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CHANGE OF FREQUENCY CHARACTERISTICS OF A FILTER USING A REACTOR WITH SMOOTHLY ADJUSTABLE INDUCTANCE

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Abstract. *Experimental studies of the proposed reactor by the authors were carried out through direct measurements of electrical quantities. Structurally, the reactor is designed as a stator of an electric machine with a single pair of poles and a rotor without windings in the form similar to an elliptical shape with flat sides. The magnitude of the inductance varies by rotating the rotor within the range from zero to ninety degrees, where zero degrees corresponds to the alignment of the stator pole axis with the longer axis of the rotor. The effectiveness of using such a reactor to complement passive controlled harmonic current filters is confirmed by corresponding calculations. It is shown that one controlled filter can replace two or more precisely tuned filters capable of absorbing only certain current harmonics.*

Keywords: electric reactor, smooth adjustment of reactor inductance, passive harmonic and interharmonic current filter

ZMIANA CHARAKTERYSTYKI CZĘSTOTLIWOŚCIOWEJ FILTRA Z WYKORZYSTANIEM DŁAWIKA O PŁYNNIE REGULOWANEJ INDUKCJI

Streszczenie. *Badania eksperymentalne proponowanego przez autorów reaktora przeprowadzono poprzez bezpośrednie pomiary wielkości elektrycznych. Konstrukcyjnie reaktor zaprojektowano jako stojan maszyny elektrycznej z pojedynczą parą biegunów i wirnikiem bez uzwojeń w kształcie zbliżonym do kształtu eliptycznego o płaskich bokach. Wielkość indukcyjności zmienia się poprzez obrót wirnika w zakresie od zera do dziewięćdziesięciu stopni, gdzie zero stopni odpowiada zrównaniu osi bieguna stojana z dłuższą osią wirnika. Efektywność zastosowania takiego dławika jako uzupełnienia pasywnych filtrów prądu harmonicznego potwierdzona jest odpowiednimi obliczeniami. Pokazano, że jeden kontrolowany filtr może zastąpić dwa lub więcej precyzyjnie dostrojonych filtrów zdolnych do pochłaniania tylko określonych harmonicznych prądu.*

Słowa kluczowe: dławik elektryczny, płynna regulacja indukcyjności dławika, pasywny filtr harmonicznych i interharmonicznych prądu

Introduction

Electric power is associated with the production of industrial goods sold to consumers, so its quality must meet certain requirements regulated by State and International standards regarding the indicators of power quality and electromagnetic compatibility requirements [1]. It is known that voltage flicker at a frequency of 5–10 Hz induces rapid fluctuations in the drive torque of the electric motor, leading to noise and rotor vibrations in the bearings, consequently reducing its operational lifespan. A similar situation occurs in the operation of power transformers, where subharmonics and interharmonics adversely affect their technical condition. The use of power electrical equipment with low electromagnetic compatibility with existing power supply systems deteriorates the quality of electrical energy in external and internal power grids. This concerns energy receivers containing elements with nonlinear volt-ampere characteristics. In this case, consumer electrical energy is considered, which generates higher harmonics and interharmonics that propagate in both low and high voltage electrical networks. The main sources of harmonics include rectifiers, inverters, frequency converters, arc and impulse welding units, arc furnaces, electromagnetic devices with nonlinear volt-ampere characteristics, and so on. If semiconductor devices generate a broad spectrum of even and odd harmonics, arc welding units generate interharmonics, which change frequency during their operation.

