The assessment possibilities of application of solar power sources in single-phases asynchronous motors

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Abstract. Energy from solar panels is a very widely form of the renewable energy, and conversion from photovoltaic and thermal power to electricity is important processes during assessment possibilities of solar panels for power supply development monitoring of quality of produced and consumed electricity. Implementation of solar panels and analysis of quality energy, production them for power supply of one and three phases transducing devices of single-phases asynchronous motors, which are consumers more than 30% of all producing power are very difficult problems of modern power supply systems, monitoring and control them.

1. Introduction

As determined from results of analyses, single-phase asynchronous motors are widely used in communal, residential and small-scale commercial applications. The advantages of single-phases asynchronous motor with one and three stators windings are widely compatible with standards single-phase power supply nets, modern renewable power sources and solar power stations on the basis of differs solar panels, accessible and commonly use, affordable and budget-friendly, simpler design and easy maintenance, smaller, lighter and sustainable, suitable for limited spaces of design, applicable in a wide range of communal and industry applications, simple starting mechanism, requiring only a single-phase power supply, improved efficiency for reduced energy consumption, known for reliability and long service life with minimal maintenance, available for customization based on specific application requirement. Also, single-phase asynchronous motors mainly operate from a single-phase net and are much simpler in design compared to commonly used three-phases electrical machines. Single-phase asynchronous motors commonly use in appliances like fans, pumps, compressors, and in small power uses devices. Practical research and experiences of exploitations determined, that single-phase asynchronous motors have very lower starting torque and are less efficient values and parameters compared to three-phases asynchronous motors [1].

Modern single-phase asynchronous motors operate on the basis of single-phases power sources nets, as a solar panels, correspond to the same technical and mechanical values and parameters as three-phases asynchronous motors.

They use electromagnetic induction to create a rotating magnetic field using the main (working) and auxiliary (phase-shifting) stators windings. In many cases, single-phase asynchronous motors fed by alternating current (AC) are equipped with working capacitors that compensate for reactive power and starting (phase-shifting) capacitors and mainly sources of nets are solar power sources – solar panels, which producing direct current (DC). Single-phase asynchronous motors with one or three stators windings have a simpler design, provide a lower starting torque and efficiency compared to three-phases asynchronous motors [2].

In graphical abstracts shown, (a) - the single-phases asynchronous motors with starting active and reactive resistances, compensating and phase-shifting capacitors and with a split-phase one stator windings and (b) - single-phase asynchronous motor with starting active and reactive resistances, compensating and phase-shifting capacitors and with a split-phase three stators' windings. A distinctive feature of single-phases asynchronous motors from three-phase ones is the creation by the stator of a pulsating field and a pulsating magnetomotive force rather than a rotating one. This pulsating magnetic field can be conditionally decomposed into two circular fields rotating in opposite directions at the same speed [3]. In the single-phase asynchronous motor with starting active and reactive resistances, compensating and phase-shifting capacitors and with a split-phase stator windings, a single-phase asynchronous motor with a starting resistance is characterized by increased values of active resistance [4]. Single-phases asynchronous motors with capacitors start - a split-phase motor in which the auxiliary winding circuit with a capacitor is connected only during starting and compensating capacitors of single-phase asynchronous motors connecting, when need reactive power during processing of motor [5].

Research objectives are selection and justification of current transducers used for measure and control of the consumption of reactive power of an asynchronous motor supplied from a single-phase power transmission nets of a solar energy panels; research of physical and technical effects, that ensure the process of signal conversion in the designs of electromagnetic current transducers used in measure and control of the consumption of reactive power of an asynchronous motor powered by a single-phase power transmission nets of a solar energy source; research of the structure of the electromagnetic current transducer for measure and control reactive power consumed by single phases asynchronous motors powered by solar energy from a single-phase electrical nets; research of the processes of generating signals in the form of output voltage in the electromagnetic current transducer for measure and control of reactive power consumed by a single asynchronous motor powered by a single-phase electrical nets of a solar energy source-panels – DCs nets [5].

In the world, to provide single-phase one- and three-winding asynchronous motors with uninterruptible and high-quality electric power, much attention is paid to the use of solar energy, which is considered a renewable energy source. In this regard, a number of research projects are being conducted to create controlled sources of active and reactive power consumed to perform useful work by electrical installations and create a rotating magnetic field in asynchronous motors, as well as to improve the corresponding elements and devices for measuring, monitoring and controlling asymmetrical and non-sinusoidal values of AC [6].

