Structure of control sensors of multi-phase reactive power currents in power supply systems

I Kh Siddikov1, P D Chelyshkov2, A B Abubakirov3, N M Nazhimatdinov3 and R Zh Tanatarov3

1 Tashkent University of Information Technologies named after Muhammad al-Kharazmi, Tashkent, Uzbekistan
2 Moscow State University of Civil Engineering, Moscow, Russia
3 Karakalpak State University named after Berdaq, Nukus, Uzbekistan

E-mail: ikhsiddikov@mail.ru, chelyshkovpd@gmail.com, aziz1306@mail.ru

Abstract. In this work, collected and distributed algorithms for parametric research and models of the process of converting reactive power sources in power supply systems (PSS) into a secondary signal U_output - the output voltage based on electromagnetic sensors are developed. Based on a graphical model of the modification process and sensor structure, it provided clarity and high formalization.

1. Introduction

A number of studies and research works are being carried out in the world on widespread use in power supply systems. Production, control and management of reactive power and energy required for these sources, while improving the quality of electricity and improving the means and devices to ensure the smooth operation of the power supply system. In this regard, it is necessary to develop models, algorithms and software solutions for elements and devices that ensure reliable operating modes of power supply systems, the amount and quality of generated electricity, as well as control and management of primary currents of reactive power sources.

The republic is taking large-scale measures to further improve the energy sector in power supply systems, as well as to create and operate elements and devices for monitoring and managing energy quality indicators. The strategy of actions for the further development of the Republic of Uzbekistan for 2017-2021 includes the following tasks: "... reduction of energy and resource consumption in the economy, social sphere, economy ... widespread introduction of energy-saving technologies into production". When performing these tasks, in particular, it is required to ensure the accuracy, speed, reliability of monitoring and control of reactive power based on power supply systems. At the same time, the development of principles, algorithms, software and tools for the operation of primary sensors, providing control and monitoring information, is one of the important issues.

Currently, extensive scientific research is being carried out in the study of the processes of converting multiphase primary currents into secondary voltage of reactive power sources of electrical systems, the development of principles for their design and application, as well as the search for effective, high-quality and reliable ways to solve energy supply problems based on primary sensors used in control and power quality management.
The analysis showed that the problems of complex application of modern equipment and technologies, modeling, algorithmization and research of devices and sensors of multiphase primary currents in the secondary voltage of monitoring and control of reactive power sources, primary currents of power supply systems with renewable energy sources for secondary voltage have not been sufficiently studied. At the same time, the issues of identification of renewable energy sources, structural and parametric studies of monitoring and control devices, development and implementation of modern principles of monitoring and control of reactive power sensors and devices for determining the quality of electricity are also not sufficiently studied [1-3].

2. Materials and methods

The study of the dynamic characteristics of the sensor for converting primary currents into secondary voltages of reactive energy and power coming from networks is carried out on the basis of modeling processes in the sensor, research visibility and a highly formalized graph model and analytical expression [1-2].

PSS requires not only the correct choice of sources of active and reactive power and electrical networks, but also their reliable monitoring and control systems, devices and sensors, as well as continuous monitoring in real time. [2-5].

The general structure of PSS networks and the directions of the primary currents $I_{A\gamma}, I_{B\gamma}, I_{C\gamma}, I_{A\Delta}, I_{B\Delta}, I_{C\Delta}$ - of reactive power sources in it and the principle of installing the sensor in PSS are shown in figure 1.

![Figure 1](image_url) General structure of PSS networks, directions of primary currents of reactive power sources $I_{A\gamma}, I_{B\gamma}, I_{C\gamma}, I_{A\Delta}, I_{B\Delta}, I_{C\Delta}$ - and the principle of sensor installation.

Here CES is a centralized power supply system, contactors KM-1, KM-n; MC microprocessor control; AC Load is an AC load.

