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Abstract: This article presents research models, physical processes and mathematical expressions of the processes, quantities and parameters in the elements and structures of three-phase electromagnetic current transformers used in measurement and control systems of asymmetrical three-phase reactive power of power supply systems.

Key words: Asymmetrical three-phase current converter sensor (AThCCS), reactive power, primary current, secondary voltage, graph model, sensitive element, static characteristics.

Introduction
In the monitoring and management of electric power supply systems in the world, great attention is being paid to determining and standardizing the values of measured and controlled quantities and parameters based on signal transformation processes, to the accuracy and reliability of measurement indicators, and to algorithms and practical software products that provide them.

Asymmetrical three-phase current converter sensor (AThCCS) requires the use of modern calculation and design complexes in research issues of three-phase primary current to secondary voltage electromagnetic converters [1, 2]. This article presents research models and mathematical expressions of the processes, quantities and parameters of the three-phase electromagnetic current transformers used in the measurement and control systems of the reactive power of the power supply systems and the elements and structures of the three-phase electromagnetic current transformers.

The diagram below shows the principle of the structure of the magnetic switching elements of the sensor for changing the reactive power $I_A, I_B, I_C$ – three-phase primary currents to the secondary voltage in the power supply of the asymmetrical three-phase current transformer sensor.
Main part

In reactive power control systems, the transformation of the current value into the output signal in the form of a voltage requires the modeling of interconnections between sections and circuits and the research of the principles of construction of converters, the study of physical and technical effects that form the basis of the converter structure. The process of converting the value of the primary currents into a signal in the form of a voltage and the algorithm of building a model of the converter structure has the following sequence, which includes the principles of signal conversion of various types of physical nature, the interaction between the sizes and parameters of the converter structure and elements, which are used to control and monitoring the reactive power corresponds to the process.

A graph model for generating the output voltage of a single-phase single-sensitive element AThCCS of a power network with a reactive power source connected to the power supply system (PSS) was formed (Fig. 2).

The generation of the output voltage of the PSS reactive power source electrical network single-phase single sensitive element AThCCS is in the form of the analytical expression (1) formed on the basis of the graph model [3, 4, 5, 6]:

$$U_q = K_{I_{k}F_i} \Pi_\mu \Phi_\mu I_k$$

(1)

where: $K_{I_{k}F_i}$ is the inter-chain connection coefficient of the process of transformation of the magnetic driving force into the primary current of the electric circuit; $\Pi_\mu$ is the coupling coefficient of the conversion of the magnetic driving force into the magnetic current; $K_\Phi\mu$ is the coupling coefficient of the conversion of the magnetic flux to the secondary output voltage; $I_k$ is the primary current of the electric circuit.

A graph model of the generated output voltage of the AThCCS two-phase single-sensitive element with distributed parameters of the power network connected to the PSS reactive power source is formed (Fig. 3).
The output voltage of a single-phase single-sensing element AThCCS with a distributed parameter is formulated in the form of the analytical expression (2) generated on the basis of a graph model [7, 8]:

\[ U_a = I_A K_{IA} K \mu K_{\Phi \mu} = 4.44w_a f \left( \frac{F_{\mu13} - F_{\mu17}}{\Pi_0 \mu_{11}} - \frac{F_{\mu17} - F_{\mu12}}{\Pi_0 \mu_{12}} \right) \]  

(2)

where: \( K_{IA} \) is the inter-chain connection coefficient of the process of changing the magnetic driving force into the primary current of the electric circuit; \( K \mu \) is the coupling coefficient of the conversion of the magnetic driving force into the magnetic current; \( K_{\Phi \mu} \) is the coupling coefficient of the conversion of the magnetic flux to the secondary output voltage; \( I_A \) is the primary current of the electric circuit; \( w_a \) – number of sensitive element windings, \( F_{\mu} \) – magnetic driving forces (respectively), \( f \) – frequency, \( \Pi_0 \mu \) – air gap coefficient.

The output voltage generation graph model for the three-phase three-sensing element AThCCS spring state with distributed parameters of the power network connected to the PSS reactive power source is presented in Fig. 4.

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**Results**

From the generated graph model, from the system of fifteen unknown equations, the distribution of the unknowns in the magnetic field is determined according to the magnetic parameters, and the values of the magnetic driving forces determine the quantities of the transfer functions.
where: $K_{IA}F_{µ}^I$, $K_{IB}F_{µ}^I$, $K_{IC}F_{µ}^I$ - the number of sensitive element windings ($w_a$, $w_b$, $w_c$), $I_A$, $I_B$, $I_C$ - primary currents, $\Pi_{ij}$, $\Pi_{µij}$ - resistances of magnetic core (sturgeon) and air gap magnetic parameters, respectively, $F_{µij}$ - magnetic core (sturgeon) sensor of magnetic forces.

$$U_a = U_a' - U_a'' = 4.44 w_f \frac{f_{µ11-µ17} + f_{µ12-µ18}}{\Pi_{µ11} + \Pi_{µ12}}$$

$$U_b = U_b' - U_b'' = 4.44 w_f \frac{f_{µ13-µ19} + f_{µ14-µ20}}{\Pi_{µ13} + \Pi_{µ14}}$$

$$U_c = U_c' - U_c'' = 4.44 w_f \frac{f_{µ21-µ27} + f_{µ22-µ28}}{\Pi_{µ21} + \Pi_{µ22}}$$

So, as can be seen from the above formula, we can get the secondary output voltage in the sensing range of the sensitive element (a coil wrapped on a flat plate) inserted into the magnetic field created by the magnetic field in a symmetrical state. If the symmetrical condition does not occur, that is, there is symmetry between the phases, in this case, the secondary output voltage will be zero.