The second source of harmonic and interharmonic currents is the commutation processes, which, due to the occurrence of overvol-tages in the windings of transformers and reactors, magnetize the magnetic cores, accompanied by the distortion of the sinusoidal waveform of currents. The duration of such processes can last up to several minutes. During the design stage, specialists try to solve the problem of electromagnetic compatibility between power electrical equipment and power supply systems by using various schematic, technical, and operational solutions [18, 26]. However, this problem remains unresolved. One of the problems of electromagnetic compatibility between energy receivers and power supply systems is the generation and propagation of higher harmonics and interharmonics in electrical networks, which penetrate into the circuits of receivers sensitive to harmonics [7]. Various harmonic current filters, both passive and active, are used to limit them. If we consider the feasibility of using active filters, such solutions make sense in cases of operating powerful power electrical equipment containing semiconductor elements. In such cases, the application of active filters can be technically and economically efficient due to their easy adaptation to the operation modes of power supply networks with a high content of harmonics and interharmonics [9, 16]. The main drawback of such filters is their complex design, high cost, and complexity of control systems, which limits their application. Passive current filters built on the basis of series-connected inductive-capacitive elements are much cheaper in terms of cost. Many specialists believe that passive filters are not very effective. However, practice shows that such filters have significant potential, especially in power grids for supplying low- and medium-power consumers. We are talking about improved designs of passive filters with the ability to change their frequency characteristics directly under voltage. Their main advantages are simplicity of design, high reliability of operation, and low cost. Therefore, the task of improving and creating controlled passive filters for higher harmonics and interharmonics in distribution and power grids is important and relevant, requiring further resolution [4, 23].

1. Materials and methods

In order to address the assigned task, the authors fabricated and utilized a filter reactor with the capability to smoothly change the position of the rotor poles within a rotation angle ranging from zero to ninety degrees. Electrical measurements were conducted using analog measuring instruments, including an ammeter with a precision class of 0.2, and a voltmeter and wattmeter with a precision class of 0.5.

For the investigation of the frequency characteristics of a single-phase passive voltage filter at 0.23 kV non-industrial frequencies, a current formed by a reactor with smoothly adjustable inductance and capacitor banks assembled from typical capacitors was subjected to mathematical modeling, considering the limits of reactor parameter variations obtained experimentally.

Depending on the power and operating voltage of filters, there are several methods for adjusting their absorption frequency. However, only certain methods are suitable for filters used in power supply systems for powerful energy receivers. Passive harmonic current filters, in which the change in inductance of the filter reactors is achieved directly under voltage by magnetizing the magnetic circuits, are among those applicable methods [11]. This approach is justified as it allows for the frequency characteristic of the passive filter to be changed within specified limits under load, without disconnecting the filter from the power grid. However, magnetization of the reactor leads to saturation of the magnetic circuit and, as a result, generates odd harmonics of voltages and currents that are multiples of the third harmonic, which also penetrate the power supply networks [2, 20].

Additionally, it has been proposed to use reactors with an additional winding through which inductance is introduced into the main winding by magnetic coupling between the main and additional windings [12, 13]. Fig. 1 illustrates the diagram of a harmonic current filter with an additional winding, which is recommended for use in power supply systems for arc steelmaking furnaces (ASF). The discrete regulation of the reactor's inductance is its main drawback, especially when the change in the frequency of interharmonics and their range occurs within a few tens of seconds. During such a short period, the transient process resulting from a step-like change in the reactor's inductance does not have enough time to dampen, and it may even induce magnetic saturation effects and the emergence of new interharmonics or a change in the frequency of existing ones.