When monitoring and controlling the primary currents generated by PSS power supplies and flowing from the transmission line using modern electronic and microprocessor means at a rated current of an electrical device or 20 volts at the outputs of sensitive elements at a rated cross-sectional area Conductor for a long time, $U_{a\gamma}, U_{b\gamma}, U_{c\gamma}, U_{a\Delta}, U_{c\Delta}$ and $U_{c\Delta}$ are required for voltage generation. $I_{A\gamma}, I_{B\gamma}, I_{C\gamma}, I_{A\Delta}, I_{B\Delta}, I_{C\Delta}$ - current-generating $F_\mu$ - magnetic driving forces (m.u.c.), m.y.c., created by ECT sources and flowing along power lines $\Phi_\mu$ - magnetic currents cross surfaces of sensitive elements located on a corresponding base in the magnetic conversion section and on the basis of interacting magnetic currents $I_{A\gamma}, I_{B\gamma}, I_{C\gamma}, I_{A\Delta}, I_{B\Delta}, I_{C\Delta}$ - primary currents $U_{a\gamma}, U_{b\gamma}, U_{c\gamma}, U_{a\Delta}, U_{c\Delta}$ and $U_{c\Delta}$ - secondary voltages output signals [6-9].

Currently, electromagnetic sensors are more widely used than other types of sensors for monitoring and controlling the reactive power of PSS when converting multiphase currents into output voltage signals. The results of the relative evaluation of the sensors are presented in table 1.
Signal conversion process. One of the main tasks of the principle of constructing multiphase sensors of primary current in the form of a secondary voltage is to simplify the design and expand the functionality of the sensor by simultaneously converting multiphase currents in power transmission networks into secondary elements.

The solution to the fundamental design problem is that information about multiphase primary currents to signals in the form of a secondary voltage signal is transmitted by an electromagnetic sensor - a device that converts current into voltage, i.e. parallel rods in the form of a magnetic circuit with a common base and sensing elements, the measurement is carried out during the modification process based on coils [1, 3, 5-12].

The shapes of the sections of magnetic transformation - the magnetic circuits of the multiphase primary current sensor - $I_{A\gamma}$, $I_{B\gamma}$, $I_{C\gamma}$, $I_{A\Delta}$, $I_{B\Delta}$, $I_{C\Delta}$ - from the reactive power source of the PSS are shown in figure 2.
Figure 2. PSS RP $I_{A\gamma}$, $I_{B\gamma}$, $I_{C\gamma}$, $I_{A\Delta}$, $I_{B\Delta}$, $I_{C\Delta}$ - principles of construction of magnetic switching parts of the sensor for converting multiphase primary currents into secondary voltage.

a) horizontally segmented structure b) parallel segmented structure.

When the primary currents of the PSS reactive power sources flow through the first $I_{A\gamma}$, second $I_{B\gamma}$, third $I_{C\gamma}$, fourth $I_{A\Delta}$, fifth $I_{B\Delta}$ or sixth $I_{C\Delta}$ field coils in the common magnetic circuit and parallel cores $\Phi_{\mu_{A\gamma}}$, $\Phi_{\mu_{B\gamma}}$, $\Phi_{\mu_{C\gamma}}$, $\Phi_{\mu_{A\Delta}}$, $\Phi_{\mu_{B\Delta}}$ and $\Phi_{\mu_{C\Delta}}$ magnetic currents are generated which also pass through the air gap between the cores.

Magnetic currents $\Phi_{\mu_{A\gamma}}$, $\Phi_{\mu_{B\gamma}}$, $\Phi_{\mu_{C\gamma}}$, $\Phi_{\mu_{A\Delta}}$, $\Phi_{\mu_{B\Delta}}$ and $\Phi_{\mu_{C\Delta}}$ of PSS reactive power supply secondary signal for control and management of primary currents, single-phase $I_{A\gamma}$, two-phase $I_{A\gamma}$, $I_{B\gamma}$ or star-connected reactive power sources $I_{B\gamma}$, $I_{C\gamma}$ and three-phase $I_{A\gamma}$, $I_{B\gamma}$, $I_{C\gamma}$ and triangular connected single-phase $I_{A\Delta}$, two-phase $I_{A\Delta}$, $I_{B\Delta}$ or $I_{B\Delta}$, $I_{C\Delta}$ and three-phase $I_{A\Delta}$, $I_{B\Delta}$, $I_{C\Delta}$ currents, sensing element (at the outputs of ordinary or flat measuring coils, gerkon, etc.) generates signals in the form of output voltages $U_{a\gamma}$, $U_{b\gamma}$, $U_{c\gamma}$, $U_{a\Delta}$, $U_{b\Delta}$, $U_{c\Delta}$ - in amounts corresponding to the currents of reactive power sources.

