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THREE-PHASE PARALLEL ACTIVE POWER FILTER SYSTEM PRE-CHARGE CAPACITOR

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Purpose. Development of a subsystem of the previous phase capacitor charging power of parallel active filter as part of the control system. **Methodology**. Based on the analysis set out in known publications implement subsystem previous charge the capacitor, which provides support and control DC voltage in a given range of compensation provided in the inactive components of power. On the basis of the order of formation current power active filter selected parameter is used to set the intensity of battery - power. The algorithm of compensation, further comprising adjusting the current power active filter equivalent to the value of charging power under conditions of capacitor voltage deviation limits specified range. **Results**. Based on an algorithm taking into account the known technical solutions developed active filter circuit of the power subsystem charge the capacitor. Through modeling experiments implemented in algorithm modes and the correct conclusions. It is noted that at the beginning of the scheme is unmanageable because of counter-diode circuit, causing the current cast, which limited inductance range of network power active filter. **Originality**. When using SAF quality testing given current vary depending on the power circuit and the voltage level of the capacitor. The voltage capacitor for handling should be higher than the voltage, in some cases - much higher. In a famous study dedicated modes SAF authors examined the scheme processes and modes of position provide the necessary current levels SAF network, but the formation of the charge in the capacitor DC link remains unexplored. There are technical solutions that provide the capacitor charging process with certain conditions and requirements, but the use of additional circuitry to implement a charge capacitor when SAF leads to complications schematics and accordingly the use of appropriate controls. **Practical value**. In the course of an experiment for the following modes: charge the capacitor SAF mode of compensation for the load conditions, compensation for increased load conditions. References 13 Figure 3.

Key words: active power filter, battery capacity, charge level of the capacitor, pq-power theory.

ТРИФАЗНИЙ ПАРАЛЕЛЬНИЙ СИЛОВИЙ АКТИВНИЙ ФІЛЬТР З ПІДСИСТЕМОЮ ПОПЕРЕДНЬОГО ЗАРЯДУ КОНДЕНСАТОРА

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На підставі аналізу теоретичних підходів і технічних рішень, викладених у відомих публікаціях, поставлено задачу керування рівнем напруги в колі постійного струму трифазного паралельного силового активного фільтру, шляхом введення обмеження максимальної напруги конденсатора, обмеження мінімальної напруги конденсатора, завдання активної зарядної потужності та відповідних зв'язків, що реалізують підсистему попереднього заряду конденсатора, яка забезпечує контроль та підтримку напруги постійного струму в заданому діапазоні при забезпечені компенсації неактивних складових потужності. На підставі аналізу порядку формування струму силового активного фільтра виділено параметр який використано для завдання інтенсивності заряду – потужність. Розроблено алгоритм компенсації, який додатково включає корегування струму силового активного фільтру на величину еквівалентну зарядній потужності за умов відхилення напруги конденсатора від меж заданого діапазону. На підставі алгоритму з урахуванням відомих технічних рішень розроблено схему силового активного фільтру з підсистемою заряду конденсатора. Шляхом проведення модельних експериментів реалізовано закладені в алгоритм режими та зроблено відповідні висновки. Відзначено, що на початку роботи схеми відбувається некеровано, через зустрічні діоди схеми, що викликає кидок струму, який обмежується індуктивністю мережевого кола силового активного фільтру.

Ключові слова: силовий активний фільтр, зарядна потужність, рівень заряду конденсатора, pq-теорія потужності.

PROBLEM STATEMENT. Way of the latest achievements in the field of compensation of capacity inactive components and reduction of the highest harmonics of current in electrical engineering, the controlled filter-compensative devices – active power filters (APF) have spread. APF are actually a part of a more general electro-energetic system, which is known as FACTS (Flexible AC Transmission Systems) [1–2]. APF is a device, which is intended for the compensation of reactive capacity and for providing high levels of power quality – harmonic filtering, voltage regulation level, balancing of asymmetrical loading, flicker decline and others. Growth in the industry dramatically variable and nonlinear loading, irregular operation of electrotechnical installations and the introduction of devices of semiconductor technology for the process control equipment, have strained the problem of power quality provision. The negative impact of nonlinear force is that it leads to a high non-sinusoidal alternating of current, consumed from the network transmitters, which leads to distortion's voltage at which the network is connected to a similar consumer. At the same time, nonlinear loading has a specific level of reactive power consumption, which leads to an increase in the loss of power system, overload of transformers, power lines and power fluctuations [3].

