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CONTROL OF THE DYNAMIC REACTIVE POWER COMPENSATION UNITS UNDER UNBALANCED LOAD CONDITIONS

Load unbalance of electrotechnological units causes emergence of voltage unbalance in a three-phase network, which negatively affects operation of other consumers. For such units dynamic reactive power compensation devices, based on static thyristor compensators, are provided. The paper considers the problems of increasing accuracy and response speed of dynamic reactive power compensation for balancing loads of the consumers. Mathematical models and algorithms for determining the parameters of unbalanced loads are described on the basis of classical power theory. Block diagram of the device for dynamic reactive power compensation and load balancing, comprising a single control loop, is described. On the results of modelling in Simulink environment of Matlab application package it is concluded that time delay of the dynamic reactive power compensation device does not exceed 0.05 – 0.08 s.

Key words: *reactive power compensation, load balancing, negative-sequence conditional power.*

Introduction

Dynamic reactive power compensation units, based on static thyristor compensators (STC), provide simultaneous optimization of such electric energy quality parameters as deviation, fluctuations and voltage unbalance [1, 2]. One of the problems, related to compensation of fast-changing network load influence, is to ensure the desired compensator response speed. This becomes especially relevant for such loads as electric-arc furnaces, electric welding units, mining electrotechnical complexes with abruptly-variable load.

STC automatic control systems of the leading world manufacturers are based on the control method with the use of rotating *dq*-coordinate system. Instantaneous components of the positive- and negative-sequence currents in rotating *dq*-coordinate system are given by [3]:

$$i_d = i_\alpha \cos(\omega t - \pi/2) + i_\beta \sin(\omega t - \pi/2); \quad i_q = i_\alpha \sin(\omega t - \pi/2) - i_\beta \cos(\omega t - \pi/2); \tag{1}$$

$$i_{d2} = i_\alpha \cos(\omega t - \pi/2) - i_\beta \sin(\omega t - \pi/2); \quad i_{q2} = i_\alpha \sin(\omega t - \pi/2) + i_\beta \cos(\omega t - \pi/2), \tag{2}$$

where i_d, i_q – positive-sequence instantaneous currents in *dq*-coordinate system; i_{d2}, i_{q2} - negative-sequence instantaneous currents in *dq*-coordinate system; i_α, i_β – instantaneous currents in αβ-coordinate system.

STC control system, which is commonly used in compensators, is a combined system including direct and reverse channels [4]. In the direct channel orthogonal *d-q* components of the load current for positive and negative sequences are calculated, on the basis of which phase conductivities (powers) are formed by means of Schteinmetz transformations.

Orthogonal components of the positive- and negative-sequence currents and voltages are calculated in the coordinate conversion units, where phase-locked loop (PLL) unit is used to ensure their correct operation in the conditions of the bus-bar phase variation and voltage shape distortion. Then output signals pass through digital sliding-average filters with tuning frequency of 50 Hz.

The task of additional reactive power generation is realized in the feedback channel, where correction signal is formed according to the difference between actual and pre-set reactive powers. Due to the presence of a proportional integrating controller there is a possibility to change the pre-set reactive power value at the secondary side of power transformers both towards reactive power consumption from the network and towards its generation.

Signals of total susceptances *B* pass through PLL units of the thyristor-reactor group (TRG) of STC and enter the inputs of non-linearity units, where inverse control characteristic of TRG α = f (B) is realized. Signals of the task for thyrister opening angles are supplied to the pulse-phase control system (PPCS), implemented on the basis of vertical principle. At the output of PPCS pulses are generated, which are supplied to the thyristor keys of TRG.

The main disadvantage of this control system is the necessity to use phase locked loop devices, realization of which is quite a challenge.

Another approach is based on building STC per-phase disturbance automatic control systems, which use powers determined by integration on half-period supply voltage. In [5] powers, obtained from the following integral expressions, are used for TSG phase power control:

$$Q_{AB} = \frac{2}{\sqrt{3}T} \int_{t_n}^{t_n+T/2} \left(u_{BC} i_A + u_{CA} i_B - u_{AB} i_C\right) dt\,;$$

$$Q_{BC} = \frac{2}{\sqrt{3}T} \int_{t_n+T/6}^{t_n+2T/3} \left(u_{CA} i_B + u_{AB} i_C - u_{BC} i_A\right) dt\,; \qquad (3)$$

$$Q_{CA} = \frac{2}{\sqrt{3}T} \int_{t_n+T/3}^{t_n+5T/6} \left(u_{AB} i_C + u_{BC} i_A - u_{CA} i_B\right) dt\,,$$

where $\underline{t_n}$ – time of maximum half-wave of the linear voltage u_{AB}; i_A, i_B, i_C – instantaneous phase currents of the load or of the network.