When the primary currents of the PSS reactive power sources flow through the first $I_{A\gamma}$, second $I_{B\gamma}$, third $I_{C\gamma}$, fourth $I_{A\Delta}$, fifth $I_{B\Delta}$ or sixth $I_{C\Delta}$ field coils in the common magnetic circuit and parallel cores $\Phi_{\mu_{A\gamma}}$, $\Phi_{\mu_{B\gamma}}$, $\Phi_{\mu_{C\gamma}}$, $\Phi_{\mu_{A\Delta}}$, $\Phi_{\mu_{B\Delta}}$ and $\Phi_{\mu_{C\Delta}}$ magnetic currents are generated which also pass through the air gap between the cores, they also pass through the air gap between the cores. Magnetic currents $\Phi'_{\mu_{1}}$, $\Phi'_{\mu_{2}}$, $\Phi'_{\mu_{3}}$, $\Phi'_{\mu_{4}}$, $\Phi'_{\mu_{5}}$ cross parallel conductors and sensitive elements (simple or flat measuring strips), where the magnetic fluxes are determined from the following expressions [4-8]:
where $I_{Ay}, I_{By}, I_{Cy}, I_{Aa}, I_{Ba}, I_{Ca}$ - reactive power sources PSS - phase currents flowing through the primary windings of sensors of multiphase power lines.

PSS reactive power is the interaction of magnetic currents generated in magnetic cores with primary voltages $U_{Ay}, U_{By}, U_{Cy}, U_{Aa}, U_{Ba}$, and $U_{Ca}$ at the output voltages of each sensing element in the switching sensor, which provides a signal in the form of a secondary voltage for monitoring and control of multiphase primary currents, given as defined as follows [13-13]:

$$
\begin{align*}
\Phi_{\mu Ay} &= \frac{(I_{Ay} W_{a1})}{R_{p1\Sigma}}; \\
\Phi_{\mu By} &= \frac{(I_{By} W_{a2})}{R_{p2\Sigma}}; \\
\Phi_{\mu Cy} &= \frac{(I_{Cy} W_{a3})}{R_{p3\Sigma}}; \\
\Phi_{\mu Aa} &= \frac{(I_{Aa} W_{a4})}{R_{p4\Sigma}}; \\
\Phi_{\mu Ba} &= \frac{(I_{Ba} W_{a5})}{R_{p5\Sigma}}; \\
\Phi_{\mu Ca} &= \frac{(I_{Ca} W_{a6})}{R_{p6\Sigma}};
\end{align*}
$$

(1)

where $W_1, W_2, W_3, W_4, W_5, W_6$ is the number of sensor element coil packs; $f$ – PSS is the frequency of the mains current change.

The sensing elements $U_{Ay}, U_{By}, U_{Cy}, U_{Aa}, U_{Ba}$, and $U_{Ca}$ of the output electromagnetic sensors for the current voltage are determined based on the connection of a flat measuring coil.

