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Measuring the Voltage of a Three-Phase Circuit in a Generator Set Control System

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ABSTRACT: The article proposes a technical implementation of a high-speed voltage sensor in a three-phase circuit of a generator set, the frequency of which changes in transient processes. Sequential differentiation, rectification and intensification of phase voltages allows one to substantially reduce the influence of the current frequency on the measured voltage during one current period.

1 INTRODUCTION

This paper is an extension of work originally presented in conference name [1].

The development of new methods and technical schemes for measuring three-phase voltage parameters for controlling autonomous generator sets is justified by a fundamentally new approach to controlling their voltage. The need to increase the speed of the three-phase voltage sensor is caused by the prospect of using asynchronous generators with capacitor excitation on ships [2,3]. There was a need for a voltage sensor that measures the average value of the three-phase voltage of an autonomous generator, the speed of which is unstable, for half the alternating current period.

Improvement of autonomous power plants, including marine transport facilities, improvement of their technical and economic indicators is the main trend in the development of ship's technology. For example, the capacity of electrical equipment installed on modern ships reaches 40% of the capacity of a power plant, therefore, the choice of an optimal composition of a power plant with improved operational qualities contributes to an increase in the efficiency of the power plant.

Currently, on sea-going ships, synchronous generators are mainly used as sources of electricity, which is explained by the simplicity of the technical means for regulating their voltage. The multi-turn excitation winding on the generator rotor makes it possible to control the voltage of the synchronous generator using relatively small currents.

However, this "simplicity" caused two other problems: the rotating slip rings on the rotor and the high inductance of the excitation circuit, which significantly reduced the speed of the voltage stabilization system.

As a result of numerous scientific and technological developments of synchronous generators and their excitation systems, generating sets have been created that have practically exhausted the possibilities for further improving the quality of electricity [4].

Modern brushless synchronous generators with inverted exciter and rotating diodes have eliminated rotating contacts but have significantly complicated the design of the generator. To increase the speed of voltage stabilization of synchronous generators, multiple excitation current forcing systems are used.

Excitation of the asynchronous generator through the stator circuit allows realizing a voltage regulation system that is practically invariant from the load, [5-8].

2 FEATURES OF AUTONOMOUS POWER SUPPLY SYSTEMS

According to the authors, a radical way to modernize an electric power plant is the use of asynchronous generators with a squirrel-cage rotor and capacitor excitation along the stator circuit, [3].

The voltage control of the asynchronous generator is carried out on the stator circuit, i.e. along the load circuit, therefore the inertia of the control and disturbance channels are the same. As shown by the research of the authors [2,5,8], this allows to create an almost load-invariant voltage stabilization system.

The voltage control of the asynchronous generator is carried out by switching to the three-phase stator winding of the capacitor banks using triacs at certain times when the voltages on the capacitor and the phase winding of the generator are equal. In this case, capacitors of different phases are switched at different times, in accordance with the shifts of the phase voltages. Therefore, the whole process of connecting a three-phase unit takes time slightly less than the network period.

2.1 *Main part*

The features of switching capacitor units determine the requirements for the speed of the voltage sensor of a three-phase network. The maximum speed of the voltage stabilization system requires reliable measurements of the RMS voltage U_s for the three-phase current period T:

$$U_s = \sqrt{\frac{1}{T}\int_0^T u^2(t)\,dt}$$

In most of the known sinusoidal voltage sensors, the average voltage value u_i is measured instead of the RMS value, which significantly reduces the computational complexity of their implementation. With insignificant nonlinear distortions, the RMS voltage value is proportional to its amplitude U_m, therefore such a replacement is quite justified.

The calculation of the voltage average value u_i is associated with the integration of the voltage instantaneous value $u\,(t)$ during the positive half-cycle of the alternating current $T\,/\,2$, [6,9]. In this case, the fixation of the voltage measurement period is carried out when the phase voltage passes through zero.