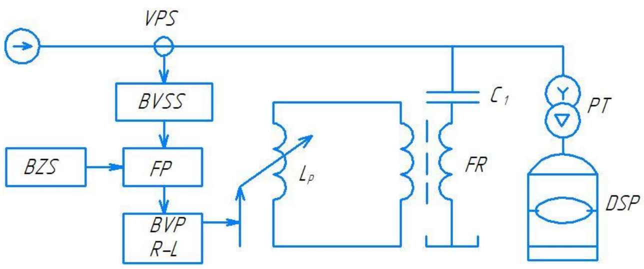

Fig. 1. Diagram of a harmonic current filter with an additional winding

Such a reactor can be successfully used in cases where smooth adjustment of its inductance, connected in the additional winding circuit, is not required, but the adjustment should be carried out directly under voltage. Problem statement: To limit multiple harmonics in power supply systems, a corresponding number of precisely tuned passive inductive-capacitive filters are required, which is not always economically and technically feasible. From a technical point of view, the occurrence of anti-filtering modes due to deviations in capacitor parameters caused by temperature influences is significant, which greatly reduces the effectiveness of the filters. Additionally, in such operating modes, parallel branches of different filters create resonant circuits in which currents with frequencies dependent on the parameters of capacitors, filter reactors, and especially the power supply system, occur. As a result, there is an additional current overload of capacitors with harmonics and interharmonics [1, 27]. The adjustment of the frequency and bandwidth of current absorption by passive filters is achieved by changing the reactor parameters. However, the above-mentioned methods of adjusting the reactor's inductance do not always allow for the tuning of passive inductive-capacitive filters to interharmonics, the amplitudes of which can reach significant values. The authors have set the task of proposing and studying the technical characteristics of a passive harmonic current filter that uses a reactor with smooth adjustment of inductance directly under voltage, and identifying reserves for expanding the limits of its parameter changes [10, 22].

Presentation of the main material. In order to solve the assigned task, an electric reactor with smooth adjustment of its inductance directly under voltage was investigated. It has a cylindrical-shaped housing 1 in which the poles 2 are mounted, and the windings 3 with their terminals 5 are placed on the poles, as shown in Fig. 2 [15]. The rotor 4 rotation angle is changed using an electric motor through a mechanical reducer within the range from zero to ninety electrical degrees. The position of the rotor corresponding to the zero angle between the axis of the poles and the rotor is when its longer axis coincides with the axis of the poles 2 (the directions of the axes are indicated by arrows in Fig. 2). It should be noted that the poles 2 and the rotor 4 are made of sheets of electrical steel, and the ratio of the height of the investigated reactor's rotor to its thickness is 1.6.

Obviously, the geometric dimensions and shape of the reactor's rotor and poles affect its inductance. In order to obtain characteristics and limits of variation of the electrical parameters of the reactor with smooth adjustment of its inductance, experimental measurements of electrical quantities were performed, which allowed obtaining the parameters of active power P and current in the windings of the stator poles I, with the applied voltage magnitude U remaining constant [3, 25].

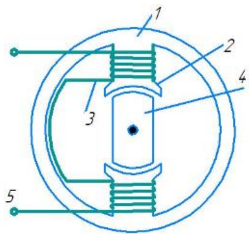

Fig. 2. Main elements of a reactor with smooth inductance control

During the research, a voltage with a frequency of 50 Hz was selected with a magnitude of 40 V, allowing the corresponding values of current and power in the reactor winding to be obtained, as shown in table 1. Measurements were taken at every 15° of rotation of the reactor rotor axis relative to the pole axis, ranging from 0 to 90° [5].

Using the values of the total and active resistances of the reactor, its inductance is determined by the

$$L_p = \frac{\sqrt{Z^2 - R^2}}{2\pi f}, \text{ H} \tag{1}$$

where f – the frequency of the supply voltage, which equals 50 Hz.

The nature and range of variation of the quality factor of a passive controlled harmonic current filter are assessed using a coefficient calculated as

$$k = \frac{\sqrt{X_P^2}}{R} \tag{2}$$

2. Results and discussion

The results of electrical measurements and calculations of parameters for the reactor with smoothly adjustable inductance are presented in table 1, it can be observed that as the rotor rotation angle increases, the ratio of active power losses to the total power of the adjustable reactor nearly doubles due to the increased current in the reactor windings. In real conditions, this indicator will continue to rise due to the increase in active power losses in the reactor caused by harmonics and interharmonics. These, when circulating in the reactor windings, create additional losses in active power within the reactor's magnetic core.