Thus, the magnetic fluxes $\Phi_{\mu Ay}, \Phi_{\mu By}, \Phi_{\mu Cy}, \Phi_{\mu Aa}, \Phi_{\mu Ba}$ and $\Phi_{\mu Ca}$ of the change sensor, which provide signals in the form of a secondary voltage for monitoring and controlling multiphase primary currents of reactive power, power values of the power system, single-phase $I_{Ay},$ wye-connected, two-phase $I_{Ay},$ $I_{By},$ or $I_{Cy}$ and three-phase $I_{Ay},$ $I_{By},$ $I_{Cy}$ and triangular connection single-phase $I_{Aa},$ two-phase $I_{Aa},$ $I_{Ba}$ or $I_{Ca}$, and three-phase $I_{Aa},$ $I_{Ba},$ $I_{Ca}$ PSS $U_{Ay},$ $U_{By},$ $U_{Cy},$ $U_{Aa},$ $U_{Ba},$ and $U_{Ca}$ provide information in the form of signals about the magnitude of currents in power lines, in general: destination magnetic circuit, coil ends, additional cores, power lines. Sensitive elements (simple and flat measuring coils) are made stationary on insulated plates and produce voltages $U_{Ay},$ $U_{By},$ $U_{Cy},$ $U_{Aa},$ $U_{Ba}$, and $U_{Ca}$ up to 20 volts, i.e. and microprocessor devices [11-13].

3. Results and discussion

The static characteristics of the network dependence of the PSS power lines of the sensor between single-phase currents and the output voltage of the sensor and the influence of the geometric dimensions of the range on the output voltage at different input currents are shown in figure 4 and 5.
Figure 3. The static characteristic between the primary current and the output voltage (the reactive power source is connected to the star - in the form of $\gamma$). $U'_{ay}$ - for a model with lumped parameters, $U''_{ay}$ - for a model with distributed parameters.

Figure 4. Diagram of the geometric dimensions of the air range and the effect of primary currents on the output voltage.

Analytical expressions of the model for studying the characteristics of the multiphase current sensor of reactive power sources of PSS, based on connection schemes in the form of a star - $\gamma$ and in the form of a triangle - $\Delta$ are represented as follows:

\[
\begin{align*}
U_{Ay} &= K_{\phi_u}U_{\mu 1}W(F_{\mu 11}, F_{\mu 14})K_{\mu_1}F_{\mu}(I_{Ay} \sin \omega t + I_{Ay}e^{-\frac{t}{\tau}}); \\
U_{By} &= K_{\phi_u}U_{\mu 2}W(F_{\mu 21}, F_{\mu 24})K_{\mu_2}F_{\mu}(I_{By} \sin 120^0 + I_{By}e^{-\frac{t}{\tau}}); \\
U_{Cy} &= K_{\phi_u}U_{\mu 3}W(F_{\mu 31}, F_{\mu 34})K_{\mu_3}F_{\mu}(I_{Cy} \sin \omega t - 120^0 + I_{Cy}e^{-\frac{t}{\tau}}); \\
U_{A\Delta} &= K_{\phi_u}U_{\mu 4}W(F_{\mu 41}, F_{\mu 44})K_{\mu_4}F_{\mu}(I_{A\Delta} \sin \omega t + I_{A\Delta}e^{-\frac{t}{\tau}}); \\
U_{B\Delta} &= K_{\phi_u}U_{\mu 5}W(F_{\mu 51}, F_{\mu 54})K_{\mu_5}F_{\mu}(I_{B\Delta} \sin 120^0 + I_{B\Delta}e^{-\frac{t}{\tau}}); \\
U_{C\Delta} &= K_{\phi_u}U_{\mu 6}W(F_{\mu 61}, F_{\mu 64})K_{\mu_6}F_{\mu}(I_{C\Delta} \sin 120^0 + I_{C\Delta}e^{-\frac{t}{\tau}});
\end{align*}
\]  

Graphical representations of the results of the study of dynamic characteristics are based on analytical expressions (3) and for the sensor of multiphase primary currents with output voltages (with the inertia of the parameters of electrical networks of PSS equal to $t = 0.04$) are shown in figure 5:
Figure 5. Dynamic characteristics of the sensor of multiphase primary currents with output voltages (with the inertia of the parameters of electrical networks of PSS equal to $t = 0.04$): a) the reactive power source is star-connected - Y, b) the source of reactive power is connected in the form of a triangle - $\Delta$.

