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The use of p-q control in single-phase active power filter for dynamic reactive power compensation

***Abstract**. The subject of the discussion is the use of single-phase active filter for compensating dynamic changes of reactive power which may occur in office buildings. This circuit consumes reactive power with high dynamic changes at the level of minutes or seconds and fractions of seconds, making it impossible to efficiently compensate reactive power with standard capacitors-based compensators. Modified p-q algorithm was used to control single-phase active power filter. The considerations were supported by simulations carried out in MATLAB-Simulink environment.*

***Streszczenie.** Przedmiotem rozważań jest zastosowanie 1-fazowego filtru aktywnego do kompensacji dynamicznych zmian mocy biernej jakie mogą wystąpić w przypadku odbiorów w budynkach biurowych. Do sterowania 1-fazowym filtrem aktywnym zostanie wykorzystany algorytm p-q. Rozważania zostały parte symulacjami przeprowadzonymi w środowisku MATLAB-Simulink. (**Zastosowanie sterowania p-q w 1-fazowym energetycznym filtrze aktywnym do dynamicznej kompensacji mocy biernej**).*

Keywords: single-phase active power filter, extension p-q theorem, dynamic reactive power compensation, power factor correction.
Słowa kluczowe: 1-fazowy energetyczny filtr aktywny, teoria mocy p-q, dynamiczna kompensacja mocy biernej, korekcja współczynnika mocy

Introduction

Costs resulting from the poor power quality on a global basis can be substantial [4]. Therefore measurements and identification of problems associated with power quality has become increasingly important. These problems depend on the type of the used loads. Different events will occur in heavy industry and different in housing estates or office buildings. From the point of view of the consumer, those parameters are important which may cause generation of additional costs in form of penalties. This is, for example, reactive power for which the relevant provisions in contracts with electricity provider are applied [6]. There are additional charges for inductive and capacitive reactive power consumption.

The paper presents an analysis of reactive power variation on the basis of the measurements in a system composed mainly of office computers [2], carried out in one of the buildings of Faculty of Electrical Engineering of the Silesian University of Technology.

The obtained measurement results were used to develop a simulation model of single-phase active power filter (APF) intended to compensate dynamic changes of reactive power. The model of APF was simulated in Matlab-Simulink. For control algorithm the modified p-q method has been used. As part of the simulation study reactive power compensation for a sample of variability reactive power load was carried out.

Characteristic of reactive power variation of loads in office buildings

Electrical loads in buildings such as offices are mainly computers, printers and small electronic equipment but also UPS devices, servers, air conditioning and ventilation equipment. All of these devices can cause problems with the power quality. Significant here is the large variability of consumed active and reactive power and harmonic generating in currents. Admittedly most of them are low-power devices but they may be hundreds or even thousands of them in one place.

Specific for office buildings is also load distribution during the week. Figure 1 shows the total power P_{tot} (10 minutes average) for the analyzed building in a period of one week. As shown the load reaches a maximum value during the day but decreases and has a constant value during the night.

In the case of reactive power one can highlight two specific aspects of the analyzed network. The first one is the character of reactive power consumed per day. Loads in office buildings during the day consume inductive reactive power. At night, while the majority of office equipment is in standby state they consume capacitive reactive power. Because the capacitive reactive power imposed fees are charged independently of the active power these values can be significant [9]. Figure 2 shows the average reactive power Q_{tot} in a period of one week.