Improving the quality performance of single-phase single- and three-winding asynchronous motors powered by single-phase electrical power grid generated by solar panels, they use converting devices and the correct selection of capacitive and inductive elements used to ensure the nominal operation of the asynchronous motor is carried out. The development of transducers that have the ability to simultaneously convert single- and three-phase currents to control primary stator currents in the form of a secondary output voltage signal, increasing sensitivity, accuracy, speed, functionality and meeting practical requirements for them in combination with the applied physical and technical effects, developing the principle of conversion and structure, ensuring normalized linear variable output signals are priority tasks of providing this research [7].

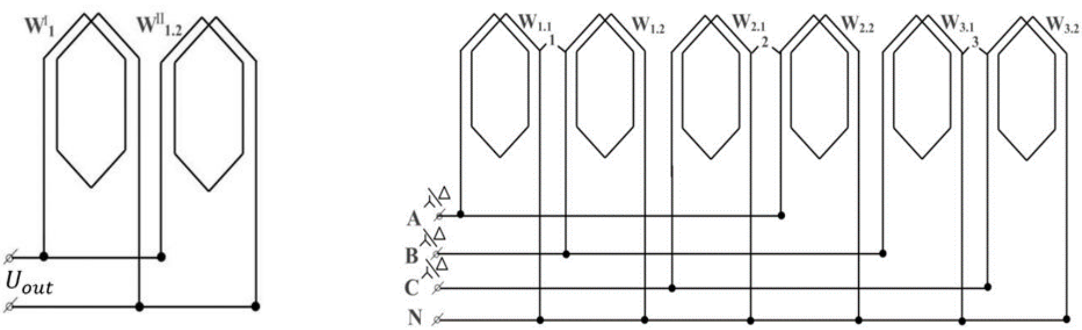
A number of scientific research are being conducted in the world and Republic Uzbekistan to improve the elements and devices for monitoring asymmetrical and non-sinusoidal values of electric energy currents, transmitted through electric nets as AC, consumed by asynchronous motors and from solar energy sources - solar panels as DC. In this research, one of the main tasks is to ensure high-quality signals when monitoring the magnitude and angular indicators of currents produced by a solar panel and reactive power consumed by asynchronous motors. The study of the processes of generating signals used in monitoring systems for indicators of electric energy generated by solar panels is one of the important issues of energy and resource conservation. Monitoring asymmetrical and non-sinusoidal values of electric energy currents of single-phases asynchronous motors from the solar panel network requires the use of advanced capabilities of modern measuring systems; in this process, the issues of developing and implementing new types of devices for the primary conversion of signals on the values of reactive currents are relevant [8].

In the Republic of Uzbekistan for 2022-2026, the tasks of the "Program for reducing losses in industries and increasing the efficiency of resource use, transition to a "green economy" and ensuring energy supply" have been defined. In fulfilling these tasks, it is important to develop principles for constructing

a transducer of single- and three-phases ACs, produced by solar panels and powered by single-phase asynchronous motors and their practical application. A number of targeted activities are widely implemented aimed at improving the elements and devices of systems for monitoring electric currents from solar panels powered by single-phase asynchronous motors.
This research work to a certain extent serves to fulfill the tasks provided for in the Decree of the President of the Republic of Uzbekistan No. UP-158 of the Action Strategy of the Republic of Uzbekistan for 2023-2030 in paragraph 52 - ensuring continuous energy supply to the economic and industrial sectors, 57-implementation of technologies, 65-further improvement of the green energy system, in the Resolutions of the President of the Republic of Uzbekistan No. PP-4249 "On the strategy for further development and reform of the electric power industry, dated July 14, 2024 No. PP-222, in the Development Strategy of the New Republic of Uzbekistan" dated March 27, 2019 and No. PP-4422 "On operational measures to improve the energy efficiency of economic and social sectors, the introduction of energy-saving technologies and the development of renewable energy sources" dated August 22, 2019, measures are defined to reduce electricity consumption by 10%, based on the regional location of the regions and cities by industrial production sectors [3-4].
During a monitoring of AC of electric power nets, consumed by single-phases, single- and three-winding asynchronous motors supplied from a single-phase power grid and DC, generated by solar panels, necessary to ensure accurate conversion of primary stator windings AC to signals, in the form of secondary output voltage. Ensuring the accuracy of the output signal from transducers of stator winding currents of single-phase asynchronous motors with one and three stator windings is based on the use of physical and technical effects involved in their conversion process.
The paper presents models and circuit solutions for the development and implementation of elements and devices for monitoring the consumed by single-phase single- and three-winding asynchronous motors when powered by a solar energy source - solar panels.