The application of APF is an effective technical solution for compensation for the non-active components of the power loadings in three-phase AC power. [4] They have a number of advantages compared to other compensating devices. APF doesn't require tuning to a specific harmonic, as a passive filter. It also automatically regulate the power index, provides the current reduction in a proportion nearly 1:10. In result it leads to the reduction of power losses in the transmission system of electrical power.

Analysis of previous studies. Research and improvement of existing system of power converter management of APF is a continuous process [4, 5] is realizing in the direction of speed increasing and the accuracy of formation of the output parameter: the current in parallel APFs, strain – in successive, or both – in combinations [5, 6].

When APF is working the quality of labour-rent of the given current depends on the parameters of the power circuit and the capacitor voltage level [4]. In such a case the voltage of the capacitor, for ensuring manageability, should be higher than main voltage, in some cases – significant higher [4]. In famous studies devoted to the APF modes, the circuit processes and modes from the perspective of providing the necessary current in the APF network link are considered by authors. But the question of the formation of the capacitor charge in the link of DC volts remains unexplored. Famous technical solutions which provide the capacitor charging process with certain known conditions and requirements [7], but the use of additional circuitry for implement a capacitor charge in APF cases produces complicates about the circuit solution and accordingly to the application of appropriate controls elements.

PURPOSE. The development of capacitor's pre-charge subsystem of the parallel three-phase active power filter is composed of a control system.

EXPERIMENTAL PART AND RESULTS OBTAINED. Most of the work in terms of analysis modes of APF capacitor in circuit of steady voltage is considered pre-charged to a certain voltage level [3, 4]. The capacitance and voltage level on its covers define specific indicators, which characterize the dynamic capabilities of a powerful APF scheme. A considerable amount of works is devoted to the selection of the capacitor capacitance and voltage values [8, 9]. The voltage on the capacitor during operation is influenced by the energy exchange process between the APF and the network node to which it is connected. Depending on the nature of current and capacity that generates the APF, the voltage change occurs in various ways. If the APF finish compensation work, reactive nature of the current filtering and its balancing, the voltage capacitor varies in a complicated manner, with a constant average of value for the period of the mains voltage. According to the studies [4, 7, 10], the change in the average value of the voltage of the capacitor for a period of mains voltage is corresponded to the accumulation of electrostatic field energy, in other words power consumption, or rather, its accumulation.

The level of this voltage is determined by changes in APF energy in the period of mains voltage $\left(t_0;t_0+T\right)$:

$$\int_{t_0}^{t_0+T}\left(u_A i_A+u_B i_B+u_C i_C\right)dt=\frac{C_{st}}{2}\left(u_{C_{st}}^2\Big|_{t_0+T}-u_{C_{st}}^2\Big|_{t_0}\right),$$

where $u_{\grave{A}}$, u_B, u_C – are mains voltage phase of ABC, $i_{\grave{A}}$, i_B, i_C – are mains current phase of ABC; C_{st} – capacitance; $u_{C_{st}}$ – voltage of the capacitor. It is admittedly if the voltage level for the period does not change, this may mean that the active power has not been exchanged with the electrical power network. The APF current is formed of compensation of some components of the power that circulates in the electric network node. The current formation algorithms, which are based on the capacity theory of S. Fryze theory [4], H. Akagi [4], H. Kim [11]. All these algorithms have in common that a variety of technical routes on the network active power is defined as the integral index:

$$P=\frac{1}{T}\int_{t_0}^{t_0+T}pdt=\frac{1}{T}\int_{t_0}^{t_0+T}\left(u_A i_A+u_B i_B+u_C i_C\right)dt,$$

and is excluded from the process of formation of the APF currents

Thus the formation of the capacitor charge is possible by forming the corresponding active power level. In addition, it should fulfill certain further conditions: the termination of the charge at a predetermined maximum value; capacitor charging while reducing to a critical level at which the loss of converter control may occur; capacitor discharge in excess of the critical level for operational data scheme.