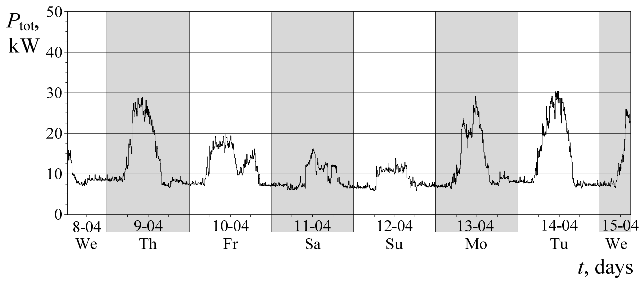

Fig. 1. Average total active power for the measured building in 1 week period

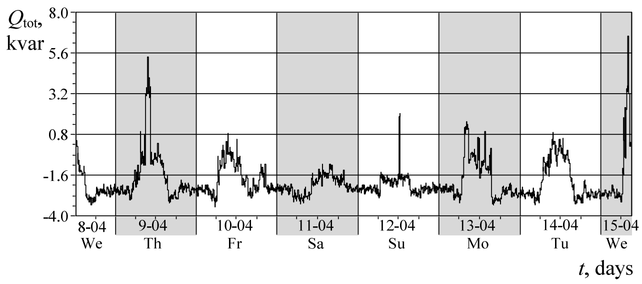

Fig. 2. Total average reactive power Q_{tot} for the measured building in 1 week period

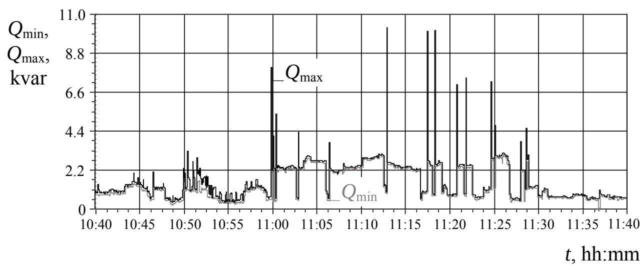

Fig. 3. An example of the maximum and the minimum value (Q_{max}, Q_{min}) of reactive power during one hour

The second aspect on which attention was drawn for the measurement of reactive power is its variability over time. The standard reactive power compensators need from several to tens of seconds to switch between each capacitor bank sections which directly stems from the time required for their discharge [8]. Figure 3 shows the maximum and minimum reactive power during one hour. As can be seen, these values can differ significantly in small intervals which could be a problem when compensation is needed.

Single-phase power system with APF

Compensation possibility of reactive power dynamic changes will be tested by simulation for single-phase power system using single-phase active power filter [1]. A simplified model of the system was shown in fig. 4. The APF is connected in parallel to the network at p point between the source of u_S with power line (R_S, L_S) and the passive receiver. Passive receiver was composed as time-variable impedance Z_L in order to force changes in reactive power.

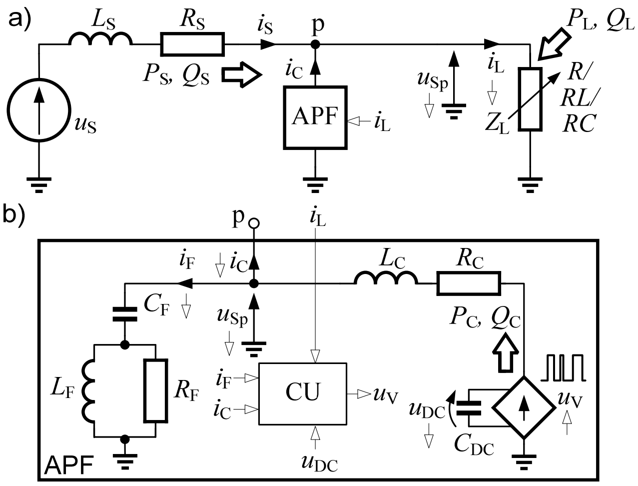

Fig. 4. A simplified model of single-phase power system with the APF, a) location of the APF in the system, b) macromodel of the APF

APF injects into line i_K current, which causes that the current drawn from the source is reduced according to:

(1) $$i_S = i_L + i_C \,.$$

A control unit (CU), of the inverter of APF is based on an algorithm p-q, which allows to compensate the reactive power of the linear and non-linear loads, as well as to reduce of harmonic current in case of non-linear loads [4] [7] [10]. Passive branch (L_F, C_F, R_F) connected in parallel to the output of inverter together with line impedance (R_S, L_S) makes a filter which purpose is to eliminate higher harmonic component of the source current generated primarily by the inverter [2].