Based on the results of the study of dynamic processes depending on changes in the values and parameters of multiphase primary currents, the mutual influence of magnetic currents and output voltages, it can be concluded that after the multiphase primary currents of the reactive power source of the PSS are connected to the electrical network, the output voltage - the output signal of the sensor reaches a stable value in $0.015 - 0.025$ sec (figure 5).

On the schemes of PSS, the sources of reactive power - cosine capacitor units are connected according to the "star - Y" and "triangle - $\Delta$" scheme, while the relative conversion error of the sensor is determined on the basis of the amount / indicators of the primary current $- I_{AY}$ and the output voltage - $U_{aY}'$, $U_{aY}''$ based on the following research.

$$I_{AY} = 76 \text{ A}; \quad U_{aY}' = 20 \text{ B}; \quad U_{aY}'' = 20.37 \text{ B};$$

$$\Delta = \frac{(U_{aY}'' - U_{aY}')}{{U_{aY}'}} \cdot 100\% = \frac{(20.37 - 20)}{20} \cdot 100\% = 1.81\%;$$

$$I_{a\Delta} = 131.5; \quad U_{a\Delta}' = 20; \quad U_{a\Delta}'' = 20.369;$$

$$\Delta = \frac{(U_{a\Delta}'' - U_{a\Delta}')}{U_{aY}'} \cdot 100\% = \frac{(20.369 - 20)}{20} \cdot 100\% = 1.8\%;$$

Based on the research of the sensor errors, it can be concluded that the characteristics of the sensor when connecting reactive power sources according to the "star - Y" scheme are adequate to the characteristics obtained according to the scheme for connecting reactive power sources according to the "triangular - $\Delta$" models with distributed parameters meet the requirements of linear output signals and increase the research accuracy by 1.8%.

Analysis of the principle of signal conversion based on the investigated electromagnetic sensor of multiphase primary currents into a secondary voltage makes it possible to evaluate and investigate the signal conversion reliability indicator and, on this basis, compose possible conditions that form the total sensor reliability. The probability of replacing transformation elements of an electromagnetic sensor that converts multiphase primary currents of a PSS into a secondary voltage (primary winding, magnetic core, sensing element and rod) is represented as follows:

$$P_1 = 0.99; \quad P_2 = 0.99; \quad P_3 = 0.99; \quad P_4 = 0.99.$$
The principle of simultaneous monitoring and control of multiphase primary currents of the process of generation, transmission and consumption of reactive electricity in PSS based on a signal in the form of a secondary voltage has been created, as a result, a simplified design and increased reliability of the sensor has been achieved.

Models of sensors of multiphase primary currents generated by reactive power sources have been developed, with the possibility of connecting according to the "star - Y" and "triangle - Δ" schemes, which make it possible to control the generated reactive power, compare the characteristics of the input current from the output voltage, a linear output signal, which increases sensor accuracy by 1.8%.

A study of the static characteristics of the multiphase primary current sensor was carried out, as a result, the adequacy of the theoretical and practical study of the sensor characteristics was substantiated, with the parameters of the secondary measuring sensitive element \( w_2 = 20 \), the consumption of values was 3-4%.

Dynamic changes in the electromagnetic sensor for converting multiphase primary currents of reactive power sources of PSS into secondary voltages, the dependence of primary currents, which are a source of magnetic fluxes and output voltages with the inertia of the parameters of the electrical network equal to \( t = 0.04 \), reaches a steady state in the interval 0.015 - 0.025 sec., And with this indicator it has been proven that the sensor is able to generate a secondary signal with a sufficient speed of response at large changes in multiphase primary currents.

Based on the sum of all possible probabilities of converting multiphase primary currents of reactive power sources of PSS into secondary voltage, the probability of the operating state of the electromagnetic sensor was determined, which was \( P = 0.92 \).

4. Conclusions

On the basis of this value, it can be concluded that the probability of an operable state of the sensor of multiphase primary currents of reactive power sources of PSS into secondary voltages \( P = 0.92 \).

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