Table 1. Results of measurements and calculations of reactor parameters

No	Measurements			Calculations				
	°F	*p, Vt*	*I, A*	*Z, Ohm*	*R, Ohm*	*X, Ohm*	*L, H*	*k*
1	0°	19.0	4.1	9.8	1.13	9.73	0.03	2.76
2	15°	20.1	4.25	9.41	1.12	9.35	0.029	2.73
3	30°	30.25	5.25	7.62	1.08	7.54	0.024	2.54
4	45°	41.25	6.25	6.4	1.08	6.3	0.02	2.32
5	60°	63.75	7.7	5.19	1.07	5.18	0.016	2.13
6	75°	74.25	8.3	4.82	1.07	4.7	0.015	2.03
7	90°	86.25	9.0	4.44	1.06	4.27	0.014	1.95

Using the results of calculations and measurements provided in table 1, graphical dependencies of the calculated electrical parameters of the reactor based on the rotor rotation angle are obtained and presented in Fig. 3.

Due to the highest total resistance of the reactor being 9.98 Ohms at a rotor rotation angle of zero degrees, the reactor current is 4.1 A. After changing the rotor rotation angle to 90 degrees, the total resistance of the reactor decreases to 4.44 Ohms, and the current increases to 9 A (Fig. 3a).

This is explained by the fact that when the axes of the poles and the rotor of the reactor coincide, the air gap between the poles and the reactor is minimal, thus maximizing the reactor's inductance. The maximum air gap between the poles and the rotor corresponds to a 90-degree angle, resulting in minimal inductance. The decrease in the total resistance of the reactor is accompanied by an increase in the reactor current and, consequently, the total losses of active power in the windings and magnetic core from 19 W to 86.25 W. In this case, the active resistance of the reactor changes from 1.13 Ohms to 1.06 Ohms, and the reactive resistance decreases from 9.73 Ohms to 4.27 Ohms (Fig. 3b). A higher value of the active resistance of the reactor corresponds to a lower current in the windings because, in this case, losses in the windings are added to losses in the magnetic cores of the pole tips and rotor, which are greater than for a 90-degree angle (Fig. 3b).

From Fig. 3, it can be observed that depending on the rotation angle of the rotor, the inductance of the reactor varies from the maximum value of 0.03 H to the minimum value of 0.014 H (Fig. 3c), approximately 2.2 times. The coefficient *k* smoothly decreases from 2.76 to 1.95 with the increasing angle (Fig. 3d), reflecting the regularity of the controlled passive current filter's quality factor change. The conducted research confirmed the possibility and approximate value of the multiple changes in inductance depending on the rotation angle of the rotor of a real reactor. It should be noted that the magnitude and limits of the reactor's inductance variation can be expanded by changing the geometric parameters of the poles and the rotor, including altering the ratio of the longitudinal axis of the moving reactor rotor to the transverse axis and the construction of pole tips. Additionally, changing the number of turns of the windings of the poles in the stationary part of the reactor can also contribute to this variation. For voltage filters up to 1 kV, a reactor with smoothly adjustable inductance is practical to use as the main element of a passive filter tuned to a specific harmonic. The proposed reactor can also be used for filters with voltages over 1 kV in the circuit of an additional winding with a voltage up to 1 kV, as the main winding of the filter reactor is connected to a high voltage circuit, particularly 6 or 10 kV. The proposed reactor can realistically be manufactured for a voltage of 6 kV or 10 kV and thus serve as the main element of a controlled filter.