Inverter voltage u_V is determined on the basis of the i_L load current, i_C compensation current and u_{Sp} voltage including the i_F current drawn by the branch (L_F, C_F, R_F) and u_{DC} voltage of inverter. The inverter voltage u_V is converted in an appropriate compensating current i_C in branch (L_C, R_C). As a result of compensation the sinusoidal current i_S is in phase with the voltage u_S. It means that power factor is corrected to the desired value PF = 1: active power of source P_S is equal to the active power consumed by the load P_L and at the same time reactive power of source Q_S = 0, which is possible when the Q_C reactive power of APF is equal to the Q_L reactive power of load. The P_C active power drawn by the APF filter should be zero.

Control system

A simplified block diagram of the control system was shown in fig. 5. Inverter switching frequency and also the frequency of the signal processing in the control circuit is f_{PWM} = 20 kHz. To filter out higher harmonic components of u_{Sp} voltage the 2nd order low-pass filter (LPF1) with 1 kHz cut-off frequency was used.

The filter effectively eliminates components of switching frequency simultaneously without changing the amplitude and phase of the 50 Hz fundamental harmonic frequency, which is used to determine reference signal. Reference of compensating current i_{Cr} is calculated according to the formula:

(2) $$i_{Cr} = i_L - i_{Lp} + i_{Fq} \,,$$

where:

i_{Lp} – the active component of the load current calculated on basis of the DC component of load active power $\overline{p}_L$, adjusted by the value of p_{Cdc} (u_{Cdc} voltage controller – block „u_{Cdc} => p_{Cdc}") which takes into account the power loss of the inverter:

(3) $$i_{Lp} = \frac{u_S\left(\overline{p}_L - p_{Cdc}\right)}{\left|U_S^2\right|} \,,$$

i_{Fq} – reactive component of current drawn by the higher harmonic filter branch (L_F, C_F, R_F) determined using the DC component of reactive power of this branch ($\overline{q}_F$).

Taking the i_{Fq} component in the algorithm into account allows reactive power compensation consumed by the branch (L_F, C_F, R_F).

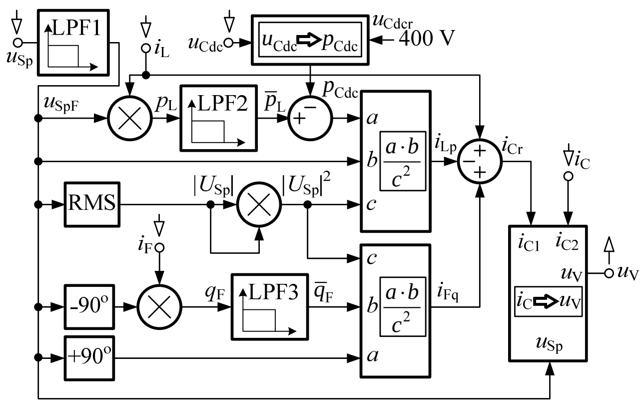

Fig. 5. Diagram of the control system

Voltage of inverter u_V is determined in block of follower controller „i_C => u_V" on the base of compensation current i_C and its reference i_{Cr}.

The choice of constant component filter of the instantaneous power

In control system (fig. 5) the lowpass filter „LPF2" was used. Its function is filtration of present constant component of the instantaneous load active power $\overline{p}_L$. In the considered single-phase system the instantaneous power waveform is characterized by high harmonic content from the fundamental harmonic frequency of f_s = 50 Hz, with the dominant harmonic frequency of $2f_s$ = 100 Hz. Therefore, to isolate the DC component lowpass filter with a sufficiently large attenuation A_{SB} at f ≥ 50 Hz should be used. Initial simulation attempts have shown that the suppression of the harmonics of at least 40 dB and the error of the filtered values of the DC component will not significantly affect the amplitude of the compensating current reference. Achieving of the above filtering task is possible by:

- selection of an appropriate low filter cutoff frequency $f_c < f_s$,
- choice of magnitude of frequency response approximation steeply sloping in the stopband, especially at the transition from passband to stopband,
- increasing approximation order r.