It is offered in [4] APF current formation for the three-phase network to perform the capacity of the submission in conditions of active and inactive, each of which has variable and constant components (pq-theory). For this purpose, Clark's transformation of voltage and load current is used.

The mains voltage at the coordinates $\alpha\beta$:

$$\begin{bmatrix}u_\alpha\\u_\beta\end{bmatrix}=\sqrt{\frac{2}{3}}\begin{bmatrix}1&-\frac{1}{2}&-\frac{1}{2}\\0&\frac{\sqrt{3}}{2}&-\frac{\sqrt{3}}{2}\end{bmatrix}\begin{bmatrix}u_{sa}\\u_{sb}\\u_{sc}\end{bmatrix},$$

where u_{sa}, u_{sb}, u_{sc} – are instantaneous mains voltage in triphasic coordinates *abc*.

Load current in the coordinates $\alpha\beta$:

$$\begin{bmatrix}i_\alpha\\i_\beta\end{bmatrix}=\sqrt{\frac{2}{3}}\begin{bmatrix}1&-\frac{1}{2}&-\frac{1}{2}\\0&\frac{\sqrt{3}}{2}&-\frac{\sqrt{3}}{2}\end{bmatrix}\begin{bmatrix}i_{lda}\\i_{ldb}\\i_{ldc}\end{bmatrix},$$

where i_{da}, i_{db}, i_{dc} – are instantaneous load current in three-phase coordinates *abc*.

Instant active and inactive power loads are according to the formula:

$$\begin{bmatrix}p_l\\q_l\end{bmatrix}=\begin{bmatrix}u_\alpha&u_\beta\\u_\beta&-u_\alpha\end{bmatrix}\begin{bmatrix}i_\alpha\\i_\beta\end{bmatrix}.$$

Instantaneous active and reactive power consist of two components: the constant (average) P_l, Q_l and variables $\tilde{p}_l$, $\tilde{q}_l$:

$$p_l=P_l+\tilde{p}_l;$$

$$q_l=Q_l+\tilde{q}_l.$$

In general, the useful component is the only constant active power P_l. If the function of compensation $\overset{\square}{p}_l$ and q_l [4], is depended on the compensator this means that the specified current compensator in the coordinates $\alpha\beta$ is:

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \frac{1}{\left(u_\alpha^2 + u_\beta^2\right)} \begin{bmatrix} u_\alpha & u_\beta \\ u_\beta & -u_\alpha \end{bmatrix} \begin{bmatrix} \overset{\square}{p}_l \\ q_l \end{bmatrix}.$$

The transformation of a given current coordinates $\alpha\beta$ in *abc* with the help of Clark's inverse transformation:

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_{\tilde{n}}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix}.$$

It gives current of APF which is necessary to form.

It is taken into account that charge or discharge of the APF capacitor hour period is bigger than the main voltage period, which corresponds to the consumption or generation of active power. It should be rationally adjust in the APF current in such a way:

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \frac{1}{\left(u_\alpha^2 + u_\beta^2\right)} \begin{bmatrix} u_\alpha & u_\beta \\ u_\beta & -u_\alpha \end{bmatrix} \begin{bmatrix} p_l - P_l \pm P_{ch} \\ q_l \end{bmatrix},$$

where P_{ch} – is the charge capacity ("+") or discharge ("-") of the capacitor.