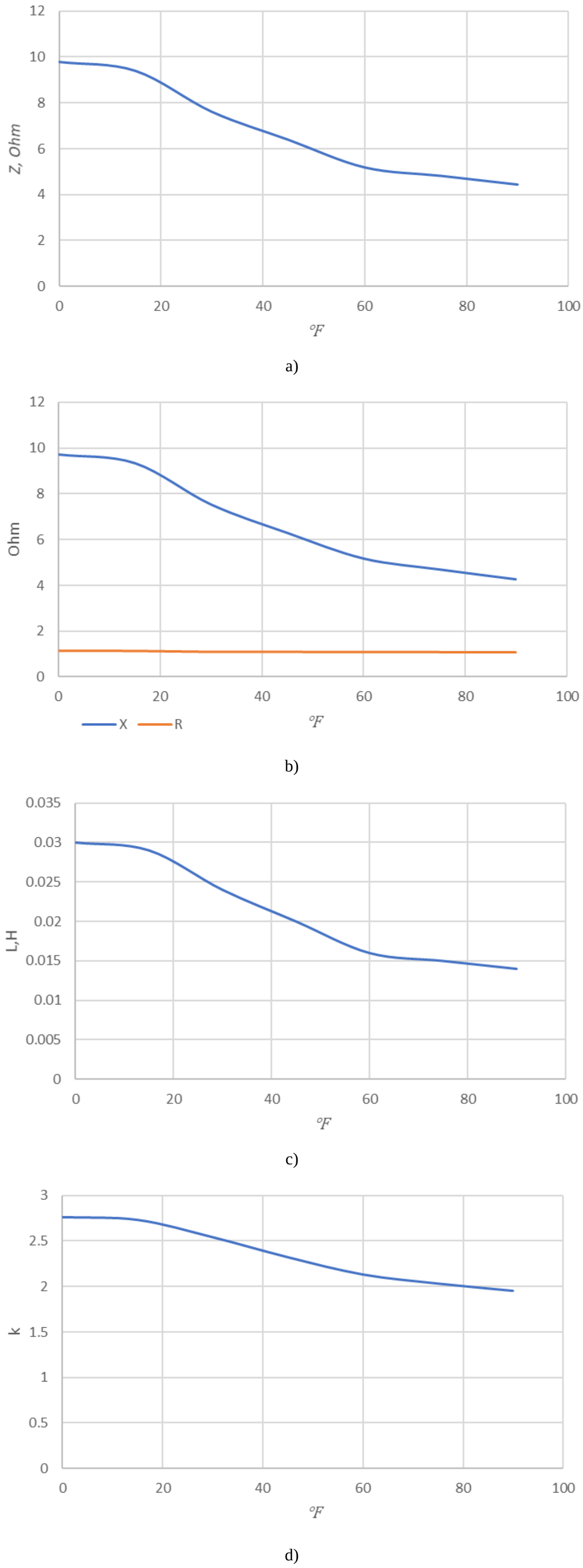

Fig. 3. Dependencies of reactor parameters on the rotor rotation angle

In Fig. 4, the diagram of a passive controlled voltage filter up to 1 kV using a reactor with smoothly adjustable inductance is presented [19]. In this configuration, a capacitor with capacitance C is connected in series with the winding of the main poles of the reactor and is connected to the phase conductor of the electrical network.

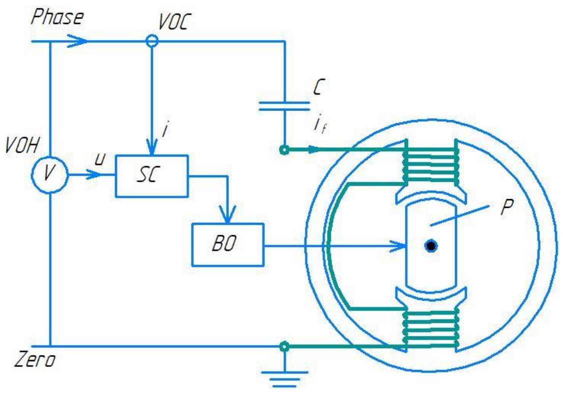

Fig. 4. Schematic diagram of a controlled harmonic current filter for voltages up to 1 kV

The measuring device for the current, connected in the cross-section of the phase conductor, records the instantaneous value of the current i, and the measuring device for voltage records the instantaneous value of the voltage (u). These values are fed into the control system, where a control signal is generated. This control signal is then input into the executive device, which commands the drive motor to rotate the rotor of the reactor with adjustable inductance [17]. In the control system, the detection of dominant harmonics or interharmonics in currents is performed, and the required values for the reactor's inductance and rotor angle are determined.

