention from short time supplying interrupts coming from the mains for selected group of loads. Second task is prevention the mains from influences of pulsating load for example start of induction motors. Third task is reactive power compensation and current high harmonics compensation. For task one and two – energy stored in SMES is used to supply load. For third task no stored energy is needed.

Motivation for interesting in the Power Conditioning System with SMES has been possibility of performing system, which ensures good power quality. The main goal of the paper is description of main parts of the PCS with SMES, its control system and operation in different conditions. Simulations and experimental results confirm proper perform of the PCS.

2. POWER CONDITIONING SYSTEM - DESCRIPTION

Presented model of Power Conditioning System with SMES is result of a project HIPOLITY financed by European Program CRAFT. In the project three SME (small/medium enterprise) and two RTD (research and technical development) providers has been involved. The consortium embraces SME's from Germany, the Netherland and Poland. The research works has been carried out by RTD's from the Netherlands and Poland. Fig. 1 shows scheme of power system including power conditioning system PCS. It consists of superconducting magnetic energy storage (SMES), power electronic converter (PEC), input filter (F) and static input switches (S).

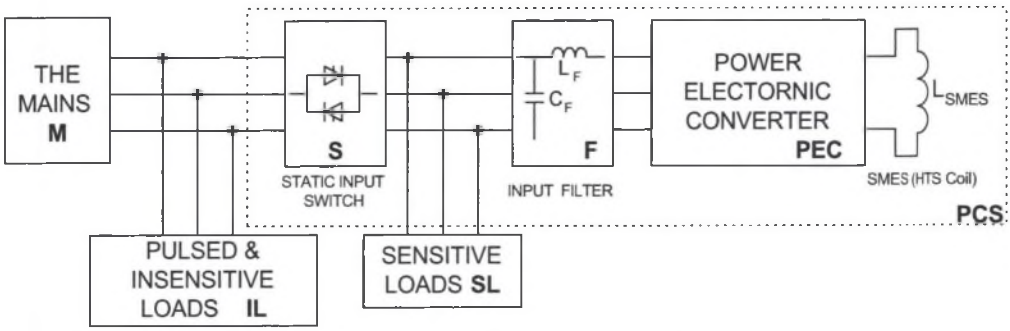

Fig. 1. Power system including power conditioning system with SMES
Rys. 1. System zasilania odbiorników zawierający kondycjoner mocy z cewką nadprzewodzącą

PEC is bidirectional power electronic converter that connects superconducting magnetic energy storage (SMES) to the mains M. In the project as a SMES a High Temperature Superconducting (HTS) coil is used. Input filter is used to form the input current of PCS (it limits amplitude of current distortion connected with PEC switching frequency). Static input switch S is used to disconnect sensitive loads S-L from the mains M if voltage sag occures in the mains. In this condition sensitive loads S-L are supplied exclusively by the PCS. For proper operation as a reactive power compensator the PCS needs current signals from group of insensitive loads that supplying can be interrupted.

Nominal parameters of model of PCS and SMES:

- nominal voltage $U_N = 400$ V,
- nominal power $S_N = 20$ kVA,
- SMES energy $E_C = 25$ kJ (laboratory model of SMES),
- SMES inductance $L_{SMES} = 12{,}5$ H,
- SMES critical current $I_C = 70$ A,
- DC nominal voltage $V_{DC} = 750$ V,
- DC capacitor $C_{DC} = 4{,}8$ mF,
- AC/DC inverter switching frequency $f_{S1} = 3$ kHz,
- DC/DC converter switching frequency $f_{S2} = 50$ Hz.

2.1. Superconducting magnetic energy storage (SMES)

In the project a High Temperature Superconducting (HTS) Coil is used as a laboratory model of Superconducting Magnetic Energy Storage (SMES). HTS technology is quite new technology for Superconductors because normally a Low Temperature Superconductor (LTS) is used in power conditioning systems. In HTS technology the coil is dipped in liquid helium and normal operation temperature is 20 K. Additionally in HTS realisation of superconducting coil it is no need of protection from superconducting state because of long time constance(about minutes). For protection only temperature sensors has been used. SMES technology as an energy storage has been chosen because of its high dynamic and infinitely amount of charge/discharge cycles that seems to be the best solution for supplying high power loads for short period of time.

HTS coil is build as a serial connection of 17 double pancakes winding. The coil is inserted in criostat that cooling of its inner space by performed criocooler.