2. Methods

During research of the processes of transformation of primary ACs of electric power of single-phases asynchronous motor, powered by solar panels DC, the main elements of monitoring are transducers of primary AC to secondary voltage, on the basis of one or three windings, as sensitive elements, which are made in the form of a ring, arranged in pairs between the stator windings and an insulating wedge, when transforming AC flow via stators windings.



a) *b)*

Figure 1. Implementation of a ring of sensitive monitoring elements - an current transducer of a single (a) and three-winding (b) asynchronous motor

Sensitive elements of monitoring, connected according to star and triangle circuits of a single- and three-winding asynchronous motor, powered by a single-phase solar energy source, having coordinated arrangements of rings in the stator space are shown in Figure 1.
Figure 1 shows: (a) –current transducer of a single-winding asynchronous motor; (b) – location in the stator slots of the current transducer of a three-winding asynchronous motor, powered by a single-phase

solar energy source; W^{I}_{1}, $W^{II}_{1.2}$ – measuring sensitive elements of the rings of a single-winding asynchronous motor; $W_{1.1}$, $W_{1.2}$ – sensitive elements of the rings of measuring the A-phase of a three-winding asynchronous motor; $W_{2.1}$, $W_{2.2}$ – sensitive elements of the rings of measuring the B-phase of a three-winding asynchronous motor; $W_{3.1}$, $W_{3.2}$ – sensitive elements of the rings of measuring the C-phase of a three-winding asynchronous motor, N- triangular connection of the neutral.

The process of transducing the stator windings current of a single-phase single- and three-winding asynchronous motor to a signal, in the form of an output voltage of a current transducer, by combining the parts of the signal conversion model, are formed as follows:

- when single-phase asynchronous motors are powered by single-phase solar energy source, the primary AC, flowing through the stators winding, create magnetic moving forces (m.m.f.) in the magnetic parts of the stator and rotors.
- in the process of interaction of electrical and magnetic quantities in an electromagnetic field, depending on the geometric dimensions of the AC transducers and based on the laws of Kirchhoff and Ohm, on the bases them will be formed an analytical expression.

ACs flowing through the stator windings of an single-phases asynchronous motor create m.m.f in the stator and rotor, the magnetic currents generated by them and the interaction of output voltages are formulated separately for each phase.

The graph model of the processes, occurring in the current transducer of a single-phase AC in single-winding asynchronous motor is shown in Figure 2.

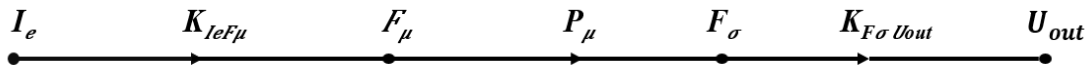


Figure 2. The graph model of the processes, occurring in the current transducer of a single-phase AC in single-winding asynchronous motor

Figure 2 shows: I_e - the primary current flowing through the stator winding of a single-winding asynchronous motor; $K_{IeF\mu}$ - the coefficient of change of the magnetomotive force of the primary current flowing from the stator; F_μ - the magnetomotive force; P_μ - the electromagnetic field parameter; F_σ - the magnetic leakage flux; $K_{F\sigma Uout}$ - the coefficient of change of the magnetic leakage flux to the output voltage.

The analytical expression for calculating the output voltage from the measuring windings, located in the appropriate order with the stator coils of a single-phase asynchronous motor powered by electricity generated by solar panels has the following form:

$$U_{out} = K_{IeF\mu} P_\mu K_{F\sigma Uout} I_e, \quad (1)$$

where: I_e - the primary current flowing from the stator of the asynchronous motor; P_μ is the electromagnetic field parameter; $K_{IeF\mu}$ is the coefficient of change of the primary current flowing from the stator of the asynchronous motor to the magnetic driving force; $K_{F\sigma Uout}$ is the coefficient of change of the scattered magnetic flux to the output voltage.

A special moment of the operating principle of a single-phases asynchronous motor, with one and three stators windings, powered by alternating current (AC) electrical nets, which connected to solar panels, which produce direct current (DC), is the creation of a pulsating magnetic field, decomposed into two identical circular magnetic fluxes with an amplitude, equal to Fmax/2 and rotating in opposite directions with the same frequency [5]:

$$n_{direct} = n_{back} = 60f/p = n, \quad (2)$$

where: n_{direct} – magnetic field rotation speed in the forward direction, rpm, n_{back} – speed of rotation of the magnetic field in the opposite direction, f – frequency of stators current, Hz, p – number of pole pairs, n – magnetic flux rotation speed, rpm.