The charge of the capacitor as part of a three-phase parallel APF should be carried out to a predetermined maximum voltage level. To check the charge level, the current level voltage of the capacitor u_C, should be monitored – which is enough to use the appropriate sensor. By placing the maximum specified level of the voltage capacitor $U_{DC}^{\max}$, signal that allows discharge is:

$$u_{dis} = \begin{cases} 1 \text{ if } u_c \geq U_{DC}^{\max}; \\ 0 \text{ if } u_c < U_{DC}^{\max}. \end{cases}$$

By placing a minimum predetermined voltage level $U_{DC}^{\min}$, the signal, which allows charge is:

$$u_{ch} = \begin{cases} 1 \text{ if } u_c \leq U_{DC}^{\min}; \\ 0 \text{ if } u_c > U_{DC}^{\min}. \end{cases}$$

In the case of discharge of the capacitor to a predetermined voltage threshold it is necessary to switch from the active mode to the filtering capacitor charge mode. For this, the signal is determined by u_{en}:

$$u_{en} = u_{ch} - u_{dis}.$$

The capacitor charging current is determined by the active charging power P_C. The higher the amplitude of the charging current, the faster the capacitor is charged to the desired value. Also on the capacitor charge rate the value of its capacity will affect, but in any case the charging power is:

$$P_{ch} = P_C \cdot u_{en}.$$

Due to changes in the present case, the order of APF current formation it may assume the values of current, which will be different from the calculation, it means, overload current. Current limitation is proposed to carry out in such a way:

The current APF value is determined for a phase line "a":

$$I_{RMS.a} = \sqrt{\frac{1}{T}\int_0^T i_a^2 dt},$$

Similarly for the phases *b* and *c*.

Determination of the multiplicity of existing K_a value of the current is towards the specified maximum:

$$K_a = \frac{I_{\max}}{I_{RMS.a}},$$

It is similar to the phase lines *b* and *c*.

Formation of the corrected multiplicity is:

$$K_a^{'} = \begin{cases} 1 \quad \text{if } K_a > 1; \\ K_a \quad \text{if } K_a \leq 1, \end{cases}$$

It is similar to the phase lines *b* and *c*.

Formation of the compensator's current limit is:

$$\begin{bmatrix} i_a^{'} \\ i_b^{'} \\ i_{\tilde{n}}^{'} \end{bmatrix} = \begin{bmatrix} K_a^{'} & 0 & 0 \\ 0 & K_b^{'} & 0 \\ 0 & 0 & K_c^{'} \end{bmatrix} \begin{bmatrix} i_a^* \\ i_b^* \\ i_{\tilde{n}}^* \end{bmatrix}.$$

Carrying out a relay current regulation, the current error Δi APF is determined by comparing the given current i'_{abc} and actual current i_{APF}:

$$\Delta i = i_{abc}^{'} - i_{APF}.$$

The pulses of the transistors control are formed in a U_{y1-6} voltage vector by the relation of:

$$U_1 = 1 \text{ if } \left(\Delta i > HB, \frac{d\Delta i}{dt} > 0\right) \cup \left(\Delta i > -HB, \frac{d\Delta i}{dt} < 0\right), \text{elså } 0;$$

$$U_2 = 1 \text{ if } \left(\Delta i < -HB, \frac{d\Delta i}{dt} < 0\right) \cup \left(\Delta i < HB, \frac{d\Delta i}{dt} > 0\right), \text{else } 0.$$

HB zone of hysteresis value is set to 1-10% of the load current. The control pulses of other transistors of the APF converter are formed in the same way.

Summarizing the foregoing formed algorithm of the three-phase parallel APF capacitor charging subsystem – see Fig. 1.