2.2. Power electronic converter (PEC)

Power electronic converter (PEC) is shown in fig. 2. It consists of input AC/DC inverter with structure similar to classical voltage inverters and output DC/DC converter. For proper operation of the PCS control of at least 8 IGBT transistors is required.

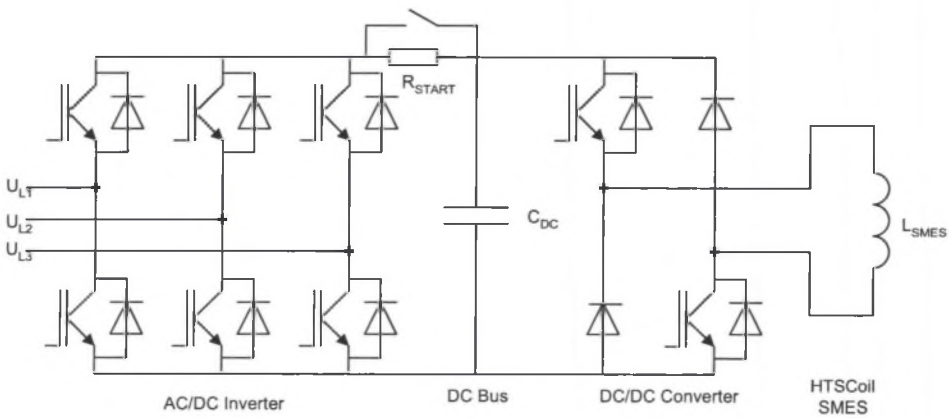

Fig. 2. Power electronic part of PCS
Rys. 2. Obwody energoelektroniczne kondycjonera mocy

Both converters enable bidirectional energy flow. EUPEC 1200V, 450 A IGBT transistors have been used in model of the PCS. The switching frequency of AC/DC inverter is constant and is equal to 3 kHz. Switching frequency of DC/DC converter is equal 50 Hz that is connected with limitation of AC losses in HTS coil.

Because of relatively low switching frequency the efficiency of PEC is about 80-90 percent. There exists problem with definition of efficiency because energy storage is used only in fault conditions and if no fault occurs the efficiency will decreaces. Authors of the paper are proposing definition of efficiency connected with constant power charging and discharging process of Superconducting Coil.

$$\eta = \frac{T_{DISCHARGE}}{T_{CHARGE}} \tag{1}$$

where:

T_{CHARGE} – constant power charge time from minimal energy (connected with constant power) to nominal energy stored in the Superconducting Coil,

T_{CHARGE} – constant power discharge time from nominal to minimal energy stored in the Superconducting Coil.

2.3. Control system and measurements

For proper operation of Power Conditioning System at least 10 signal are required to be measure in control system: two line to line the mains voltages, two line to line load voltages, two inverter currents, two load currents, capacitor voltage and coil current. If loads are divided in sensitive and insensitive loads additional two current signals are required. System with control strategy that is changing in different operation condition has been chosen as a controller. The control system, CS, with measuring sensors is depicted in fig. 3.

Three main task are realised in control system:

- faults detection base on monitoring of the mains voltages and loads currents - operation condition and control strategy in controller depends of detected faults,
- controlling the AC/DC inverter,
- controlling the DC/DC converter.

Control strategy in different operation condition is described in next chapter. Controller is realised on 16-bit DSP microcontroller TMS320F2812 that is very fast and has enough peripherals to control both converters and measure all required signals [11].

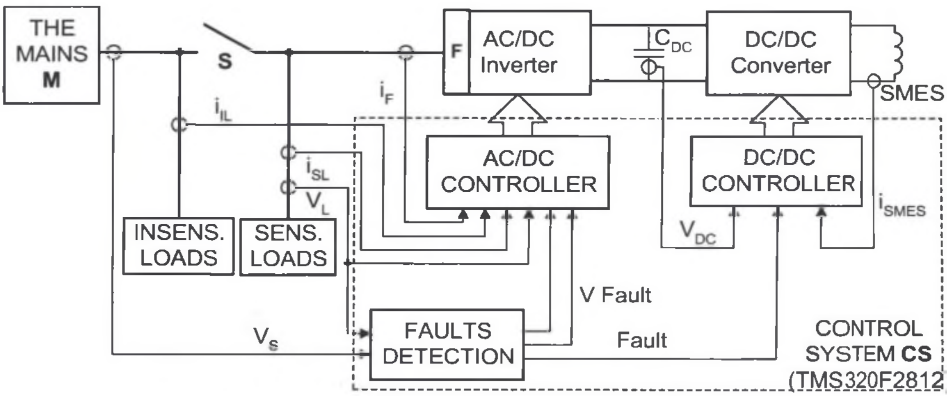

Fig. 3. Control system of Power Conditioning System
Rys. 3. Schemat układu sterowania kondycjonera mocy