Obtaining the proper dynamics of the APF during the filter selection should be done by choosing the smallest possible settling time t_{set} (calculated up to 90% of steady-state amplitude) and the smallest amplitude $\Delta Y_{max\%}$ of the overshoot (expressed as a percentage determined of steady-state amplitude). For the amplitude $\Delta Y_{max\%}$ it was assumed that it should not exceed 15%. As part of the work tens of configurations of low pass filters with cutoff frequency f_c, with 3 dB magnitude of frequency response ripple in passband were examined. All fundamental approximations of frequency response magnitude: Bessel, Butterworth, Chebyshev I, elliptic, Chebyshev II [5] [11] were taken into consideration. Chebyshev II filter with order $r = 4$ and cut-off frequency $f_c = 23$ Hz in the optimal way suppresses harmonics ($A_{SB} \geq 40$ dB at $f \geq 50$ Hz) with the shortest settling time. Magnitude of frequency response $|Y(jf)|$ of the selected filter was presented in fig. 6, whereas its step response $y(t)$ was presented in fig. 7.

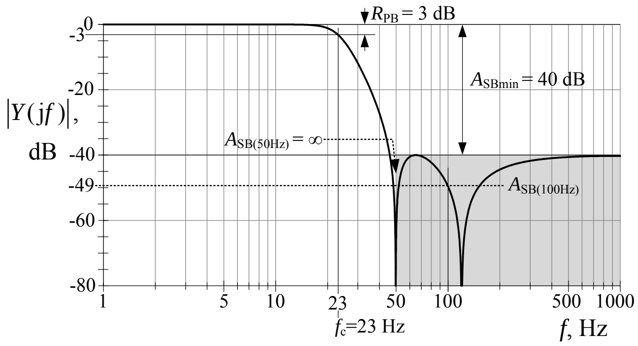

Fig. 6. Magnitude of frequency response of selected filter

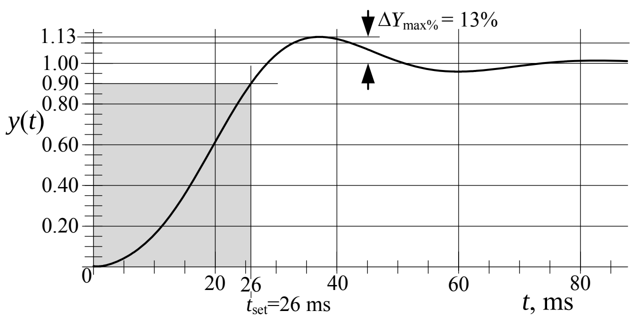

Fig. 7. Magnitude of frequency response of selected filter

In order to filtrate constant component of reactive power $\overline{q}_F$ of passive filter, filter "LPF3" identical to "LPF2" was used.

Matlab-Simulink model

The simulation model a single-phase power system was implemented in Matlab-Simulink and includes:

- sinusoidal source (Es),
- line impedance (Zs),
- 4-transistor inverter (Bridge) with DC capacitor (CDC),
- a branch for shaping compensation current (LC, RC),
- a branch (LF, CF , RF) of the higher harmonics filter,
- an inverter control circuit (Control) and a receiver (Load).

Reactive power of load Q_L was changed in the subsequent states of 1 ÷ 5 lasted 0.2 seconds, according to the sequence: 1) 1 kvar, 2) 2 kvar, 3) –1 kvar, 4) 0 and 5) 1 kvar. Active power of load in each state was P_L = 1 kW. Diagram of the used model was shown in fig. 8.

