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LIMITATIONS OF CURRENT OF THE THREE-PHASE ACTIVE POWER FILTER IN THE CONDITIONS OF OVERLOAD AND SHORT CIRCUIT

Purpose. The purpose of the work is to develop a method of limiting the maximum allowable level of current of a three-phase active power filter in conditions of overload or short circuit and a system for the implementation of the method. *Methodology.* For research purposes, the provisions of the *pq*-theory of instantaneous power, the method of the theory of automatic control in systems with relay controllers, and the methods of simulation in the visual programming environment were used. *Results.* Both the overloading mode and the short circuit emergency mode, using the proposed solution, do not lead to significant changes in the voltage level on the accumulation capacitor, thus maintaining the stability of the power part of the active power filter. *Originality.* In the case of temporary overloads of current and short circuits at the network node to which a active power filter is connected, the current's limiting is performed by scaling the current to the level allowed by normal operation of the semiconductor elements of the device, which allows the basic operating algorithm to be implemented in the specified modes. *Practical value.* The proposed solution can be used as a mean to protect the power part of the device in case of overload, which, in the event of emergencies, and their elimination will automatically restore the normal mode of the device. References 11, tables 2, figures 5.

Key words: active power filter, *pq*-theory of instantaneous power, relay current control, effective current value, hysteresis zone.

Цель. Целью работы является разработка методики ограничения до предельно допустимого уровня тока трехфазного силового активного фильтра (САФ) в условиях перегрузки или короткого замыкания и системы для реализации методики. *Методика.* Для проведения исследований использовались положения *pq*-теории мгновенной мощности, метод теории автоматического управления в системах с релейными регуляторами, методы моделирования в среде визуального программирования. *Результаты.* Как режим перегрузки, так и аварийный режим короткого замыкания, с использованием предлагаемого решения, не приводят к существенным изменениям уровня напряжения на накопительном конденсаторе, соответственно поддерживая стабильность работы силовой части силового активного фильтра. *Научная новизна.* При временных перегрузках по току и коротких замыканий в узле сети, к которому присоединяют силовой активный фильтр, ограничения его тока выполняются путем масштабирования действующего тока до уровня допустимого в условиях нормальной работы полупроводниковых элементов устройства, позволяет в указанных режимах реализовывать основной алгоритм работы. *Практическое значение.* Предложенное решение может быть использовано как средство защиты силовой части устройства в случае перегрузки, или в случае возникновения аварийных ситуаций, а их устранение обеспечит автоматическое обновление нормального режима устройства. Библи. 11, табл. 2, рис. 5.

Ключевые слова: силовой активный фильтр, *pq*-теория мгновенной мощности, релейное регулирование тока, действительное значение тока, зона гистерезиса.

Introduction. In industry, frequency converters, thyristor converters, inverters, rectifiers are widely used designed to control the flow of energy of electromechanical and electrical devices. These converters by the operation principle of their power unit have a significant impact on the quality of electrical energy. Thus, they negatively affect the electromechanical and electrical engineering devices, electric machines and apparatus. The compensation of resulting from the operation of such converters the reactive power and the filtration of higher harmonics of current generated by the above devices is at present a topical task. The use of harmonic filters and compensating capacitor batteries in the case of controlled converters does not lead to the desired result in ensuring the quality of electric energy [1].

Innovation in the issue of compensation of reactive power and filtration of higher harmonics of current is the use of active compensating devices - active power filters (APF) [2, 3]. APF have the ability, thanks to the algorithm, to perform compensation of reactive power and filtering of higher harmonics of current. The APF current is formed on the basis of active filtering algorithms based on one of the theories of power: the

theory of full power Frise [4], *pq*-theory of instantaneous power [5], *pqr*-theory of instantaneous power [6], and others. It depends on the neutral mode of the network node to which APF is connected which in turn affects the structure of its power unit.

Analysis of previous research. The APF current is formed on the basis of the load current and the network voltage in accordance with the existing methods for determining the components of power or current [4-6].

In the nodes of the system of electric consumption there are modes caused by overloads of technological mechanisms. This is possible, both in the technological process, and in case of emergency. A critical case of an overload of a network node is the emergence of a short circuit in the current or adjacent area. Taking into account the algorithm of operation, in the event of emergencies or overload, the control system of the APF will attempt to form a current that is likely to exceed the calculated current of the power unit. Definitely at the design stage of the industrial sample, elements of protection will be introduced into the power part of the APF but the problem of protection may be resolved in another way.