3. OPERATION CONDITIONS

Proposed power conditioning system with SMES can operate in three possible operation conditions:

- The Compensation Condition (CC). In this condition the PCS operates like an Active Power Filter – energy stored in HTS coil is not used. AC/DC Inverter compensates the reactive power of the loads, reduces harmonics and ensures symmetrical currents in the mains if loads are asymmetrical. DC/DC Converter controls the HTS coil current and compensates energy losses in the HTS coil.
- The Load Overcurrent Condition (LOC). This condition is connected with pulsating loads. If sensitive and/or insensitive loads current changes to value higher than required the PCS will limit amplitude of the mains current to required value. In this condition power to the load is delivered from the mains and from the HTS coil. DC/DC Converter controls DC capacitor voltage and AC/DC Converter injects energy into the load and limits current of the mains. If overcurrent decays finish PCS will change operation condition to Compensation Condition.

- The Voltage Sag Condition (VSC). This condition will be detected if the voltage sag occurs in any phase. Then the sensitive loads will be disconnected from the mains (by static input switch, S - fig.1) and the PCS will work like an Uninterruptible Power Supply (UPS). In this condition at the expence of energy stored in SMES a sinusoidal load voltage is generated. DC/DC Converter controls DC capacitor voltage C_{DC} and AC/DC Converter injects energy into the load and controls the load voltage.

Operation of proposed PCS with SMES in different operation condition is presented in next chapters.

4. SIMULATION RESULTS

The simulation of model of the PCS with SMES has been done in the Matlab-Simulink with use Power System Blockset Toolbox. A simulation has been performed taking into account assumptions about switching frequencies of both converters, delays in realisation of control system, etc. Selected simulation results are presented in this chapter.

Fig. 4 shows operation of PCS in Compensation Condition. A load in each phase is serial connection of different value of resistor and inductor that generates asymmetrical currents.

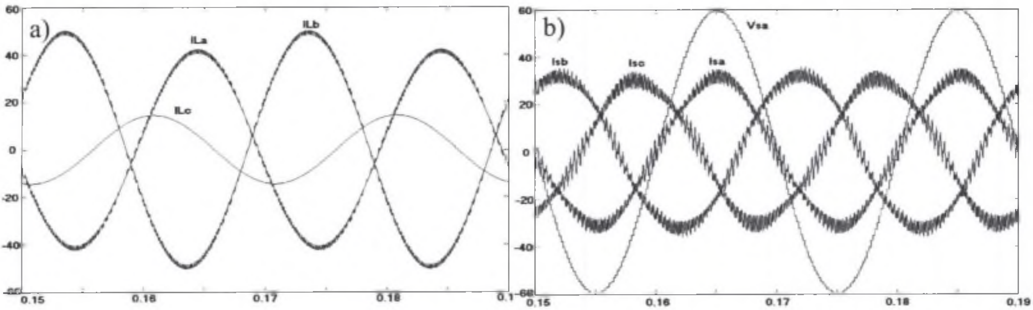

Fig. 4. Operation of PCS with asymmetrical RL load: a) phase load currents; b) the mains phase voltage and the mains phase currents

Rys. 4. Praca kondycjonera mocy, PCS, w przypadku niesymetrycznego obciążenia RL: a) prądy fazowe obciążenia; b) napięcie i prąd fazowy sieci zasilającej

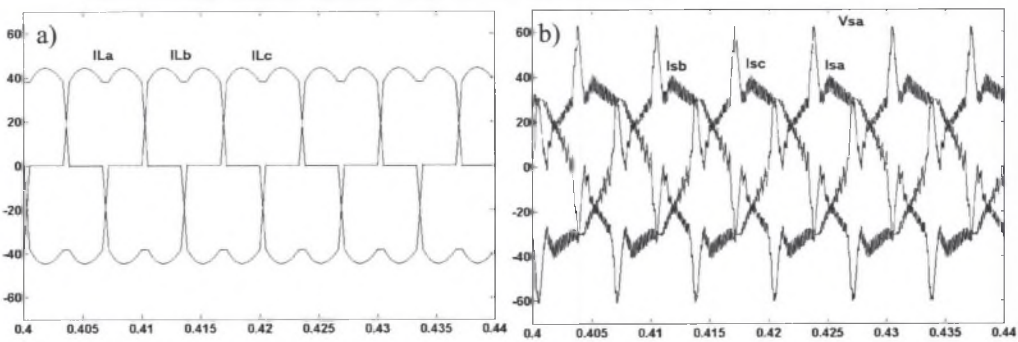

Fig. 5. Operation of PCS with nonlinear load: a) phase load currents; b) the mains phase voltage and phase currents