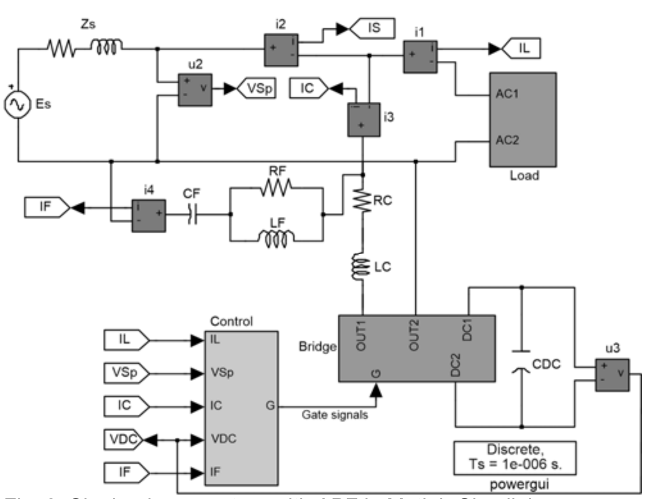

Fig. 8. Single-phase system with APF in Matlab-Simulink

Simulation results

Waveforms of load current i_L, source current i_S, APF current i_C and u_{Sp} voltage for the subsequent states (1÷5) of load reactive power changes were shown in fig. 9.

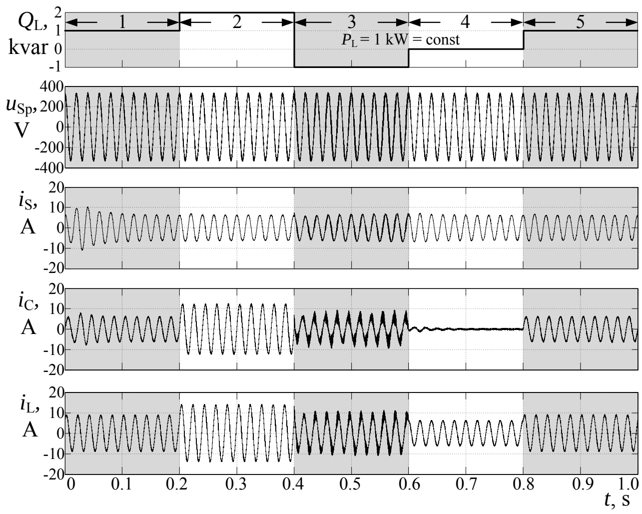

Fig. 9. Current waveforms: i_S, i_C, i_L and u_{Sp} voltage waveform for whole sequence of load reactive power changes (1÷5)

Immediately after system startup (state 1) during the transitional approx. 50 ms APF starts to generate the compensate current i_C with a noticeable overshoot, which results in overshoot in source current i_S. This phenomenon does not occur with step change of reactive power at the transition between the next states. For capacitive reactive power of load (state 3) compensating current i_C has an increased content of switching component. However higher harmonic components are not so much visible in the current source through the use of a higher harmonic filter.

Changes of APF active power P_C and APF reactive power Q_C during the following states 1÷5 were shown in fig. 10. As expected, the reactive power of APF Q_C varies according to the change of reactive power load Q_L with settling time of approx. 20 ms (1 period of fundamental frequency). In states 1÷3 and 5, value of reactive power Q_C is ca. 1-2% lower (ΔQ_C) then reactive power Q_L. In state 4 when $Q_L = 0$, reactive power $Q_C = 0$, which proves the proper reactive power compensation of higher harmonic filter.

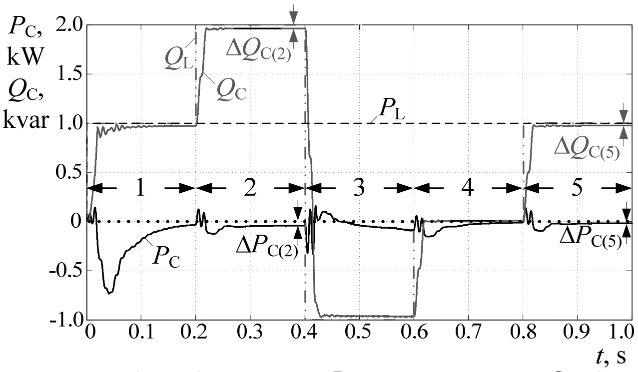

Fig. 10. Waveform of active power P_C and reactive power Q_C of the APF in states 1÷5

However more rapid transients states of P_C active power are in case of states 2÷5 where reactive power of load is changed. Settling time of the APF active power is significantly longer – in the range of 50 ÷ 200 ms depending on the type of load change. Power P_C in state 4 ($Q_L = 0$) is set at zero, while in other states ($Q_L \neq 0$) at the level of negative ΔP_C close to zero and $-\Delta P_C$ is approx. 1-3% of load reactive power module $|Q_L|$.