The model with distributed parameters of the physical process in the electromagnetic transducers of primary currents flowing from the stator winding of a single-phase three-winding asynchronous motor fed by a single-phase solar energy source is shown in Fig. 3. In Fig. 3 the determining ones are: U_{Ie}, U_{IIe}, U_{IIIe}, - primary voltages supplied to the stator of the asynchronous motor; P_{e1}- P_{e2} -P_{e3} - asynchronous motors stators parameters; I_{IA} -I_{IIA} -I_{IIIA} - primary currents of the stator windings of the asynchronous motor; F_{μ} - magnetic fluxs; $K_{IAF\mu}$ -$K_{IIAF\mu}$ -$K_{IIIAF\mu}$ - coefficients of conversion of primary current into magnetic fluxes; $PO_{\mu 1.1}$ - $PO_{\mu 1.2}$ - $PO_{\mu 1.3}$ - air gap resistance; $P_{\mu 1.1}$…… $P_{\mu 2.3}$ - magnetic core parameters.

The primary current flowing through the stator windings of a three-phase asynchronous motor and as the primary windings of an electromagnetic transducer, powered by a single-phase source DC of solar energy source, representing the output voltage, is formulated as follows [6-10]:

$$\begin{cases} \frac{F_{\mu 1.1}-F_{\mu 2.1}}{PO_{\mu 1.1}}+\frac{F_{\mu 1.1}-F_{1.2}}{P_{1.1}}+\frac{F_{\mu 1.1}-F_{\mu 1.2}}{P_{1.2}}=\frac{K_{Fe1Ue1}U_{e1}-F_{\mu 1.2}}{P_{e1}} \\ \frac{F_{\mu 2.1}-F_{\mu 1.1}}{PO_{\mu 1.2}}+\frac{F_{\mu 2.1}-F_{3.2}}{P_{\mu 2.1}}+\frac{F_{\mu 2.1}-F_{\mu 2.2}}{P_{\mu 2.1}}=\frac{K_{Fe2Ue2}U_{e2}-F_{\mu 2.1}}{P_{e2}} \\ \frac{F_{\mu 3.1}-F_{3.2}}{PO_{\mu 1.3}}+\frac{F_{\mu 3.1}-F_{\mu 3.2}}{P_{3.1}}+\frac{F_{\mu 3.1}-F_{\mu 3.2}}{P\quad_{3.2}}=\frac{K_{Fe3Ue3}U_{e3}-F_{\mu 3.1}}{P_{e3}} \\ \frac{F_{\mu 2.1}-F_{2.2}}{PO_{\mu 1.1}}+\frac{F_{2.1}-F_{3.2}}{P_{\mu 2.1}}+\frac{F_{\mu 2.1}-F_{\mu 1.1}}{P_{\mu 2.2}}=\frac{K_{Fe1Ue1}U_{e1}-F_{\mu 1.2}}{P_{e1}} \\ \frac{F_{\mu 2.2}-F_{\mu 2.1}}{PO_{\mu 1.2}}+\frac{F_{\mu 2.1}-F\mu_{3.2}}{P_{\mu 2.1}}+\frac{F_{\mu 2.2}-F_{1.2}}{P_{\mu 2.3}}=\frac{K_{Fe2Ue2}U_{e2}-F_{\mu 2.1}}{P_{e2}} \\ \frac{F_{\mu 3.2}-F_{2.2}}{PO_{\mu 1.3}}+\frac{F_{\mu 3..2}-F_{\mu 2.1}}{P_{\mu 2.1}}+\frac{F_{\mu 3.2}-F_{\mu 3.1}}{P_{\mu 2.2}}=\frac{K_{Fe3Ue3}U_{e3}-F_{\mu 3.1}}{P_{e3}} \end{cases} \quad (2)$$

where: $F_{\mu 1.1}$ .... $F_{\mu 2.3}$ – magnetic moving forces; $PO_{\mu 1.3}$ – $PO_{\mu 3.3}$ - air gaps resistances; K_{FeUe1}, - K_{FeUe2} - K_{FeUe3} - coefficients of change of magnetic leakage flux on output voltage; $P_{\mu 1,1}$-$P_{\mu 3,3}$ - magnetic fluxes parameters; U_{e1}- U_{e2} -U_{e3} - voltages supplied of the stator windings of the single-phases asynchronous motor.