Let's consider the frequency characteristics of controlled filters designed for absorbing frequency bands of currents in nodes of electrical networks with voltages up to 1 kV, formed on the basis of standard parameters of capacitors and reactors with smoothly adjustable inductance.

With the goal of selecting reactor parameters for filters with two frequency intervals, specifically for 200 Hz using capacitor CP2-0.5-36 with a total capacitance of 458 μF, and for 300 Hz using capacitor CP-0.5-18 with a nominal voltage of 500 V and a total capacitance of 398 μF.

The inductance of the controlled reactor for filters with the adopted minimum frequency and given capacitor capacitance is determined by the expression:

$$L_p^{(k)} = \frac{1}{(2\pi \cdot k \cdot f)^2 C}\text{, mH} \qquad (3)$$

where k – the number of the minimum current harmonic, f – is the fundamental frequency of the supply voltage, C – the capacitance of one phase of the capacitor.

For the previously accepted parameters of the capacitors, the maximum inductance of the reactor for the fourth harmonic filter is 4.2 mH, and for the sixth harmonic filter, it is 2.15 mH. Experimentally, it has been demonstrated that the minimum inductance of the smoothly adjustable reactor is 2.1 times less than the maximum. Therefore, the minimum inductance for the fourth harmonic filter is 1.96 mH, and for the sixth harmonic filter, it is 1.0 mH.

Taking into account the limits and the nature of changes in the inductance of the adjustable reactor, a frequency range has been obtained that can cover both filters [8, 24]. In figure 5, graphical dependencies of the frequency characteristics of the fourth harmonic filter (Fig. 5a) and the sixth harmonic filter (Fig. 5b) are presented. It can be observed that the frequency interval covered by the filter initially tuned to the fourth harmonic is approximately 96 Hz, while the filter initially tuned to the sixth harmonic covers about 135 Hz.

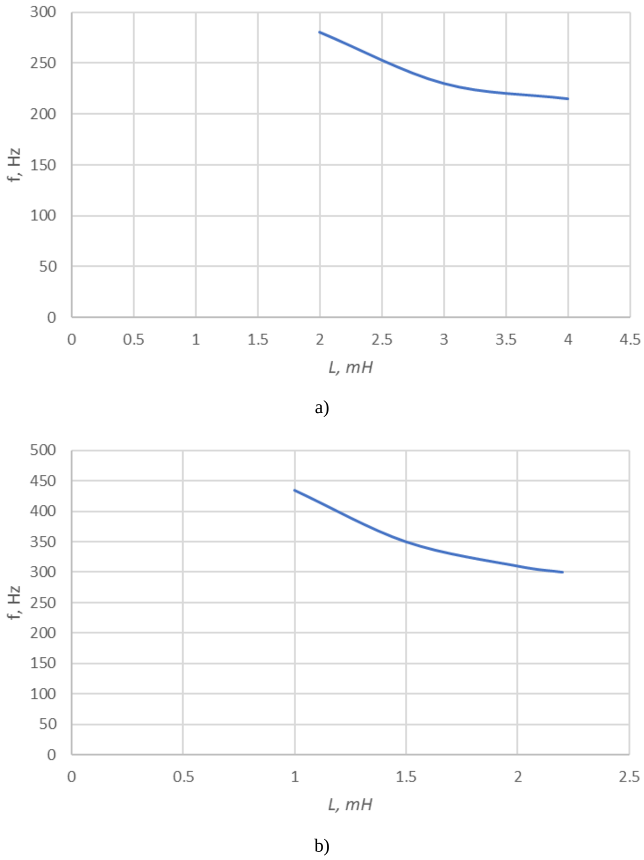

Fig. 5. Dependencies of frequency ranges of controlled filters on inductance

From Fig. 5, it can be seen that both filters are capable of absorbing harmonics and interharmonics in the frequency range from 200 Hz to 435 Hz, replacing five precisely tuned filters that cannot absorb interharmonics.