A significant disadvantage of such sensors is the dependence of the output signal not only on the voltage U_m, but also on the frequency of the current $\omega = 2\pi\,/\,T$, as shown in our article [1]:

$$u_i = \int_0^{\frac{T}{2}} u(t)\,dt = \int_0^{\frac{T}{2}} U_m \cdot \sin\frac{2\pi}{T} t \cdot dt == -\frac{U_m T}{2\pi}\cdot\cos\frac{2\pi}{T}\cdot t\,\Bigg|_0^{\frac{T}{2}} =$$

$$= -\frac{U_m T}{2\pi}\cdot(\cos\pi - \cos 0) = \frac{U_m \cdot T}{\pi} = \frac{2U_m}{\omega}$$

In marine generator sets with a diesel drive engine, a significant frequency deviation is allowed, both in steady-state and in transient modes, [10-12]. In this case, the instability of the frequency of the current ω will introduce significant errors in the output signal of the voltage sensor, [4].

The article [13] describes and investigates a method for calculating the average value of an alternating voltage u_{di} by sequential differentiation, rectification, and integration of phase voltages $u\,(t)$ during a half-period of alternating current $T\,/\,2$:

$$u_{di} = \int_0^{T/2}\left|\frac{du(t)}{dt}\right|dt = 2U_m$$

The integration period $T/\,2$ is set by a synchronizing pulse which action in during positive value of the measured voltage. At the end of the measurement process, the amplitude of the sync pulse becomes equil zero, the value of the integral is memorized and stored until the next measurement period.

Simple circuit solutions of analog voltage sensors are proposed for both single-phase and three-phase circuits, which made it possible to significantly reduce the dependence of the output signal of the voltage sensor u_{di} on the current frequency f, [5,6], Fig. 1. In the frequency range from 40 to 50 Hz, the voltage measurement error is about 2%, at $f = 45\,Hz$ it is -0.6%, and at $f = 55\,Hz$ it is +0.9%.

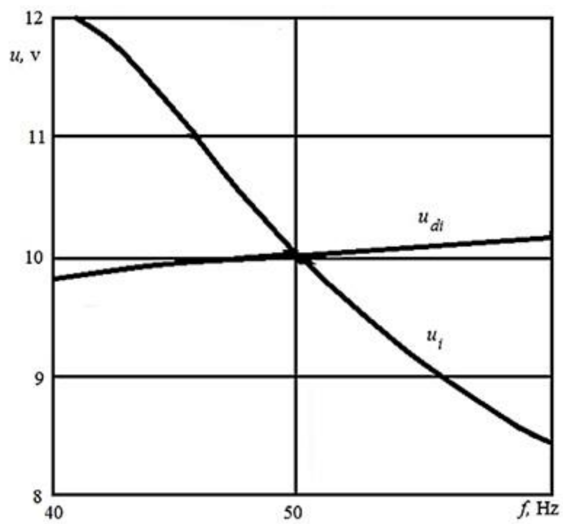

Figure 1. Dependence of the output signal of the AC voltage sensor on the current frequency: u_i – integration of the rectified voltage; u_{di} – preliminary differentiation, rectification, and integration of voltage

A diagram of the analog implementation of the proposed method for a three-phase network is shown in Fig. 2.

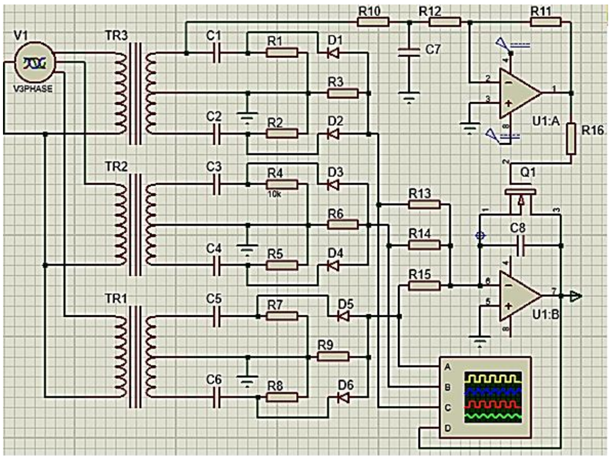

Figure 2. Analog part of the sensor for the average voltage of a three-phase network