$I_A$, $I_B$, $I_C$ - primary currents (in the range of 1-500 amperes) as the main variables in the given model. $W_A$, $W_B$, $W_C$ - number of windings of input windings (1-10), number of windings, $w_a$, $w_b$, $w_c$ - sensitive elements (windings), number of windings of output windings (1-90), conversion of the winding to the range, researches were carried out on the basis of the model.

The analytical expression of output voltage depending on the number of primary and secondary windings is determined as follows:

$$U_q = \frac{4.44 \mu_0 w_1 w_2 f F r I_k}{\delta}$$

where: $w_1$ is a single-phase current conductor of the electrical network - the number of primary windings; $w_2$ - the number of secondary windings; $f$ - frequency; $F$ - cross-sectional surface; $I_k$ is the primary current flowing from the single-phase current conductor the primary circuit of the transformer; $\delta$ - the air gap where the secondary windings are located; $\mu_0$ is the magnetic absorption of the air gap.
Asymmetrical three-phase reactive power primary current $I_k=100$ A sensing piece shows the variation of the output voltage at different values of the number of windings (Fig. 5).

**Figure 5.** Static characteristics of the dependences of the number of secondary windings between the primary currents of asymmetrical three-phase reactive power and the sensor output voltage.

$w_2$ – is a description of the dependence of the change in the number of secondary windings on the change in output voltage obtained on the basis of the aggregated parameter model (based on equation 5, $I_A$ is the change in the output voltage corresponding to the current).

**Discussion**

Currently, there are direct and alternating current sensors, but it is necessary to consider their advantages and disadvantages when choosing the optimal type of direct and alternating current sensors in the control of three-phase reactive current asymmetry of electric power supply sources, and to evaluate the prospects of their development and use in the control system. The relative evaluation of current sensors is presented in table 1 [9, 10].

<table>
<thead>
<tr>
<th>№</th>
<th>Type</th>
<th>Measurement limit</th>
<th>Error</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Electro mechanic</td>
<td>0-1000 A</td>
<td>5 %</td>
<td>The simplicity of the structure</td>
<td>The presence of a moving part</td>
</tr>
<tr>
<td>2</td>
<td>Rogowski belt</td>
<td>10-100 A</td>
<td>0,2 - 0,5 %</td>
<td>The simplicity of the structure</td>
<td>Large volume-weight indicators</td>
</tr>
<tr>
<td>3</td>
<td>Resistive</td>
<td>0-10 kA</td>
<td>0,2 - 0,5 %</td>
<td>The simplicity of the structure</td>
<td>The need to break the chains</td>
</tr>
<tr>
<td>4</td>
<td>Magneto resonant</td>
<td>0-10 kA</td>
<td>0,01 - 0,03 %</td>
<td>High precision</td>
<td>The need to break chains at the source</td>
</tr>
<tr>
<td>5</td>
<td>Current transformer</td>
<td>0-150 kA</td>
<td>0,2 - 0,5 %</td>
<td>Reliability, simplicity of service</td>
<td>Large volume-weight indicators</td>
</tr>
<tr>
<td>6</td>
<td>Magneto galvanic</td>
<td>0-200 kA</td>
<td>0,1 - 0,5 %</td>
<td>High accuracy and sensitivity</td>
<td>Constructive and schematic complexity</td>
</tr>
<tr>
<td>7</td>
<td>Magneto-optical</td>
<td>0-200 kA</td>
<td>0,05 - 0,1 %</td>
<td>Possibility of application in high voltage lines</td>
<td>The complexity of the structure and measurement scheme</td>
</tr>
<tr>
<td>8</td>
<td>Asymmetrical three-phase current converter sensor</td>
<td>0-500 A</td>
<td>0,2 - 0,45 %</td>
<td>Simplicity of the constructive structure, reliability, economy, accuracy and application in asymmetrical currents</td>
<td>Sensitivity to external magnetic fields and temperature dependence</td>
</tr>
</tbody>
</table>

The sensitive element of the sensor that converts the current value into an output signal in the form of a voltage (flat measuring rod) and the type of internal magnetic conductor plate located in the
slot of the magnetic conductor fully satisfy the requirements set in the control of power supply imbalances.

**Conclusion**

1. The need to take into account the interaction of three-phase currents flowing from the primary phases of electric networks with the help of electromagnetic converters, to analyze the magnitudes and changes of magnetic currents and to generate signals in the form of voltage in the secondary circuit made it possible to create a new category of three-phase current-to-voltage converters.

2. The characteristic features of signal sensors for measurement and control of symmetrical three-phase reactive power source currents were analyzed, and as a result, it was found that signal sensors for measurement and control are an important tool for detecting mutual asymmetry.

3. Graph models provided an opportunity to study the signal transformation process and structure of three-phase current sensors on the basis of clarity and high formalization.

4. Created cumulative and distributed parameter graph models to determine the values of the output voltages of the electromagnetic current to voltage converters $U_A$, $U_B$, $U_C$ based on the criterion of perpendicularity and uniform distribution of the crossing of the surface of the sensitive elements of the magnetic current converter and the values of the magnetic driving force and magnetic flux of the control converters an accurate calculation method has been developed.

5. The graph and analytical models of physical and technical effects that can be used in the sensor structure made it possible to rationalize the magnitudes and parameters of the process of converting primary currents to secondary output voltages $U_n$, as well as the geometric dimensions of the sensor switching parts.

**Reference**