The structural diagram of the filter control system is shown in Fig. 6. In this diagram, instantaneous values of voltage and current from the measurement devices are directed into memory blocks for storing the instantaneous values of voltage and current over a specified time interval. This time interval is set by the time interval assignment block for recording instantaneous voltage and current values [21]. The instantaneous values of voltage and current from the memory blocks are then input into blocks for isolating the first harmonic of voltage and current. In these blocks, the first harmonic components are subtracted from the instantaneous values of voltage and current, resulting in the instantaneous values of voltage and current without the first harmonic. By determining the effective value of the voltage difference ΔU_{THD} and dividing it by the effective value of the first harmonic voltage, the distortion factor of the voltage waveform over the specified time interval is obtained [6].

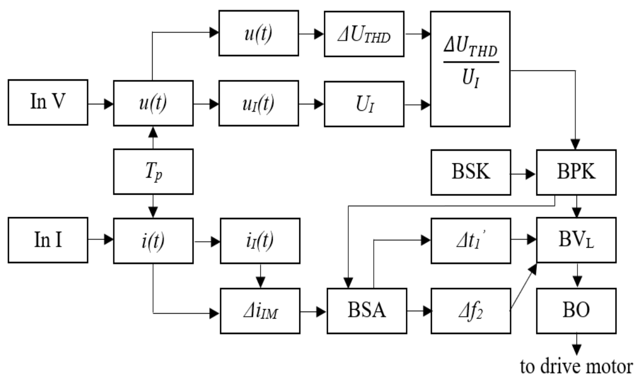

Fig. 6. Structural diagram of passive current filter control system

If this coefficient is less than the one set by the K-setting block, then the comparison coefficient signal is sent from the comparison coefficient block to the spectral analysis block, which continues to monitor voltage and current. If the coefficient K exceeds the value set by the K-setting block, then a signal from the comparison coefficient block is sent to the spectral analysis block, where spectral analysis of the instantaneous current difference is performed on the specified time interval. The frequency range is divided into two subranges, which are sent to the blocks F_1 and F_2 according to the frequency ranges of the first and second controlled filters, respectively. The selected frequencies in the F_1 and F_2 blocks, corresponding to the maximum amplitudes, are sent to the BV_L block, where the rotor turning angle of the controllable reactor is selected, corresponding to the required inductances for filter tuning.

The approximate techno-economic calculations were based on a comparison with direct current (DC) motors, which are structurally very similar to the reactor with adjustable inductance for voltages up to 1 kV. The results indicated that the cost of the reactor is nearly three times lower than that of a DC motor [12, 14].

The range of inductance variation can be increased by optimizing the geometric parameters of the poles and rotor. The cost of reactors with adjustable inductance at 6 kV was not assessed in this study, but it might be slightly higher than that of reactors with fixed inductance. In real-world conditions, this difference is in favor of the reactor with adjustable inductance, as it allows for the direct adjustment of the current absorption frequency under voltage.

The conducted research demonstrates that the effectiveness of such filters is significantly higher than those precisely tuned to a specific frequency. Therefore, they deserve more detailed investigations and further utilization.

3. Conclusions

Based on the conducted experimental research and corres–ponding calculations, the feasibility of using the proposed reactor with smoothly adjustable inductance for controlled harmonic and interharmonic current filters has been demonstrated.

The results of the investigation of the physical model of the reactor with adjustable inductance confirm the feasibility of implementing such a reactor design for controlled passive filters of harmonics and, particularly, interharmonics.

The simulation results indicated that the controlled harmonic and interharmonic filter can attenuate the frequency range within 90 to over 135 Hz, depending on the minimum frequency to which the filter is tuned. At lower frequencies, the range is narrower, but as the frequency increases, the absorption range of frequencies by the specified filter expands. This highlights the need to consider careful selection of reactor and capacitor bank parameters.

The obtained frequency response characteristics of controlled filters indicate that it is possible to restrict a wide range of harmful current frequencies in electrical networks with a minimal number of controlled filters, which is economically advantageous compared to non-controlled filter options.

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