Elements of the APF power unit are selected based on the calculation mode: switching frequency, operating (nominal) current and operating (nominal) voltage, voltage of the accumulation capacitor in the circuit of constant sign voltage [7, 8].

Thus, the problem arises of limiting the given current of the APF in the part of the active filtering algorithm under the following conditions:

1) in the case of overloading of the APF –at a load current, the effective value of which exceeds the maximum permissible level for which the power part of the APF is calculated;

2) in the conditions of the short circuit of the load circuit of the APF in the current or adjacent areas of the power supply system for a period sufficient to trigger the emergency automatics.

The goal of the work is the development of a method for limiting up to the maximum permissible level of three-phase active power filter current in conditions of overload or short circuit and a system for the implementation of the technique.

Main material. APF provides the formation of a given current i_{apf}^* which during the operation of the device is compared with the actual current of the APF (current received from the sensors), the adjustment of the output parameter by the deviation. On the principle of relay regulation, the current error, or rather its sign, is a sign for the formation of pulses of control transistors of upper or lower arm of the converter [11].

Execution of the limitation by applying an appropriate line of limitation will lead to a change in the shape of the current, accordingly, it will lead to a violation of the procedure of formation of current and, as a consequence, of the principle of compensation. Thus, as a rational solution, the idea of scaling the current to a value that does not exceed the permissible actual value of the current of semiconductor valves of the power part I_{max} is proposed.

On the basis of the above, the following method of APF current limitation is proposed:

1. Set the value of the maximum current I_{max} due to the properties of the valves of the converter of the APF.

2. Determine the actual value of the given current of the APF for the period of the basic harmonic ($T = 0.02$ s):

$$I_{RMS} = \|i_{apf}^*\| = \sqrt{\frac{1}{T} \int_{t_0}^{t_0+T} (i_{apf}^*)^2 dt} . \quad (1)$$

3. Determine the ratio of the determined actual current value to the given maximum.

$$k = \frac{I_{max}}{I_{RMS}} . \quad (2)$$

4. In the event that the actual value of the APF current is below the maximum, no limitations are required, that is, the scale factor must be equal to one. In case if the actual value of current of the APF is above the maximum, it is necessary to comply with the limit on the value of the excess, in this way, the scale factor:

$$K = \begin{cases} 1, & \text{for } k \geq 1 \\ k, & \text{for } k < 1 \end{cases} . \quad (3)$$

Such conditions may be fulfilled using the limitation block.

5. The set actual current values of the APF is scaled:

$$i_{apf}^{**} = K \cdot i_{apf}^* . \quad (4)$$

To implement the developed technique, a block diagram of the subsystem of the current limitation of the active power filter shown in Fig. 1 is proposed.

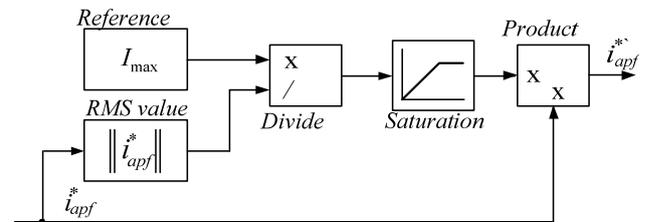


Fig. 1. Block diagram of the subsystem of the current limitation of the APF

The proposed block diagram (Fig. 1) is implemented in the subsystem of current formation (*pq-theory power control*), the control system of the APF in the composition of the electric power complex whose model (Fig. 2) is constructed in a graphical environment of simulation modeling and described in [9]. To determine the current of the compensation of the APF, the *pq*-theory of instantaneous power [4] was chosen, and as the method of pulse control of transistors of the converter - the method of relay current control (RCC) [11], the block (*Relay current control*) (Fig. 2).