Rys. 5. Praca kondycjonera mocy, PCS, w przypadku obciążenia nieliniowego: a) prądy fazowe obciążenia; b) napięcie i prąd fazowy sieci zasilającej

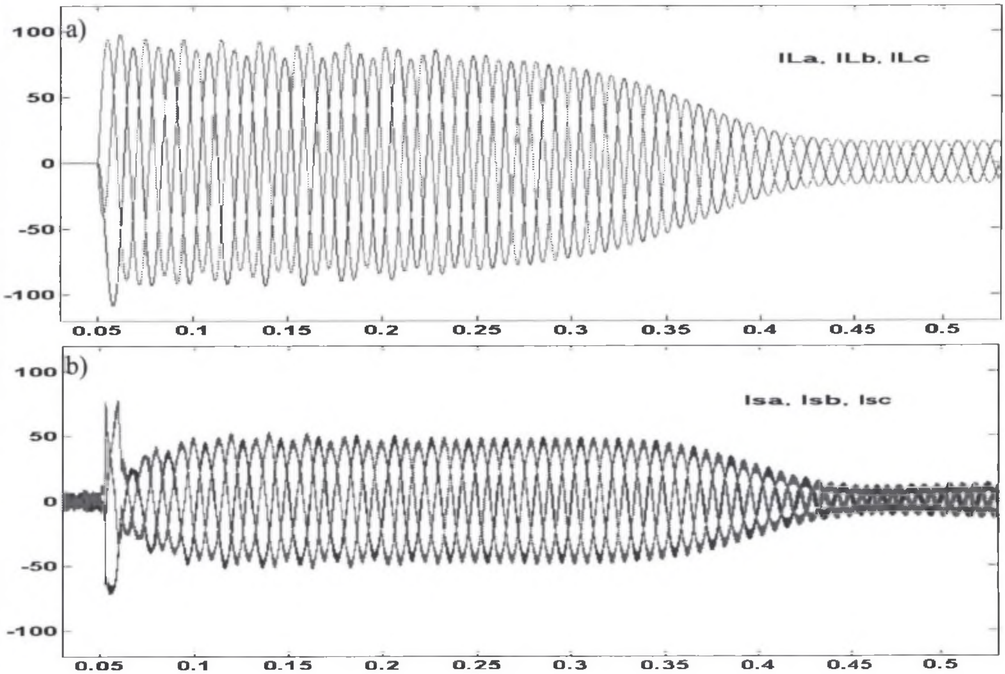

Fig. 6. Start of asynchronous motor - overcurrent condition: a) load currents; b) the mains currents
Rys. 6. Rozruch silnika asynchronicznego - warunek przeciążenia prądowego: a) prądy fazowe obciążenia; b) prądy fazowe sieci zasilającej

