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КВАДРАТУРНИЙ ФАЗООБЕРТАЧ ДЛЯ ВИМІРЮВАЛЬНИХ СИСТЕМ КОНТРОЛЮ ЯКОСТІ ЕЛЕКТРИЧНОЇ ІЗОЛЯЦІЇ

В статті наведено приклади схемотехнічної реалізації фазообертачів для отримання фазового зсуву на 90º та використання у вимірювальних системах контролю та діагностики технічного стану електричної ізоляції. Розроблені в статті схемотехнічні рішення засновані на використанні аналогового помножувача сигналів реалізованого у мікросхемі AD633. Необхідне значення фазового зсуву забезпечується шляхом додавання попередньо зсунутого на певний кут вхідного гармонічного сигналу до сигналу, що має зменшену амплітуду та протилежну фазу. Вирівнювання амплітуд сигналів на вході та на виході фазообертача забезпечується за рахунок детектування їх середніх випрямлених значень із подальшим визначенням добутку їх відношення на попередньо отриманий зсунутий на 90º сигнал із зменшеною амплітудою.

Ключові слова: фазовий зсув, аналогові електричні ланцюги, контроль ізоляції, гармонічний сигнал.

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QUADRATURE PHASE SHIFTER FOR THE MEASUREMENT SYSTEMS OF TESTING OF ELECTRICAL INSULATION

Quadrature phase shifters are widely used in practice of development of measurement systems intended for the measurements of dielectric dissipation factor and electrical capacitance. This article presents the examples of implementation of phase shifters intended to obtain the value of phase shift equal to 90º for the applying in measurement systems of monitoring and diagnosing the technical condition of electrical insulation. The developed solutions are based on applying of the analog signal multiplier implemented in the AD633 integrated circuit. The required value of phase shift is provided by adding a pre-shifted at a certain angle input harmonic signal to a signal with the reduced amplitude and the opposite initial phase. The article is also focused on the development of schematic solutions which can be used in order to remove the undesirable for many practical applications discrepancy between the amplitudes of the input and the output signals. This alignment of amplitudes is provided by the detection of their average rectified values with subsequent multiplication of their ratio by the shifted at 90º signal with the reduced amplitude. The designed schematic solutions imply the applying of analog circuits which contain the input phase shifter, low pass filter, voltage summing amplifier, two detectors of average rectified values, three analog multipliers and one voltage divider.

Keywords: phase shift, analog circuits, insulation testing, harmonic signal.

Introduction. The values of electrical capacitance, as well as the dielectric dissipation factor are widely used for the purposes of diagnostics and testing the quality of electrical insulation [1, 2]. Pretty often their measurements are carried out by using the same equipment and the same techniques which have been developed in common practice of impedance measurements. In this case measurements can be made by using a broad variety of various methods and various schematic solutions. The quadrature phase shifting circuits is a pretty spread constituent part in many measurement systems intended for impedance measurements. Typical example is the described in [3] measurement system intended for the measurements of electrical capacitance and dielectric dissipation factor.

Due to the wide use of the quadrature phase shifting circuits in measurement systems intended for impedance measurements the problem of their development based on the applying of various integrated circuits becomes pretty actual. This paper presents the design of two quadrature phase shifting circuits implemented based on the analog multiplier AD633. The first circuit allows to attain the 90º shifted signal with the reduced amplitude with respect to the input sine signal. The level of this mitigation depends on frequency of the input signal. Since the dependent on frequency mitigation of amplitude can be objectionable for some measurement systems this paper also presents the approach for the alignment of amplitudes of the input and the output signals. This alignment of amplitudes is attained by using the detected average rectified values of the input and output signals.

The objective of this paper is the design of electrical circuits intended to generate the orthogonal harmonic signals for applying in measurement systems for the assessment of quality of electrical insulation.

Quadrature phase shifter with amplitude loss. The designed electrical circuit which allows to attain the 90º phase shift is based on the applying of the following trigonometric equality:

$$A\sin(\omega t-\varphi)=A\sin(\omega t)\cos(\varphi)-A\cos(\omega t)\sin(\varphi), \quad (1)$$

where A, ω and φ respectively denote the amplitude, the angular frequency and the initial phase of the input harmonic oscillation. Taking into account the trigonometric equality (1) it can be concluded that the necessary value of phase shift can be ensured by shifting the input signal to some angle φ with further subtraction of the proportional to the multiplier cos(φ) sine wave from this previously shifted signal. The oscillation on the output of the phase shifting circuit will be determined by the remaining alternating term: $-A\cos(\omega t)$. The same very principle of adding the preliminary shifted signal to the proportional to the multiplier cos(φ) harmonic oscillation has been implemented in 90º phase shifting circuit, described in the patent [4]. For out particular case the harmonic oscillation on the output of the phase shifting circuit will lag the input harmonic oscillation. The block diagram of the presented approach for phase shifting is given in the Fig. 1.