A disadvantage of this method is insufficient speed of response and accuracy, as measurements are performed once on the supply voltage period.

In [6] STK automatic control system is developed, which consists of two loops: for reactive power compensation and for load balancing. Operation of the first disturbance control loop is based on the algorithm of current control of STC phase reactive power in accordance with the formulas:

$$Q_{AB}(t) = \frac{1}{3}\left[Q(t) + Q_2(t) + \sqrt{3}P_2(t)\right];\; Q_{BC}(t) = \frac{1}{3}\left[Q(t) - 2Q_2(t)\right];\; Q_{CA}(t) = \frac{1}{3}\left[Q(t) + Q_2(t) - \sqrt{3}P_2(t)\right], \qquad (4)$$

where $Q(t)$, $P_2(t)$, $Q_2(t)$ – current values of reactive power, real and imaginary components of the negative-sequence conditional power of the load respectively.

The second deviation control loop is based on the procedure of correction of reactive power ΔQ, consumed from the network.

Current values of active and reactive powers, real and imaginary components of negative-sequence conditional power of the load are obtained on a sliding time interval of the duration, equal to the half-period ($T/2$), with the application of orthogonal αβ-coordinate system

$$P(t) = \frac{2}{T} \int_{t-T/2}^{t} (u_\alpha i_\alpha + u_\beta i_\beta) dt;\; Q(t) = \frac{2}{T} \int_{t-T/2}^{t} (u_\beta i_\alpha - u_\alpha i_\beta) dt\,; \qquad (5)$$

$$P_2(t) = \frac{2}{T} \int_{t-T/2}^{t} (u_\alpha i_\alpha - u_\beta i_\beta) dt;\; Q_2(t) = \frac{2}{T} \int_{t-T/2}^{t} (u_\beta i_\alpha + u_\alpha i_\beta) dt, \qquad (6)$$

where u_α, u_β –instantaneous voltages in αβ-coordinate system.

In [7] response speed of the loop of STK automatic control system is investigated in the case of load balancing according to the following conditions:

$$Q_{AB}(t) = \frac{1}{3}\left[Q_2(t) + \sqrt{3}P_2(t)\right];\; Q_{BC}(t) = \frac{1}{3}\left[-2Q_2(t)\right];\; Q_{CA}(t) = \frac{1}{3}\left[Q_2(t) - \sqrt{3}P_2(t)\right]. \qquad (7)$$

Besides, reactive power is separately investigated with the application of PI controller in the deviation control loop.

Separate study of balancing and compensation does not give comprehensive information of the efficiency of STK automatic control system. Another disadvantage is the use of powers (5), (6), which in many cases does not ensure sufficient accuracy of the balancing process.

Research aim is investigation of the possibility to increase accuracy of response speed of the reactive power compensation and load balancing simultaneously by means of STK.

Substantiation of the research results

In order to increase accuracy and response speed, it is expedient to use informative parameters, determined on the basis of classical power theory. According to the classical power theory [8] a three-phase system with unbalanced load could be characterized by active and reactive powers and negative-sequence conditional powers [9]:

$$P(t)=\frac{2}{T}\int\limits_{t-T/2}^{t}(u_\alpha i_\alpha+u_\beta i_\beta)dt;\;\; Q(t)=\frac{2}{T}\int\limits_{t-T/2}^{t}(u_\alpha' i_\alpha+u_\beta' i_\beta)dt\,; \qquad (8)$$

$$P_2(t)=\frac{2}{T}\int\limits_{t-T/2}^{t}(u_\alpha i_\alpha-u'_\beta\, i'_\beta\,)dt;\;\; Q_2(t)=\frac{2}{T}\int\limits_{t-T/2}^{t}(u'_\alpha\, i_\alpha+u_\beta i'_\beta\,)dt, \qquad (9)$$

where the operation of phase shift by -90 e. degrees is indicated by a prime. Such approach complicates, to a certain extent, realization of measuring power converters, while at the same time reduces fluctuations at the output of converters of the reactive and complex conditional power components, which could provide faster system response due to the possibility of increasing PI regulator integration factor.

In order to determine the response speed and to analyze stability of the reactive power compensation process with simultaneous load balancing by means of STK, the control system simulation in *Simulink* environment of the *Matlab* application package was performed. The model for studying unbalanced modes of the load assembly is presented in Fig. 1.The model consists of power supply 1, load 2, automatic control system 3, which comprises power measurement conversion unit, unit of PI controllers, pulse-phase control system, as well as of power unit 4.