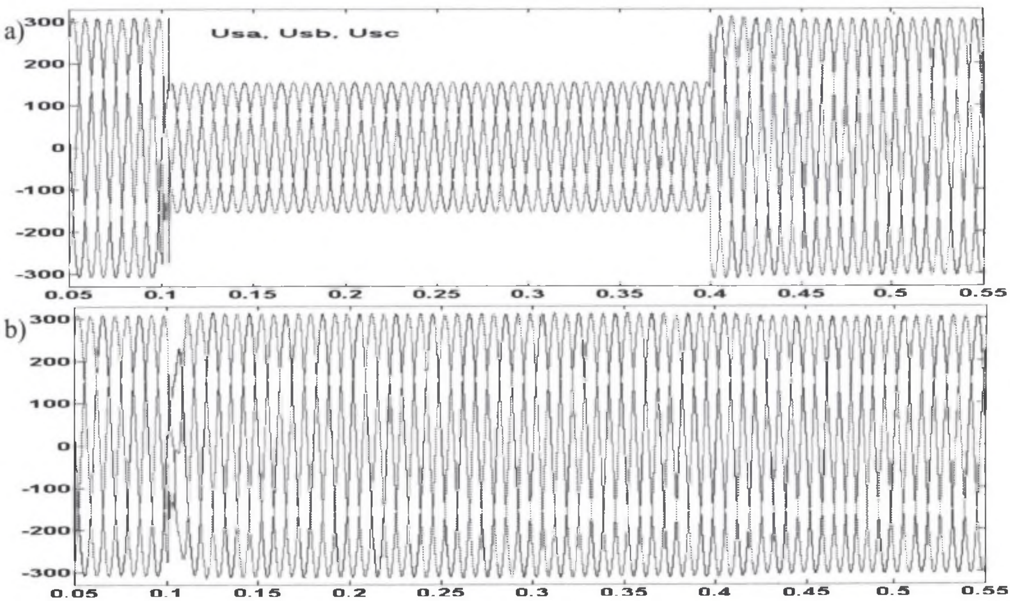

Fig. 7. Three phase voltage sag - voltage sag condition: a) the mains voltage; b) load voltages
Rys. 7. Trójfazowy zapad napięcia - warunek zapadu: a) napięcia sieci zasilającej; b) napięcia na zaciskach obciążenia

Although asymmetrical load currents (fig. 4a) the PCS can ensure symmetrical sinusoidal currents in the mains with no phase shift between phase voltage and current (fig. 4b). This provides that from the mains side only an active power is delivered. Current distortions are caused by relatively low switching frequency of the transistors.

Fig. 5 illustrates the operation of the PCS when it is works as current harmonics compensator with thyristor bridge rectifier with fire angle α = 30 as a nonlinear load. Line currents in this situation are quasi-sinusoidal but there exists relatively high distortion connected with rapid change of load current. This distortion is caused by relatively low dynamics of PCS limited by switching frequency and input inductors. Distortion can be decreased by higher switching frequency but this increase loses in transistors.

Operation of PCS in overcurrent condition is shown in fig. 6. If active component of load current is higher than required value (fig. 6a) the PCS uses energy stored in HTS coil to limit the mains currents to required value (fig. 6b).

The last case illustrates the PCS behaviours when voltage sag occurs. The connection between the load and the mains is broken (switch S is off) and PCS supplies sensitive load S-L and ensures sinusoidal load voltages (fig. 7). After the end of voltage sag the load is resynchronised with the mains (It needs resynchronisation afterwards).

5. EXPERIMENTAL RESULTS

Since the objective of the project (HIPOLITY) is the real laboratory system (at the first step). It has been designed and commissioned and then tested and measured. Selected experimental results are presented in fig. 8 - 10.

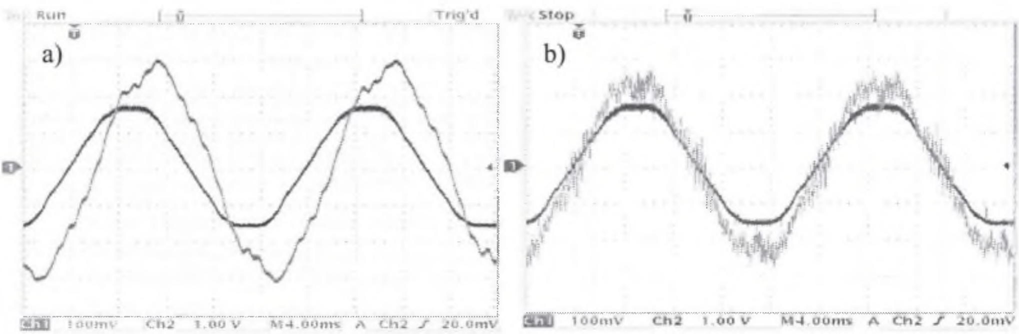

Fig. 8. Reactive power compensation of asynchronous motor: a) the mains voltage and load current (without PCS); b) the mains voltage and current (with PCS)

Rys. 8. Kompensacja mocy biernej przy obciążeniu silnikiem indukcyjnym: a) napięcie sieci zasilającej i prąd obciążenia (przed kompensacją); b) napięcie sieci zasilającej i prąd sieci zasilającej (po kompensacji)

In fig. 8 and 9 the operation of laboratory model of the PCS as a reactive power compensator and active power filter is illustrated. The loads are asynchronous motor (fig. 8) and parallel connection of asynchronous motor and thyristor bridge rectifier. It can be seen that operation of the PCS is provided and distortion in the mains current, connected with rapid load current, change decrease if active component of load current increases.