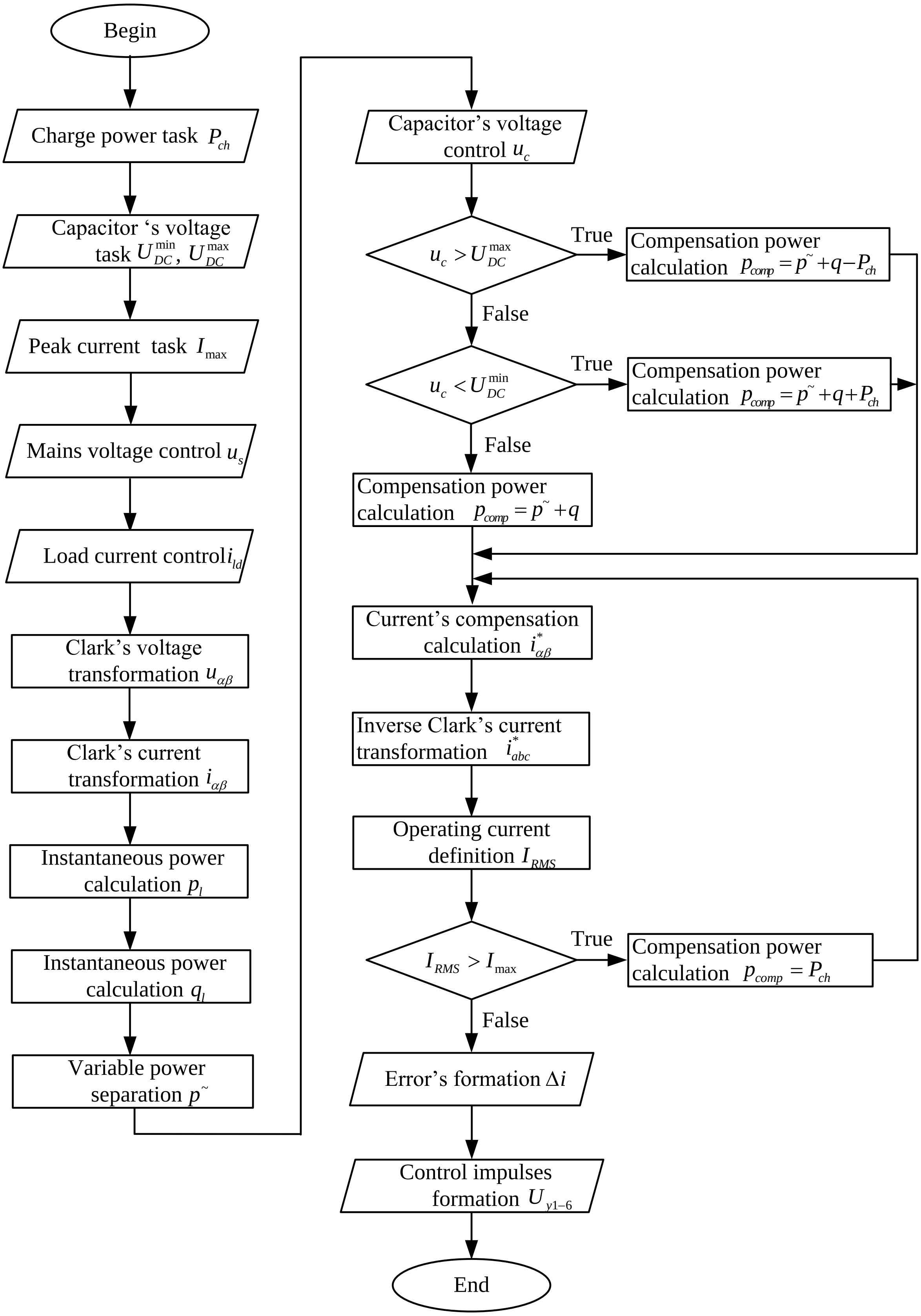

Figure 1 – Algorithm for the capacitor charge when using *pq*-theory of instantaneous power

Illustration 2 is a functional block diagram of a three-phase parallel active power filter subsystem of the pre-charged capacitor, in which 1 – transistor converter; 2 – sensors of actual filter current; 3 – chokes; 4 – mains voltage sensors; 5 – sensors of current of the load; 6 – capacitor; 7 – capacitor voltage sensor; 8 – limitation of the maximum voltage of the capacitor; 9 – limitation of the minimum voltage of the capacitor; 10 – task of the active battery power; 11 – definition of active battery power; 12 – definition of the instantaneous voltage at the coordinates $\alpha\beta$; 13 – definition of the instantaneous load power; 14 – allocation of constant active power component; 15 – definition of instantaneous load current coordinates $\alpha\beta$; 16 – definition of instantaneous inactive power load; 17 – definition given current in the coordinates $\alpha\beta$; 18 – the transformation of a given current in the $\alpha\beta$ coordinate *abc*; 19 – determination of the current effective value of a given current; 20 – maximum given current; 21 – definition of the multiplicity of the actual value of the current; 22 – formation of the corrected multiplicity; 23 – the formation of a limited given current; 24 – formation of the control pulses.