Galvanic isolation and lowering of phase voltages are provided by three transformers TR1, TR2 and TR3 with two output windings having a common point, which makes it possible to realize full-wave rectification of the alternating voltage of each phase using diodes $D1 - D6$. Differentiation of input signals is performed by RC - circuits $R1C1 - R6C6$. Further addition and integration of the measured signals is carried out by the operational amplifier $U1{:}B$, the integration constant of which is determined by the product of the capacitance $C8$ on the resistance $R13$ (R14, R15). Synchronization with the mains and discharge of the integrating capacitor is performed by pulse shunting with the field-effect transistor $Q1$, which is controlled by the operational amplifier $U1{:}A$. Synchronizing circuit $R10 - C7$ is connected to the secondary winding of the phase transformer. Oscillograms of the rectified phase voltages and the sensor output signal are shown in Fig. 3.

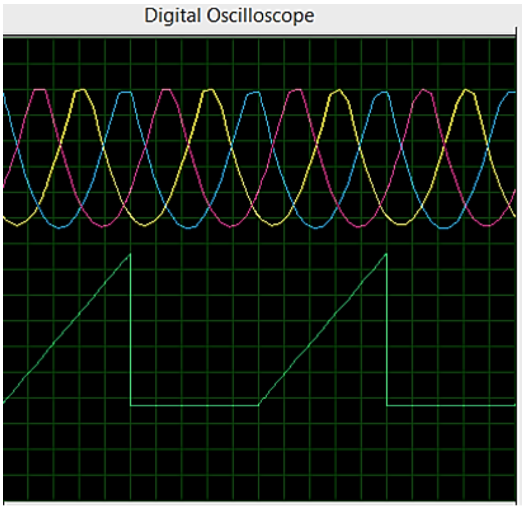

Figure 3. Oscillograms of the voltage sensor of a three-phase network

The main advantage of the proposed circuit is the close to linear waveform at the output of the operational amplifier $U1{:}B$ at symmetrical phase voltages. In this case, the slope of the characteristic is proportional to the amplitude of the phase voltages. This makes it possible to quickly measure the amplitude of symmetrical voltages.

However, with unbalanced voltages, the form of the charge of the capacitor $C8$ ceases to be strictly linear, but at the end of the half-period $T/2$, the value of the output signal is proportional to the average value of the unbalanced phase voltages.

When regulating the voltage of an autonomous generator, the deviation of the average value of the phase voltages from the given one is used, depending on which a control action is formed on the excitation system of the generator.

Therefore, the authors checked the error D of measuring the average value of the asymmetric phase voltages. The voltage amplitude of one of the phases U_{m1} varied from 0 to 150% of the nominal value at 100% amplitudes of the other two phases. The obtained values of the output voltage of the u_{di} sensor in relative units were compared with the theoretical ones shown by the dotted line. These results are shown in Fig. 4.

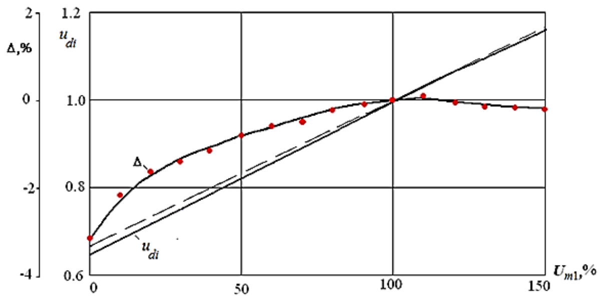

Figure 4. Accuracy and error in measuring the average value of asymmetric phase voltages

When one of the voltages changes from 80 to 120%, the average value of the three voltage phases changes from 0.933 to 1.067. In this case, the sensor error is within the range of 0.1 - 0.6%.