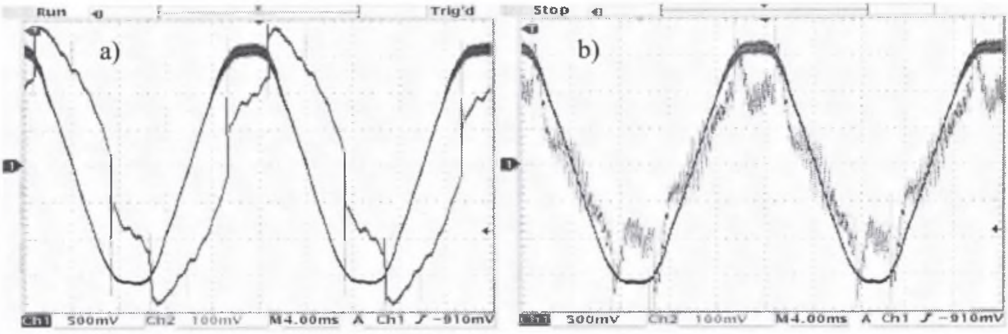

Fig. 9. Reactive power and high harmonics compensation: a) the mains voltage and load current (without PCS); b) the mains voltage and current (with PCS)

Rys. 9. Kompensacja mocy biernej i wyższych harmonicznych w prądzie: a) napięcie sieci zasilającej i prąd obciążenia (przed kompensacją); b) napięcie i prąd sieci zasilającej (po kompensacji)

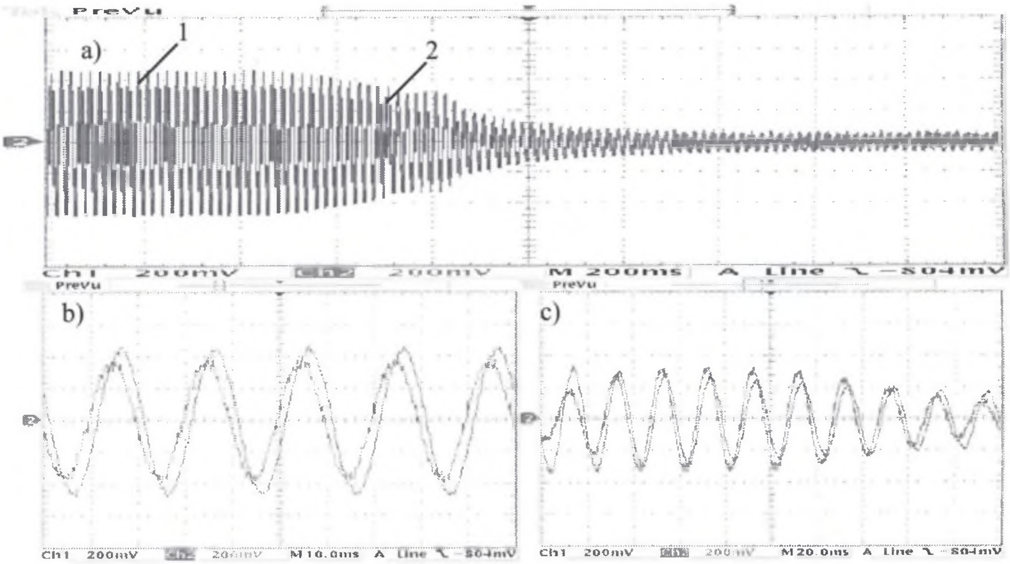

Fig. 10. Overloaded asynchronous motor - overcurrent condition: a) the mains and load currents; b) zoom at point 1; c) zoom at point 2

Rys. 10. Przeciążony silnik indukcyjny - warunek przeciążenia prądowego: a) prąd obciążenia i sieci zasilającej ; b) powiększenie w punkcie 1; c) powiększenie w punkcie 2

Fig. 10 depicts the mains current limitation in situation when asynchronous motor is overloaded. In this situation PCS – supplies load with additional power and thanks to that the mains currents are limited to require value (fig. 10b). After the overcurrent is ceased the PCS automatically changes its control strategy, recharges HTS coil and operates as a compensator.

6. CONCLUSIONS

The paper presents the Power Conditioning System (PCS) with SMES. It has been proved that the PCS ensures good power quality. The control strategy that is of variable structure performs operation due to actual conditions. The PSC with SMES decreases negative influence of different loads on the mains and also prevents these loads from voltage sags and short supply interruption coming from the mains. Presented results of experimental research confirm possibility to control both converters inside the PCS system via only one DSP processor.

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