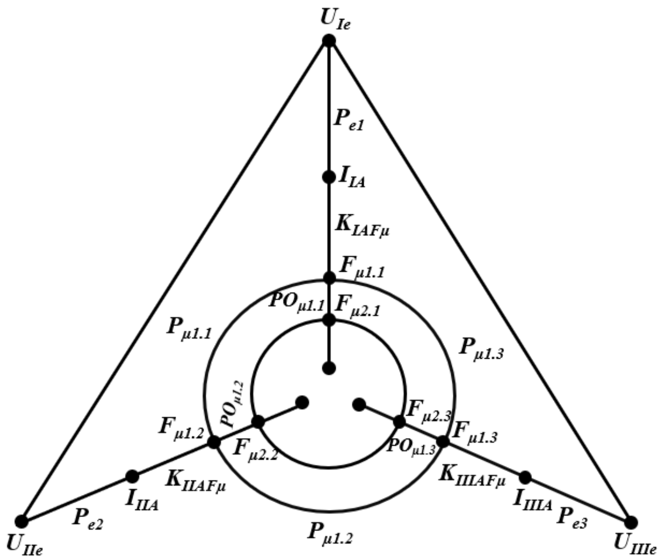
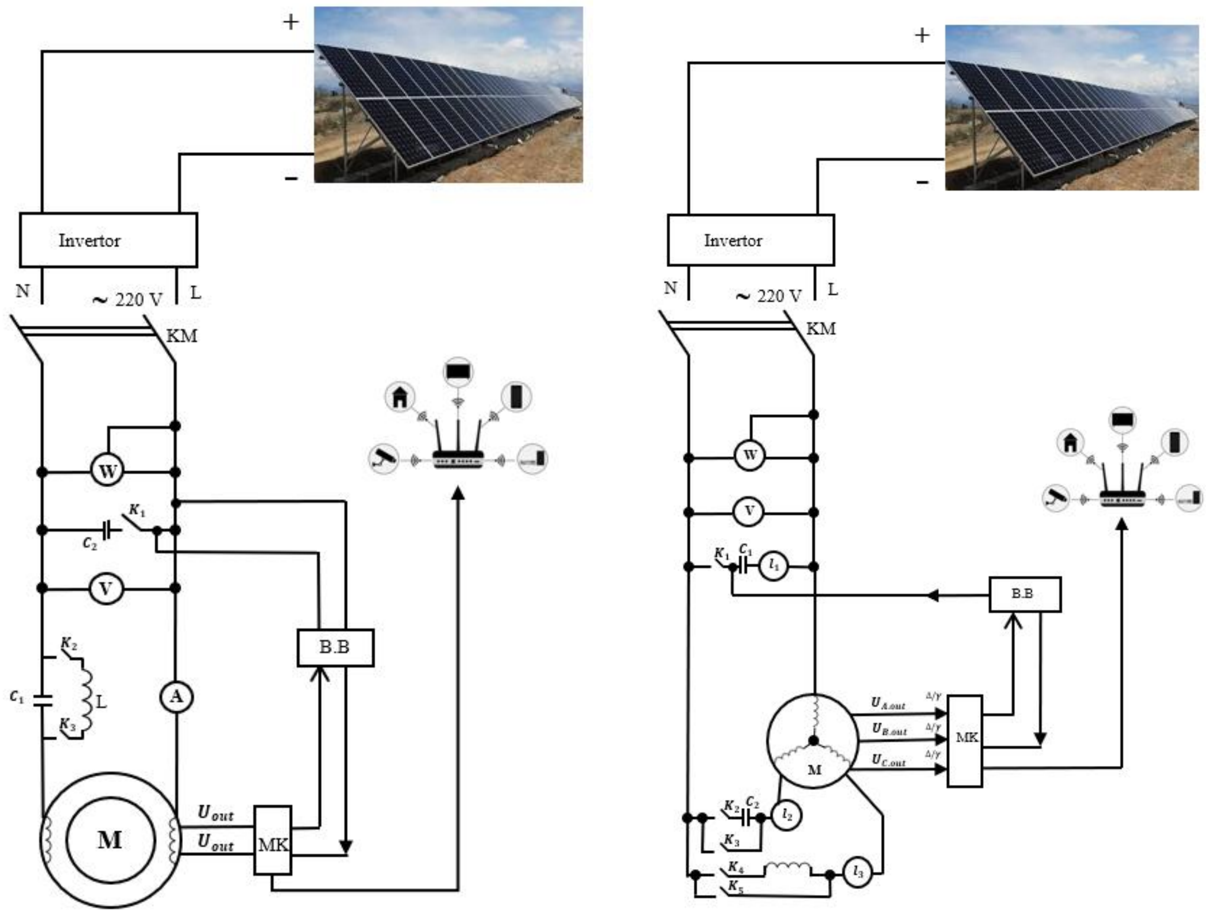


Figure 3. The graph model with distributed parameters of the physical process in the electromagnetic transducers of primary currents (AC), flowing from the stator winding of a single-phase three-winding asynchronous motor fed by a single-phase DC net of solar energy source

Analytical formulas for calculating signals - output voltage at the output of the electromagnetic transducer of AC of single-phase single- and three-winding stator windings of an asynchronous motor are formed on the basis of the above system of equations and characteristics of the electromagnetic transducer [11-15] .