Computer and physical modeling of the proposed three-phase voltage sensor has shown that with an asymmetry of the generator phase voltage up to 50%, the output voltage of the sensor retains a sawtooth shape, close to linear.

With a complete disconnection of one of the phases, the error was 3.2%. Oscillograms are shown in Fig. 5.

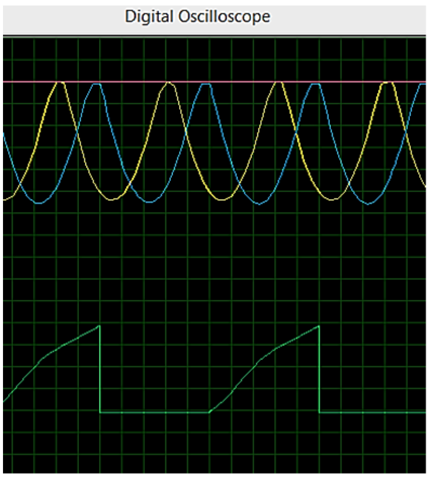

Figure 5. Oscillograms of the voltage sensor of a three-phase network when one of the phases is disconnected

The voltage waveform in Fig. 5 is already significantly different from the linear one. The voltage sensor circuit of a three-phase network remains operational even when two phases are disconnected, i.e. for single-phase use. Oscillograms are shown in Fig. 6.

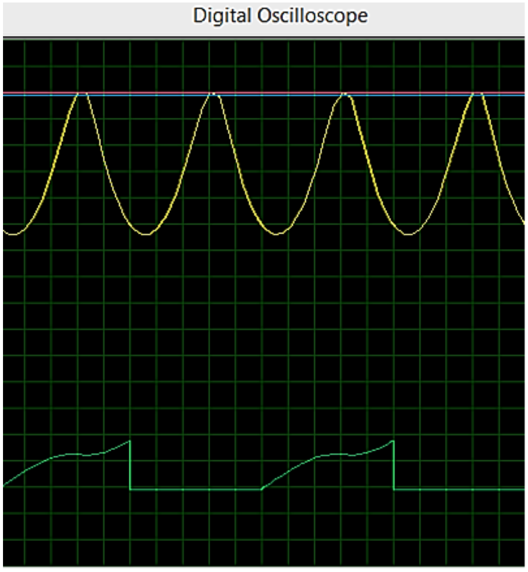

Figure 6. Oscillograms of the voltage sensor of a three-phase network when two phases are disconnected (single-phase mode)

The process of integrating the measured signal is quite simply implemented in software in the digital part of the sensor by summation after differentiation and rectification of signals from phase voltages.

Synchronization of the sensor with the power grid is also easily implemented by the controller by comparing the instantaneous signal of one of the phases with a given constant level.

At the same time, the operations of differentiation and rectification are implemented by local radioelements using capacitors, resistors and diodes, i.e. without ICs containing operational amplifiers. This circumstance makes it possible to optimize the ratio of the analog and digital parts of the sensor according to the criterion of ease of implementation. Such a diagram of a three-phase voltage sensor is shown in Fig. 7. Electrical isolation, differentiation and rectification of phase voltages are performed by the analog part of the circuit, and integration and synchronization are performed by the controller, Fig.8.

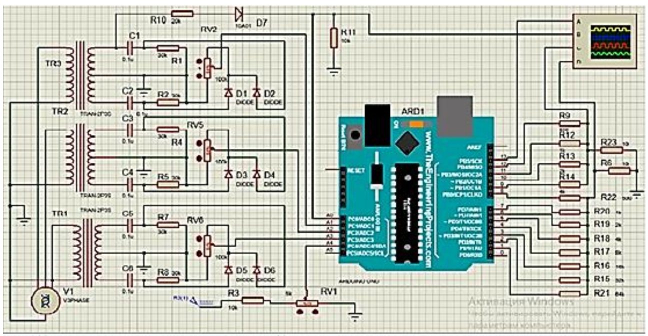

Figure 7. Circuit of a three-phase voltage sensor with digital integration and formation of a synchronization pulse