The nonlinear load is represented by a three-phase thyristor converter (*Thyristor converter*) with an active-inductive load (*RL-load*) with parameters $R_{ld} = 0.666 \Omega$ and $L_{ld} = 0.0386$ H which at a control angle of 45° in a thyristor converter corresponds to calculated power $P_{ld} = 66$ kW, $Q_{ld} = 135$ kVAr. By the load parameters, taking into account the permissible deviation of the voltage, the three-phase source of electric energy [10] (*Three-phase source*) with the following parameters is calculated and introduced to the circuit: the current value of the interphase voltage $U_s = 380$ V, frequency $f_s = 50$ Hz, active and reactive resistances respectively $R_s = 0.1 \Omega$ and $L_s = 1.3 \cdot 10^{-5}$ H.

Elements of the power part of the three-phase APF are calculated according to the method [7]: reactor inductance $L = 0.0054$ H; capacitor voltage $U_{dc} = 2000$ V; capacitor capacitance $C = 20 \cdot 10^{-3}$ F [9]. The value of the hysteresis zone (current tube) in the RCC method is $HB = 10$ which corresponds to 5% of the nominal load current [11].

The operation of the model was studied in the mode of exceeding the maximum operating current in the case of overload (Fig. 3, 4) and in the emergency short circuit mode (Fig. 5, 6) using the *Three-Phase Fault* block (Fig. 2).