3. Results and Discussions

The main characteristics of the transducers of AC, which convert the primary single-phase currents of a single- and three-winding of stators of asynchronous motor, from a single-phase power transmission net of the power supply system and generated by solar panels are the static and dynamic characteristics of the current transducers of the electrical energy [16-18].



a) *The Single-phase asynchronous motor with starting active and reactive resistances, compensating and phase-shifting capacitors and a split-phase one stators windings*

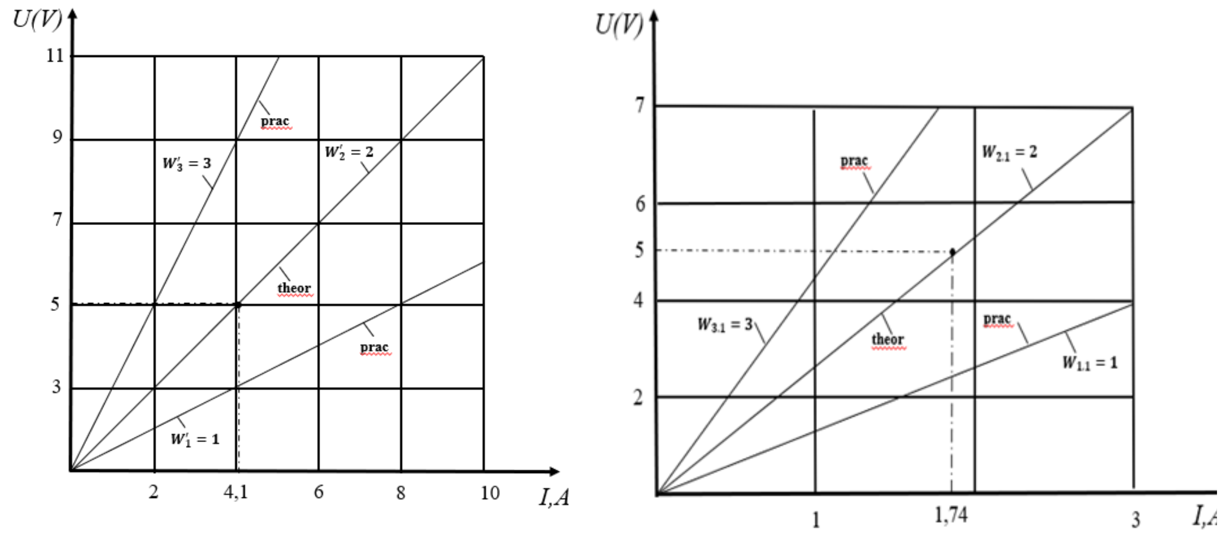
b) *The Single-phase asynchronous motor with starting active and reactive resistances, compensating and phase-shifting capacitors and a split-phase three stators' windings*

Figure 4. Starting Active and Reactive Resistances, Compensating and Phase-Shifting Capacitors, and Split-Phase Three Stator Windings

The static characteristics of the secondary output voltages from transducer and the primary current of the stators winding of asinchronous motor shown in Figure 4, (a) - static characteristic of a single-phase, single-winding, with power 550 W, (b) - static characteristic of a three-winding, asynchronous motor with power 250 W.

The adequacy of the results of theoretical and practical research showing the dependence of the currents of stator winding of a three-winding asynchronous motor, powered by a single-phase power transmission net of AC, generated by solar panels DC, and the secondary output voltage of an electromagnetic current transducer was tested as follows [19]:

$$\delta = \frac{U_{prac.} - U_{theor.}}{U_{prac.}} 100\% = \frac{5{,}03 - 5}{5{,}03} 100\% = 0{,}6\% \quad (4)$$



a) **b)**

Figure 5. The static characteristics of the secondary output voltages from windings of electromagnetic current transducer and the AC of the stators winding of single-phases asynchronous motor