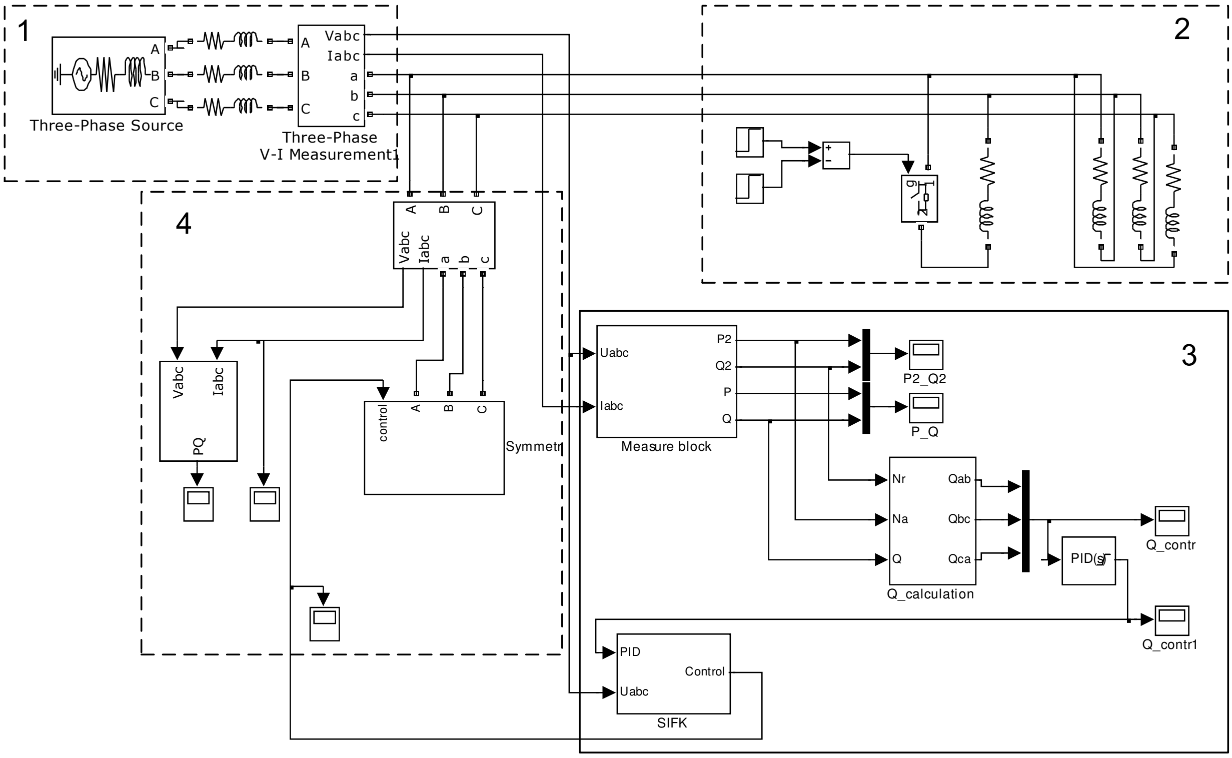

Fig. 1. Model for studying the dynamic reactive power compensation unit

Dependencies of the active and reactive powers in the load assembly during compensation and balancing processes in the case of PI controller application after its adjustment are presented in Fig. 2. Dependencies of the complex conditional power components are shown in Fig. 3. Fig. 4 presents dependencies of STK phase powers. Simulation was performed for the case of switching a three-phase unbalanced load at the moment $t = 0$, application of the additional single-phase load at the moment $t = 0{,}15$ s and load shedding at the moment $t = 0{,}25$ s.

Reactive power minimum and negative-sequence conditional power minimum are used as regulation criterion. In this case conditions of the reactive power compensation and load balancing have the form of (4).

Complex phase powers of the three-phase unbalanced load are $\underline{S}_{AB} = 100 + j50$ kV·A; $\underline{S}_{BC} = 120 + j60$ kV·A; $\underline{S}_{CA} = 120 + j60$ кV·A, additional single-phase load $\underline{S}_{AB} = 30 + j30$ кV·A (load parameters are reduced to the voltage 10,0 кV). In this case static characteristics have quadratic dependence of powers on the voltage in the network node (in the model active and reactive loads are represented by resistances).