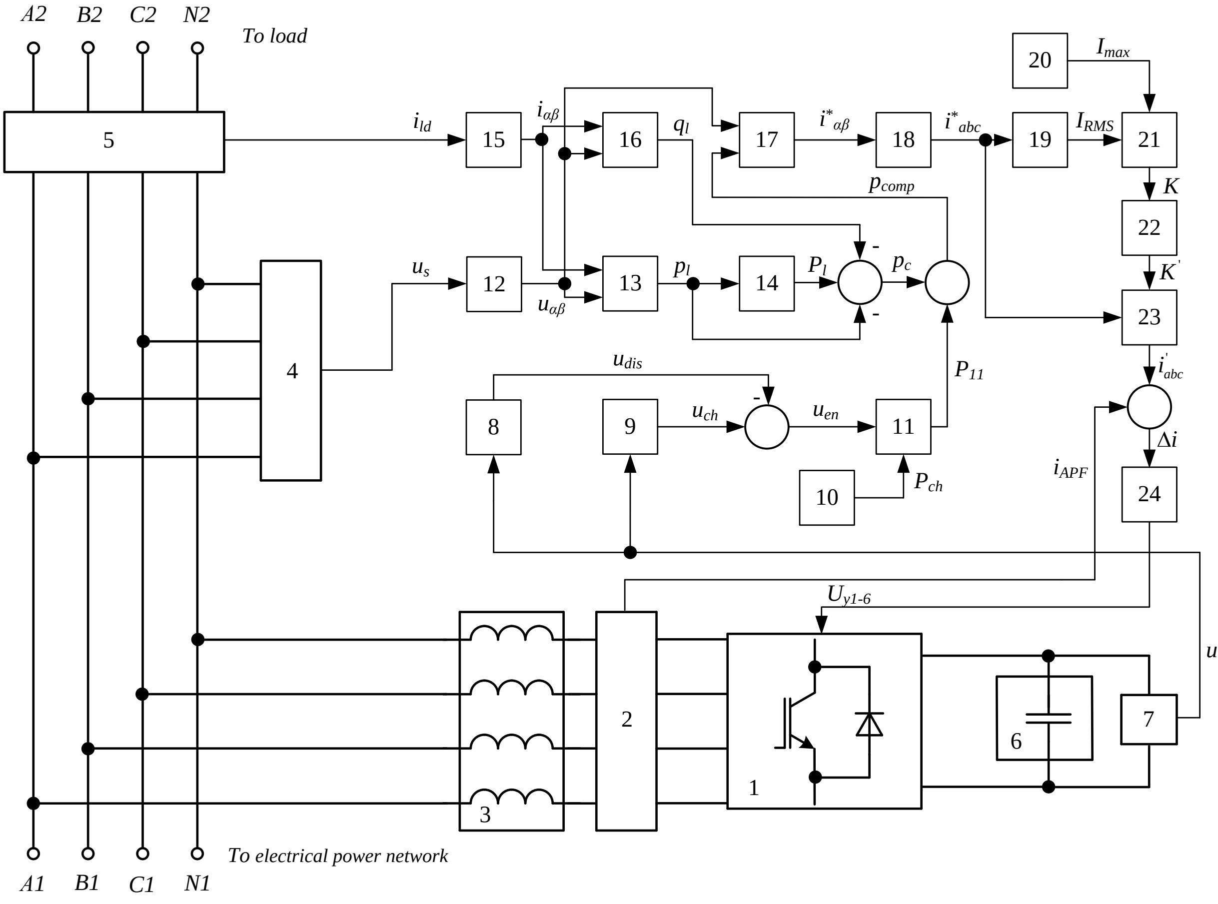

Figure 2 – Functional diagram of the three-phase parallel active power filter of the pre-charged subsystem of the capacitor