On the bases of calculations established, that the adequacy indicator of the voltage of an asynchronous motor with two sensitive monitoring elements in the stator winding, located according to the star and triangle schemes, changes of the primary currents of the electromagnetic transducer to a secondary signal, fully meets the requirements for modern measuring and control equipment [20-22].
The value of total harmonic distortion (Total Harmonic Distortion - THD) of non-sinusoidal AC generated by magnetic constructions of single-phases an asynchronous motor was determined as follows and its value in % [23]:

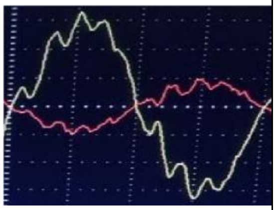
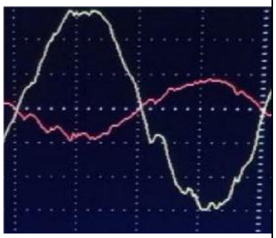
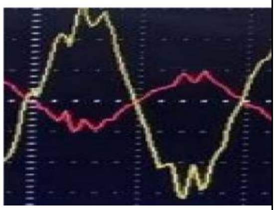
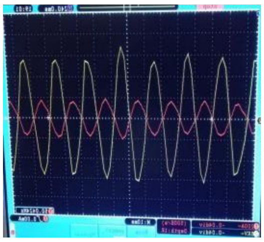
$$THD_i\% = \sqrt{\sum_{k=2}^{N}\left(\frac{I_k}{I_1}\right)^2}\ \%, \tag{5}$$

where: N – total number of harmonics; k - initial value of the first harmonic; I_1 – current of the first harmonic; I_k - currents of high harmonics.
In single-phases asynchronous motors, high harmonics of currents lead to a decrease in the power factor, and it is defined as:

$$\cos\varphi_i = \frac{\cos\varphi}{\sqrt{1+(THD_i)^2}}, \tag{6}$$

where: $\cos\varphi$ – nominal power factor of single-phase asynchronous motor; THD - total harmonic distortion of the non-sinusoidal AC.
When single-phase asynchronous motors are powered from a single-phase solar power grid, due to the effect of higher harmonic currents, there is an increase in electrical and electromagnetic power losses and a decrease mechanical power [24-26]. The dynamic characteristics of monitoring the output values of the electromagnetic current transducers during the nominal load of single-phase single-windings asynchronous motor with phase-shifting inductance (L), phase-shifting (C_1) and reactive power compensating capacitors (C_2) are presented in Table 1.

Table 1. The dynamic characteristics of monitoring the output values of the electromagnetic current transducers during the nominal load of single-phase single-windings asynchronous motor

Schemes	Oscillograms	*THD* [%]	Output voltage, U_{out}, [*V*]	Current I_{in}, [*A*]
Scheme with C_1		*THD* = 6,4 %	U_{out} = 3,04 *V*	I_C = 0,97 A
Scheme with C_1 and L		*THD* = 6.01 %	U_{out} = 3,11 *V*	I_{C1} = 1,04 *A* I_L = 0,30 *A*
Scheme with C_1 and C2		*THD* = 5,8 %	U_{out} = 4,1 *V*	I_{C1} = 0,78 *A* I_{C2} = 0,33 A
Scheme with C_1, C_2 and L		*THD* = 4,5 %	U_{out} = 4,3 *V*	I_{C1} = 0,75 *A* I_{C2} = 0,36 A I_L = 0,22 A

As can be seen from the presented results of the research, when a single-phase stator winding is connected to the power grid with a solar panel, only through a phase-shifting capacitor (C_1) with THD = 6.4% and through a phase-shifting inductance (L), phase-shifting (C_1) and compensating (C_2) capacitors (with L, C_1 and C_2) with THD = 4.5%, the non - synodalities index improves to Δ = ((6.4 – 4.5) / 4.5) * 100% = 42,2% in the nominal load of an asynchronous motor.The results of the research shows, that by reducing the indicators of higher harmonics of currents flowing via the stator winding of a single-phase asynchronous motor, by filtering harmonic AC, will get possible to increase the active power factor, prevent motor overheating and ensure efficient operation of the asynchronous motor. Experimental stand for research of an electromagnetic transducer of stator currents of a single-phase single-winding asynchronous motor powered by a source - a solar energy panel presented in Figure 5.