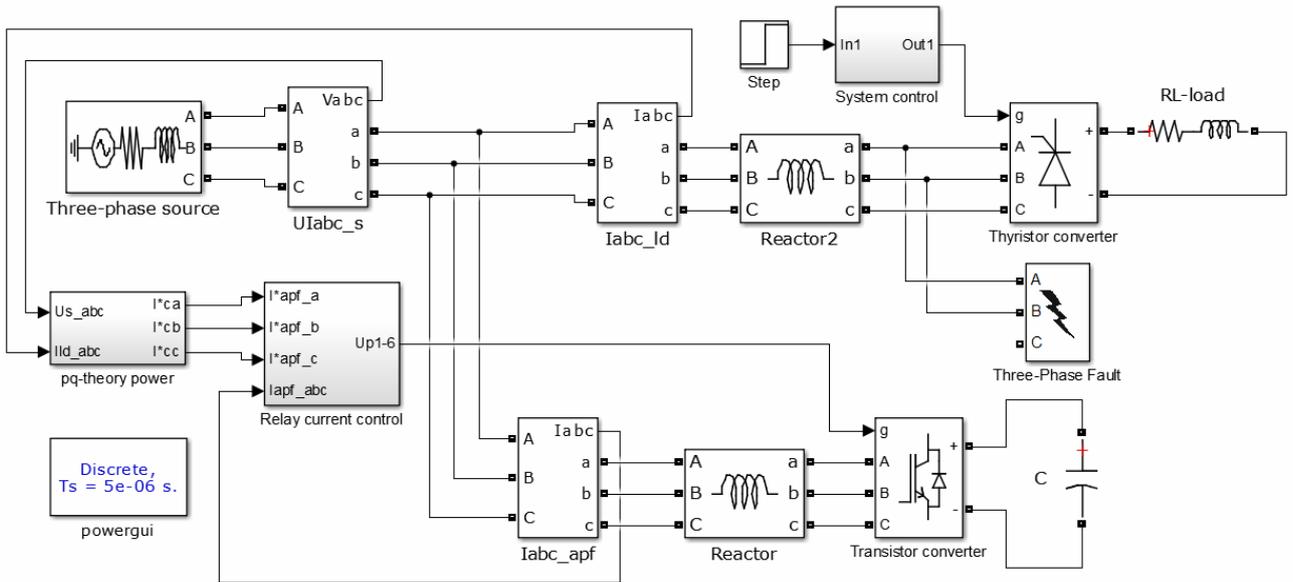


Fig. 2. Matlab Simulink model of the electric power system with three-phase APF

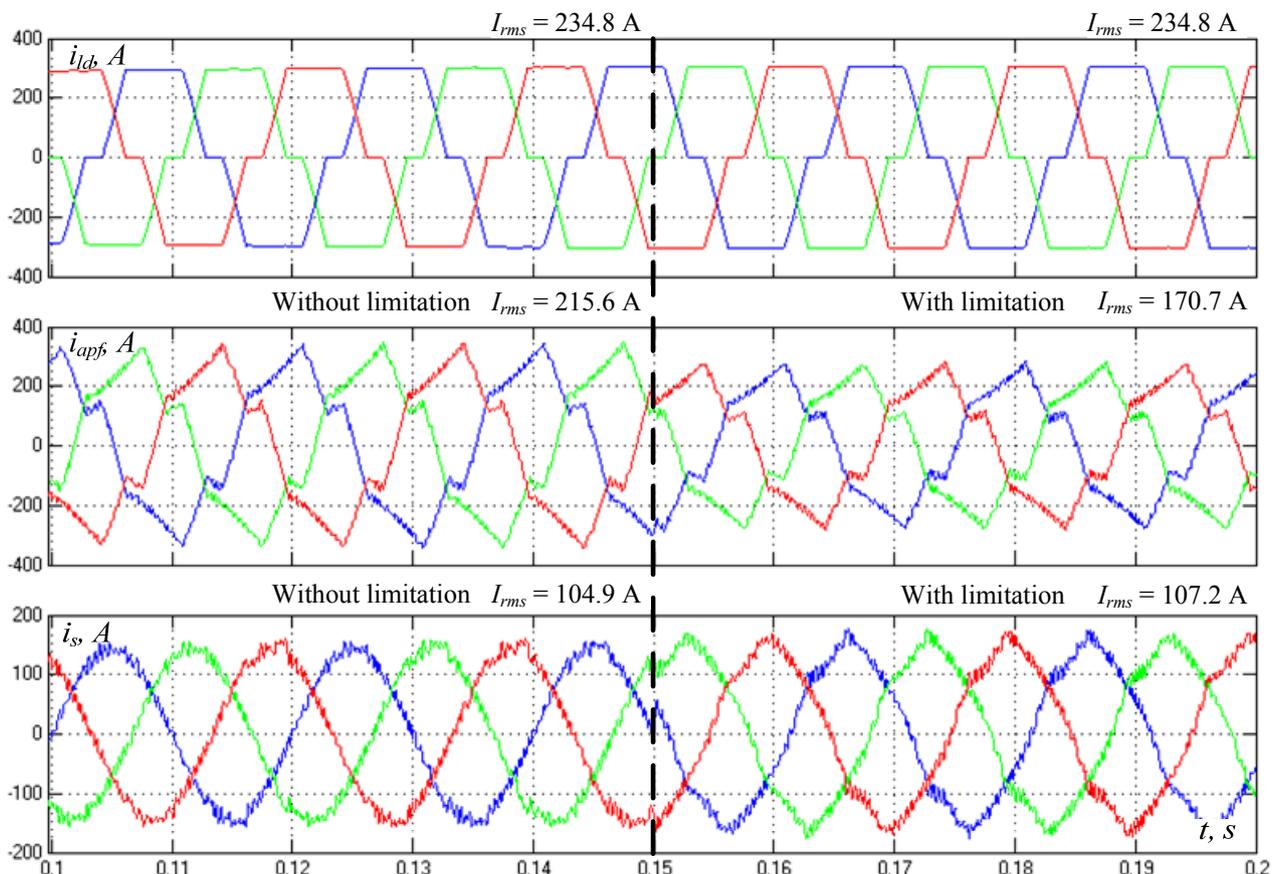


Fig. 3. Oscillograms of currents: of load current i_{ld} , actual of the APF i_{apf} and of the network i_s without and with limitation by maximum current value

Overload mode. The study was conducted with current limitation and without limitation. The given maximum actual value of current is set at the level $I_{max} = 170$ A. The results of simulation with the specified conditions are shown in Fig. 3. At the time interval (0.1-0.15 s) the current limiting subsystem is not active, there is an overload of the APF converter by working current of 215.6 A, while the compensation efficiency can be estimated by the integral indicators - Table 1 (without limitation). At the time interval (0.15-0.2 s), the current limiting subsystem is activated and the actual value of the APF current is reduced to the established maximum level, while the compensation indicators deteriorate – Table 1 (with limitations), but the device provides a reduction in reactive power and a coefficient of distortion of current.