In the first and third segments of the time dependencies (Fig. 4) reactive power compensation and load balancing in a steady-state mode is provided by the following values of STK phase powers: $Q_{AB} = 47{,}3$ kVAr; $Q_{BC} = 45{,}2$ kVAr; $Q_{CA} = 68{,}2$ kVAr, in the second segment the required STK phase power values are as follows: $Q_{AB} = 75{,}8$ kVAr; $Q_{BC} = 62{,}3$ kVAr; $Q_{CA} = 50{,}4$ kVAr. Relative values of STK phase powers in Fig. 4 are determined relative to STK total power of 300 kVAr.

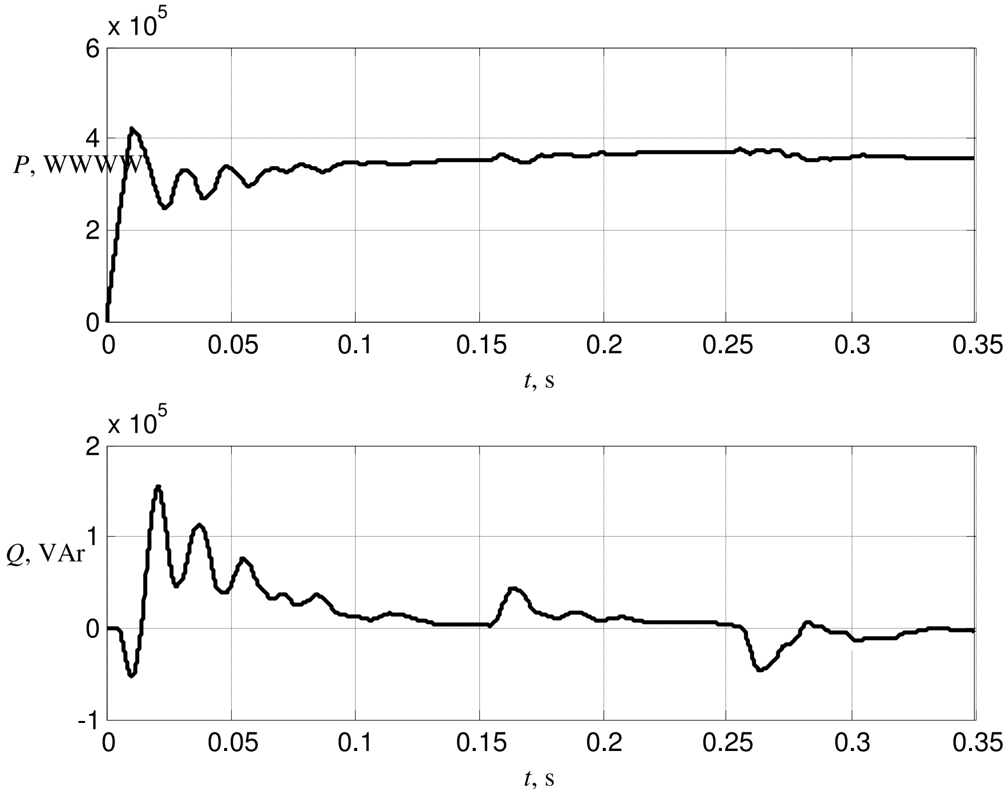

Fig. 2. Active and reactive power dependencies

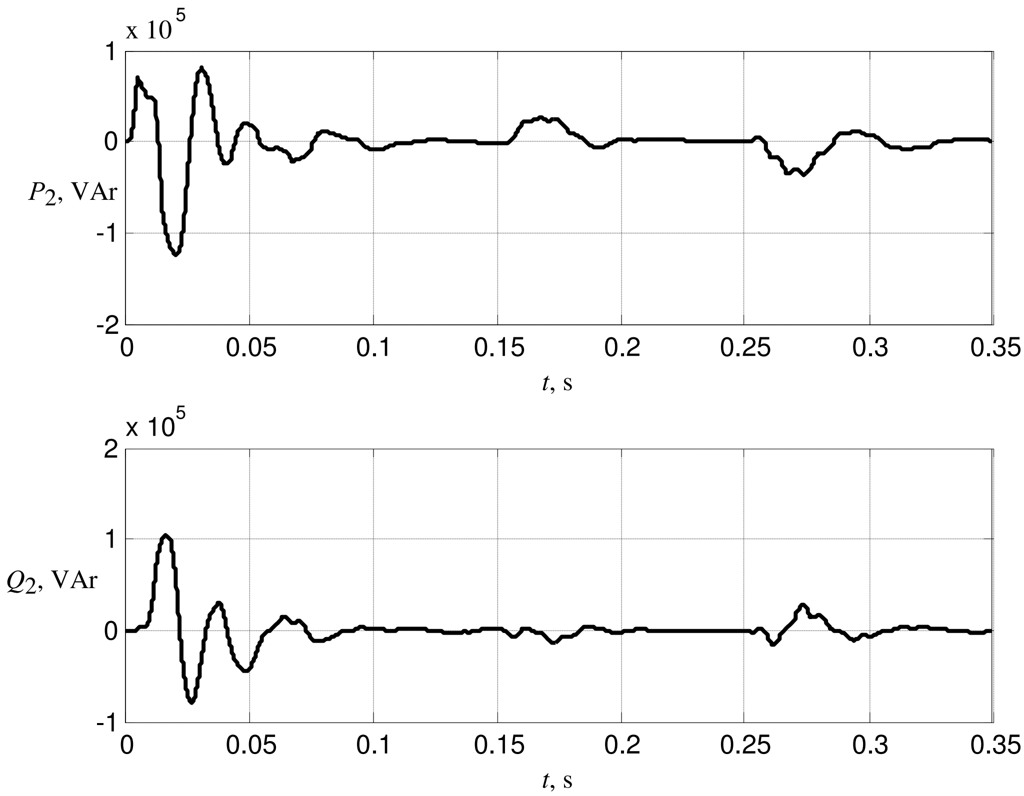

Fig. 3. Dependencies of the components of the negative-sequence complex conditional power

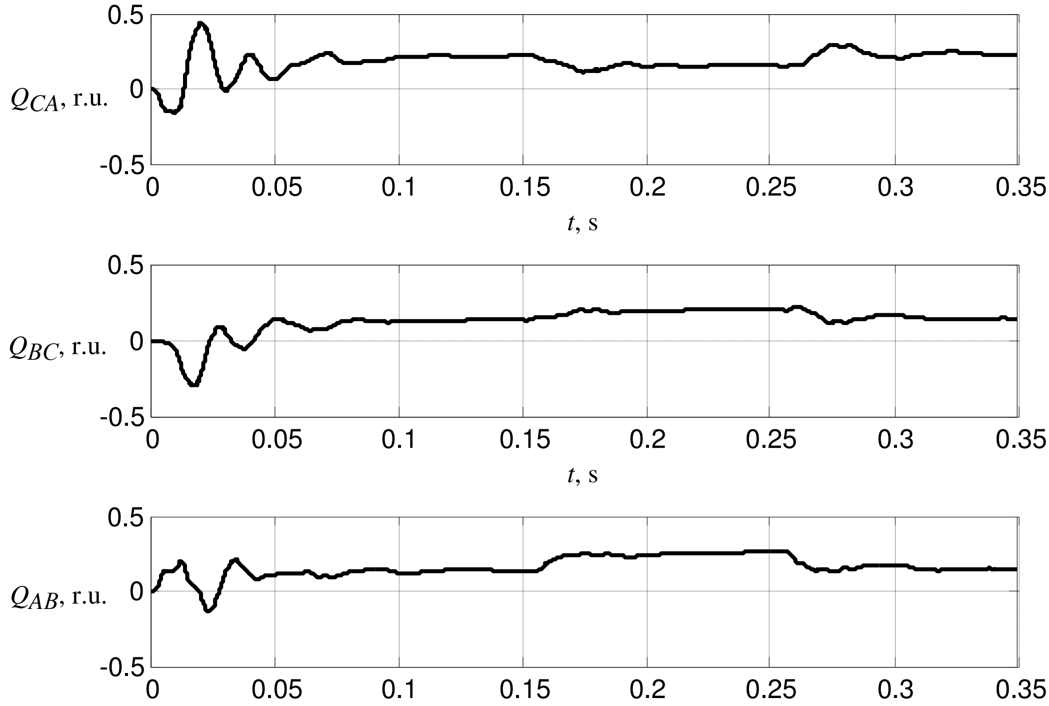

Fig. 4. Dependencies of STK phase powers

From the presented dependencies it follows that combining reactive power compensation and load balancing loops provides fast response with time delay of about 0,05 ... 0,08 s.

Conclusions

A possibility to increase accuracy and response speed of dynamic reactive power compensation with simultaneous load balancing is considered. Mathematical models and algorithms for determining parameters of the unbalanced loads are investigated on the basis of the classical power theory. Structural diagram of the dynamic reactive power compensation unit with load balancing, which comprises a single control loop, has been developed. A possibility to control dynamic reactive power compensation units by combining reactive power compensation and load balancing loops is shown. Response time delay of the dynamic reactive power compensation device does not exceed 0.05 – 0.08 s.

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