In a visual environment of Matlab/Simulink R2014a a model with three-phase power system for APF was created (Fig. 2). The parameters of circuit elements are designed for the following reasons: non-linear load has a calculated power: $P = 30\,\text{kW}$, $Q = 66\,\text{kVA}$ – thyristor converter with *RL*-load $R_{ld} = 2\Omega$; $L_{ld} = 0.0116$ H. Power distribution is provided by a three-phase source with a rated voltage of $U_s = 380$ V and a frequency of 50 Hz. Equivalent electrical power network active and reactive resistances are calculated on the allowable voltage losses of their 7 %, respectively consist of $R_s = 0.1\ \Omega$; $L_s = 1.3\cdot 10^{-5}$ H. APF parameters are calculated by the method [8,9]: APF reactor inductance $L = 0.0054\,\text{H}$; capacity of the capacitor $C = 20\cdot 10^{-3}\,\text{F}$; voltage $U_{dc} = 2000\,\text{V}$. Hysteretic zone HB in the method of the *RPC* should not exceed 10% of the load current [12].

The experiment was performed for the following modes: capacitor charge APF, compensation regime under the load action, compensation under increased load, hysteresis zone $HB = 6\,\text{A}$, minimal allowable voltage $U_{DC}^{\min} = 1800\,\text{V}$, given voltage of the capacitor $U_{DC}^{ref} = 2000\,\text{V}$, a task of an active battery power $P_{ch} = 30000\,\text{W}$.

The study illustrates by timing diagram in Fig. 3. At the time interval occurs $0 \le t \le 0.01\,\text{s}$ uncontrollable current race, with the amplitude of the current, which is limited by the inductance range of APF electrical power network. In the interval $0.01 < t \le 0.125\,\text{s}$ controlled charge capacitor is implemented and therefore the current compensator, with not taking into account of modulating component has a sinusoidal mains current form due to the action of the compensator and load different from harmonious. At time $t = 0.3\,\text{s}$ with the implemented change in load by controlling the thyristor converter control of an angle from 45 to 0 degrees. This causes a change in the current compensator and certain discharge of the capacitor during the transition process.