Table 1

Summary results of study of the overload mode

Parameter	Without APF	Without limitation	With limitation
P, W	21300	21870	20630
Q, VAr	44270	-275.5	8621
I_{rms}, A	234.8	104.9	107.2
$THD_I, \%$	13.96	6.24	7.94
I_{apf}, A	-	215.6	170.7
$THD_{Iapf}, \%$	-	15.2	16.23

Based on the diagram of the change in the voltage of the accumulation capacitor (Fig. 4), the voltage deviation does not exceed 1%. At the same time reducing the value

of the current causes an increase in the energy reserve of the capacitor.

Short circuit mode (SC). The SC research was performed by simulating the phase-to-phase short circuit of two phases to the ground at the load node. In the system model a block is additionally introduced that implements the mode of short circuit in Fig. 2 (*Three-Phase Fault*) by closing the two phases to resistance $R = 0.001 \Omega$, at the interval of time (0.1-0.2 s).

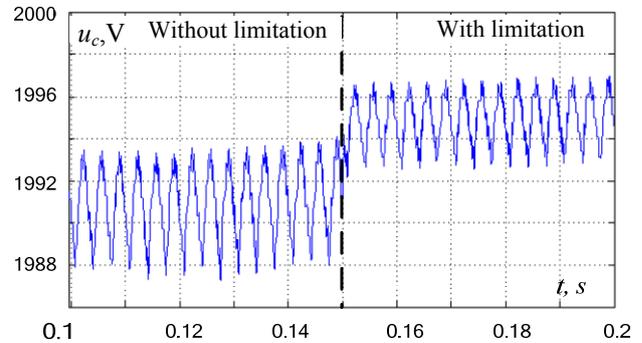


Fig. 4. Capacitor voltage with limitation and without limitation by the maximum current value

Due to the fact that the short circuit is realized using the ohmic resistance (Fig. 5), at the interval of the short circuit current caused by the active power significantly exceeds the current due to reactive power and distortion power.