Transformers TR1-TR3 reduce phase voltages and provide electrical isolation of power and measuring circuits. Capacitors C1-C6 and resistors R1, R2, R4, R5, R7, R8 perform differentiation, and diodes D1-D6 rectify phase voltages. Then the analog signals are fed to the analog ports A1-A3 of the controller. The controller interface (terminals 1 to 8) outputs some bytes of information from the voltage sensor in digital form, and digital-to-analog conversion of the output signal of the three-phase circuit voltage sensor is performed on the resistors R15-R22 and R6.

A resistor-diode divider R10-D7-R11 is used for synchronizing with the mains voltage, the output signal of which is put to port A0.

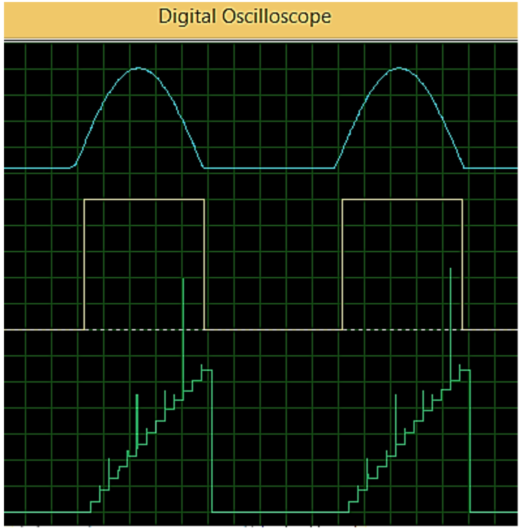

Figure 8. The operation oscillograms of a three-phase voltage sensor with digital integration and synchronization with the network

In Fig. 9 shows the operation of the voltage sensor (green) and the regulator with integral control law (red).

The controller has a digital integral regulator - pins 9-12. The digital-to-analog conversion of the regulator signal is performed on resistors R9, R12-R14 and R23. The setpoint of the regulator input to the controller by means of the resistors R3 and RV1 via port A4.

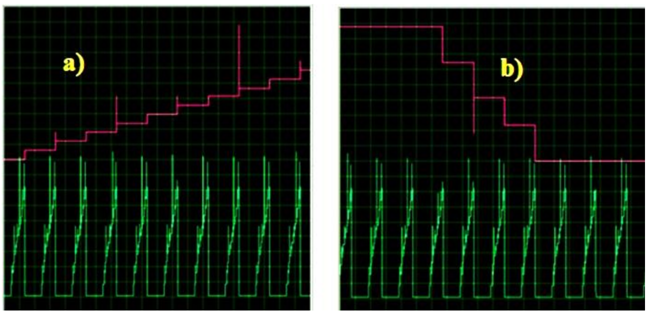

Figure 9. An output signals oscillograms of the integral controller:
a - an increase in the control action with a minimum intensity
b - decrease in control action with threefold intensity

When simulating and for setting up the program code, pins 1-8 can be used to output internal program variables. For example, in Fig. 9 shows the operation of the voltage sensor and regulator with an integral control law. In Fig. 9, a, b, the upper diagram reflects the output signal of the integral regulator, and the lower diagram illustrates the result of software integration of the sensor signal of a three-phase circuit.

Digital integration of the sensor signal of a three-phase circuit and the formation of a synchronizing pulse allows you to optimize the ratio of the analog and digital parts of the sensor according to the ease of implementation criterion.

3 CONCLUSIONS

The developed sensor of the average value of three-phase voltage measures in half the period of the alternating voltage.

Preliminary differentiation of phase voltages made it possible to reduce the dependence of the sensor output signal on the current frequency by 9 ... 12 times.

The linearity of the sawtooth output of a three-phase transducer can significantly improve the performance of the transducer.

The proposed method and scheme for the implementation of a three-phase sensor remains operational in case of phase failure and for single-phase use.

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