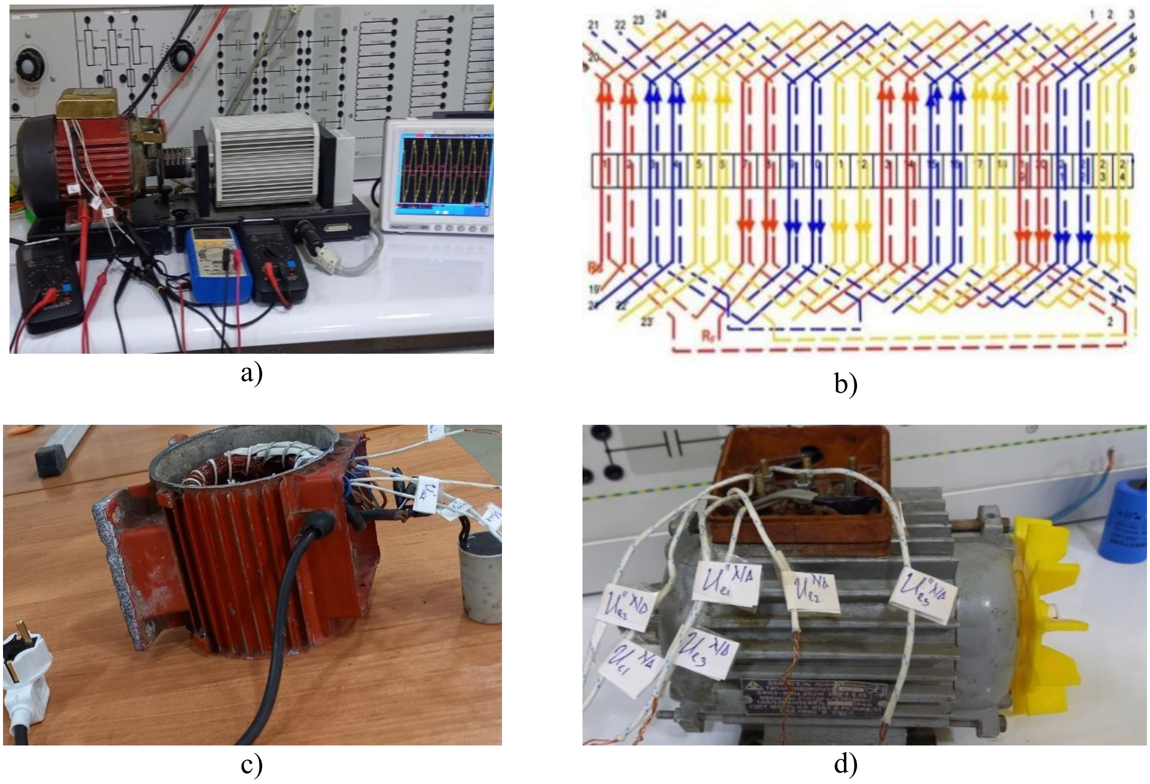


Figure 5. Experimental stand for research of an electromagnetic transducer of stator currents of a single-phase single-winding asynchronous motor powered by a source - a solar energy panel: *a - a stand for experimental measurements of the process in the electromagnetic transducers of the stators current of a single-winding asynchronous motor; b - a method for placing measuring sensitive elements of rings between the slots of the stator and insulating wedges of an asynchronous motor; c - a device, which the measuring sensitive elements of the rings are placed in the slots of the stator of a single-winding asynchronous motor; d - a device, which electromagnetic current transducers connected according to a star-triangular circuit are placed between the slots of the stator and the insulating wedges of a single-winding asynchronous motor.*

4. Conclusions

The conclusion of this study is as follows:

a) The principle of signal transforming construction of electromagnet transducer of a reactive powers current of a single- and three stators winding of asynchronous motor, powered by a single-phase nets of a solar panels – solar energy source was developed;
b) A graph model of signal conversion processes occurring under normal and non-sinusoidal conditions has been developed as a result of electromagnetic current conversion;
c) Models and analytical expressions of the transform of signals based on the primary currents of the power consumed by an asynchronous motor, supplied from the single-phase electrical nets of the solar energy source was formulated;
d) The structure of electromagnetic current switch of the primary currents of the asynchronous motor reactive power was developed with improve technical and performance characteristics construction on the basis of star and triangle connection schemes of the rings of sensitive elements.
e) Solar panels, as renewable energy sources, can be effectively integrated into power systems. Harmonizing energy supply and consumption based on daily data allows for the determination of key operational parameters for both solar and hydroelectric power plants, considering the unique characteristics of their supply and consumption modes;

f) When a single-phase stator winding is connected to the power grid via a solar panel using only a phase-shifting capacitor (C1), the total harmonic distortion (THD) is 6.4%. However, by employing a combination of a phase-shifting inductance (L), a phase-shifting capacitor (C1), and a compensating capacitor (C2), the THD is reduced to 4.5%.

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