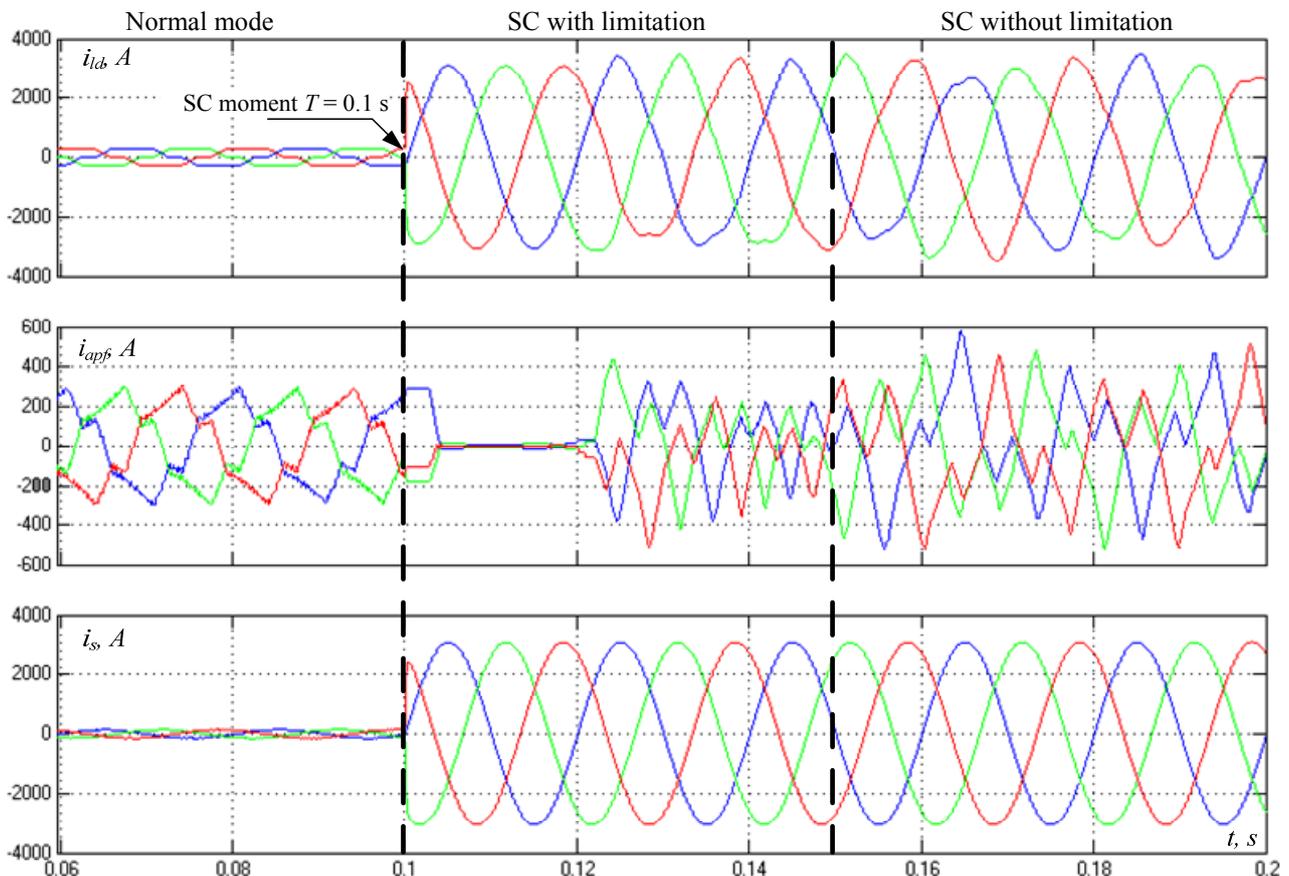


Fig. 5. Oscillograms of currents: of load current i_{ld} , actual of the APF i_{apf} and of the network i_s in the short circuit mode without and with limitation by maximum current value

Under the conditions of the short circuit mode, the operation of the block (*pq-theory power control*) is violated due to a significant decrease in the network voltage. In this case, the APF continues to provide compensation of the load current (Table 2 without limitation) and current limitation in the interval 0.1-0.15 s (Table 2 with limitation). Additionally, it should be noted that the use of the limitation leads to a decrease in overcompensation of reactive power.

The analysis of the voltage of the accumulation capacitor during the implementation of the short circuit mode shows, as in the previous case, a slight increase in the amplitude of the voltage pulses, which does not exceed 3 %.

Thus, the implementation of the proposed method, where the limitation up to the maximum allowable level of current of a three-phase APF in conditions of overload or short circuit is performed by scaling the current value of SAF to the level acceptable in the normal operation of semiconductor elements, allows, in the specified modes, to implement the basic algorithm of the operation of the APF, which is confirmed by the presented results of the research of the computer model of the system (Fig. 3-6).

Table 2
Summary results of study of the three-phase short circuit mode

Parameter	Without APF	Without limitation	With limitation
P, W	21300	4418	4671
Q, VAr	44270	-490	16,29
I_{rms}, A	234.8	2172	2171
$THD_I, \%$	13.96	0.8	0.8
I_{apf}, A	-	317.8	161.8
$THD_{Iapf}, \%$	-	60.9	70.6

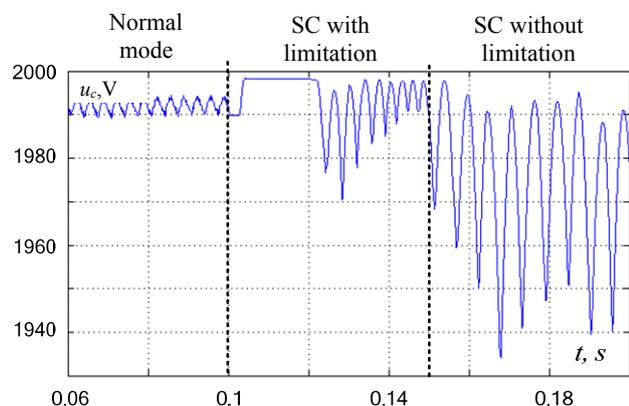


Fig. 6. Capacitor voltage at steady state without limitation by the maximum value and with limitation in the short circuit mode

Conclusions.

1. A method of limiting up to the maximum permissible level of current of a three-phase APF and a block diagram of the current limiting subsystem of the APF are proposed which allows to realize the basic algorithm of operation of the APF in the modes of its overload or short circuit.

2. Implementation of the proposed method allows to protect the power part of the APF in the case of emergency overload and short-circuit modes as well as provides automatic updating of the normal operating mode of the APF after the elimination of emergency modes by the system of emergency automatics.

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