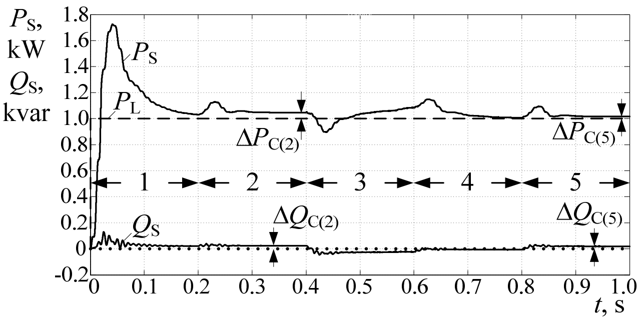

Fig. 11. Waveform of active power P_S and reactive power Q_S of source in states 1÷5

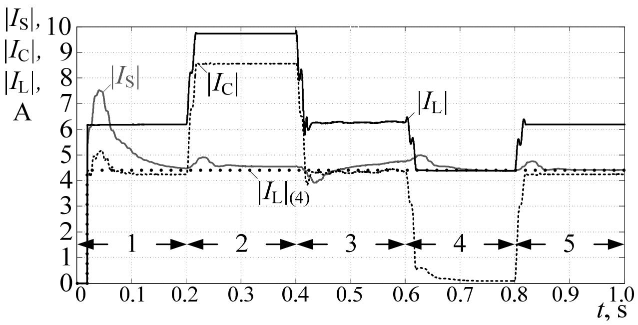

Fig. 12. Changes of RMS value of currents: source $|I_S|$, load $|I_L|$ i APF $|I_C|$ in states 1÷5

Changes of source active power P_S and source reactive power Q_S for states 1÷5 were shown in fig. 11. Source active power (P_S) is a sum of inverter power losses ($-P_C$) and the load active power (P_L). Reactive power Q_S is difference of load reactive power load (Q_L) and APF reactive power supplied to the line. Value of Q_C power in states 1÷3 and 5 ($Q_L \neq 0$) is smaller from the expected value Q_L by ΔQ_C which is 1-2% of Q_L. In case of state 4 ($Q_L = 0$) reactive power Q_S is equal 0, which additionally proves correct reactive power compensation of (L_F, C_F, R_F) branch.

Figure 12 shows the changes in the RMS value of currents: source $|I_S|$, load $|I_L|$ and APF $|I_C|$ in the following states 1 ÷ 5, which confirms the correct operation of dynamic reactive power compensation of the load. RMS value $|I_S|$ in each state is fixed to the minimum level $|I_L|_{(4)}$ which is achieved in state 4 when load consumes only active power. Value of $|I_C|$ current in each states achieves steady state in 20 ms.

Summary

The paper presents a simulation model of a single-phase active power filter with a control system based on modified p-q method. Proper selection of signal filters to averaging instantaneous active and reactive power and proper selection of the parameters of used PI controllers allows to achieve good dynamic properties of the system. It has been confirmed by the simulation results carried out in Matlab-Simulink.

In response to changes in reactive power of load APF generates follower changes of reactive power supplied into the network with setting time not greater than 20 ms. Such a short response time on reactive power changes provides considerable advantage over conventional capacitors banks-based compensators.

An additional benefit of the presented APF compared to traditional compensators is high accuracy of compensation, because the uncompensated reactive power is approx. 1-2% of the compensated power. In addition, the great advantage is the ability to compensate not only inductive power but also capacitance reactive power, which is generated by receivers in an office building at night.

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