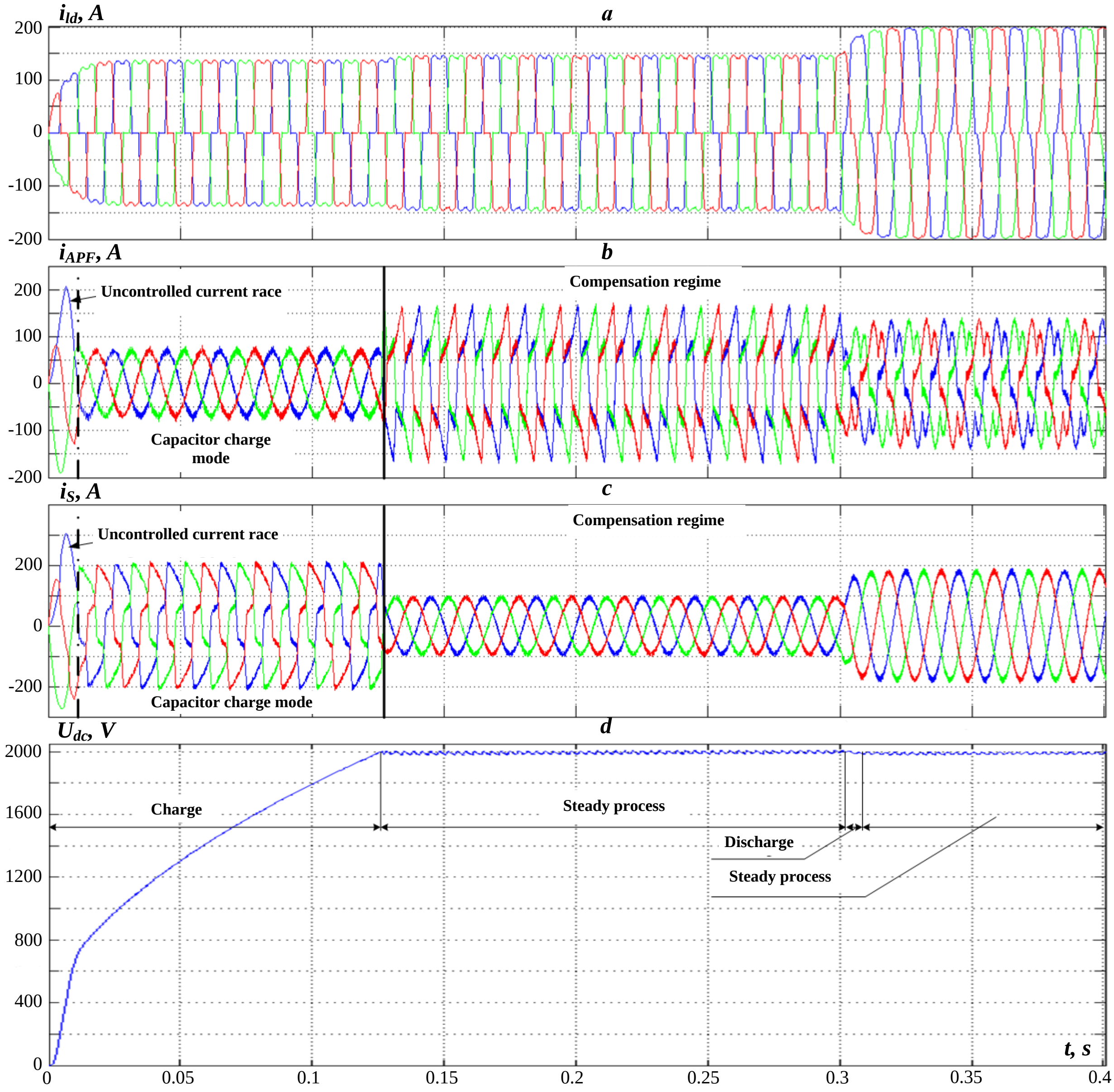

Figure 3 – Oscillograms, in which: a – load current i_{ld} ; b – given APF current i_{APF} ;
c – mains current i_S ; d – capacitor voltage U_{dc}

CONCLUSIONS. 1. The process of APF voltage control of he capacitor can be technically implemented without usage of additional devices, by adjusting the basic compensation algorithm.

2. The process of controlling by the charge of the capacitor requires restrictions on the minimum level voltage, provided management of APF, for a maximum voltage and current conditions on the choice of the elements of the power circuit.

3. The charging process and discharging of the capacitor may occur along with the process of compensation and no matter, as long as does not exceed the maximum current of the compensator valve.

4. Charge the capacitor at the beginning of the scheme takes place uncontrollably through the counter of the diodes circuit, causing an inrush current, which is limited inductance range of APF network.

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ТРЕХФАЗНЫЙ ПАРАЛЛЕЛЬНЫЙ СИЛОВОЙ АКТИВНЫЙ ФИЛЬТР С ПОДСИСТЕМОЙ ПРЕДВАРИТЕЛЬНОГО ЗАРЯДА КОНДЕНСАТОРА

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На основании анализа теоретических подходов и технических решений, изложенных в известных публикациях, поставлена задача управления уровнем напряжения в цепи постоянного тока трехфазного параллельного силового активного фильтра, путем введения ограничения максимального напряжения конденсатора, ограничения минимального напряжения конденсатора, задача активной зарядной мощности и соответствующих связей, реализующих подсистему предварительного заряда конденсатора, которая обеспечивает контроль и поддержание напряжения постоянного тока в заданном диапазоне при обеспечении компенсации неактивных составляющих мощности. На основании анализа порядка формирования тока силового активного фильтра выбран параметр, который используется для задания интенсивности заряда – мощность. Разработан алгоритм компенсации, который дополнительно включает корректировки тока силового активного фильтра на величину эквивалентную зарядной мощности в условиях отклонения напряжения конденсатора от границ заданного диапазона. На основании алгоритма с учетом известных технических решений разработана схема силового активного фильтра с подсистемой заряда конденсатора. Путем проведения модельных экспериментов реализованы заложенные в алгоритм режимы и сделаны соответствующие выводы. Отмечено, что в начале работы схемы происходит неуправляемо, через встречные диоды схемы, вызывает бросок тока, который ограничивается индуктивностью сетевого круга силового активного фильтра.

Ключевые слова: силовой активный фильтр, зарядная мощность, уровень заряда конденсатора, pq-теория мощности.

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