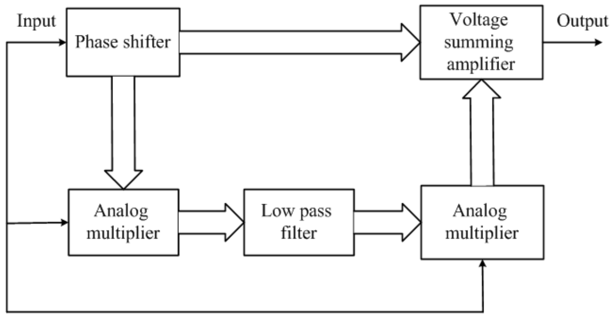

Fig. 1. Block diagram of the analog phase shifting circuit with the loss of amplitude

The phase shifter is used in order to provide the initial phase shift φ with respect to the input signal in order to build the quadrature phase shifting circuit according to the trigonometric equality (1) and the presented principle of phase shifting.

The analog multiplier with the low pass filter are used in order to obtain the value of voltage equal to cos(φ). This value of voltage is used in the second multiplier in order to obtain the waveform of voltage: $A\cos(\varphi)\sin(\omega t)$. The subtraction of this signal from the previously shifted input harmonic oscillation allows to obtain the remaining alternating term: $-A\cos(\omega t)$, which lags 90º the input sine signal.

The designed phase shifting circuit is presented in Fig. 2. This particular configuration is intended for the input signals with the amplitude equal to 1 volt. The initial phase shifter is built by using the operational amplifier AD711. For the selected configuration of phase shifter the value of phase difference between its input and output signals can be calculated according to the well known from the theory of phase philtres relation:

$$\varphi = -2\arctan(RC\omega), \tag{2}$$

where R denotes the resistance of the connected to the non-inverting input of the amplifier resistor. The affect of the input resistance of this phase shifter on the source of the input voltage can be mitigated by the inclusion of supplementary unity-gain amplifier between the source of the input voltage and the input of phase shifter. The analog multiplier is built on specialized integrated circuit AD633. The output voltage of this multiplier is determined according to the following expression [5]:

$$U_{out} = \frac{(U_{x1} - U_{x2})(U_{y1} - U_{y2})}{10} \cdot \left(\frac{(R_1 + R_2)}{R_2}\right) + S, \tag{3}$$

where U_{x1}, U_{x2}, U_{y1}, U_{y2} denote the values of the input voltage for the pins x_1, x_2, y_1, y_2, R_1 and R_2 denote the resistors used in order to adjust the value of the output voltage and S denotes the value of the optional voltage added to the summing pin Z. For the selected configuration of the multiplier its pins x_2, y_2 and Z are grounded and the resistors R_1 and R_2 allow to attain the total gain of the multiplier equal to 20. This value of gain is necessary in order to offset the default division of the output signal by 10 and to obtain the output voltage of the low pass filter equal to cos(φ). After the multiplication of two sine signals with the amplitudes A_1, A_2 and some value of phase shift φ the value of voltage on the output voltage of the low pass filter is equal to: $0.5A_1A_2\cos(\varphi)$. Therefore, the selected gain of the AD633 integrated circuit also allows us to remove the affect of the multiplier $0.5A_1A_2$ on the output voltage of the low-pass filter. Since the value of amplitude of the input signal is equal to 1 volt, the selected values of R_1 and R_2 allow to obtain the value of voltage on the output of the low pass filter equal to cos(φ). The necessity of compensation of the multipliers: $0.5A_1A_2$ and 0.1, which appear after the multiplication of the input and the preliminary shifted signals by using the first analog multiplier AD633 (designated as U_2 in Fig. 2), imposes the restriction for the designed phase shifter. For the presented in Fig. 2 electrical circuit the selected values of R_1 and R_2 allow to offset the multipliers: $0.5A_1A_2$ and 0.1 only for the case when the amplitude of the input harmonic oscillation is equal to 1 volt. For the case of the input signal with the other amplitude these multipliers will not be compensated and therefore the values of R_1 and R_2 should be adjusted in order to attain the gain which will guarantee that the value of voltage on the output of the low pass filter is equal to cos(φ). It should be noted that for the AD633 integrated circuit this adjustment should be made taking into account the admissible range of values of the resistors R_1 and R_2 and also the imposed constraint for practical applications of the ratio: $(R_1 + R_2)/R_2$, which is limited to 100 [5].

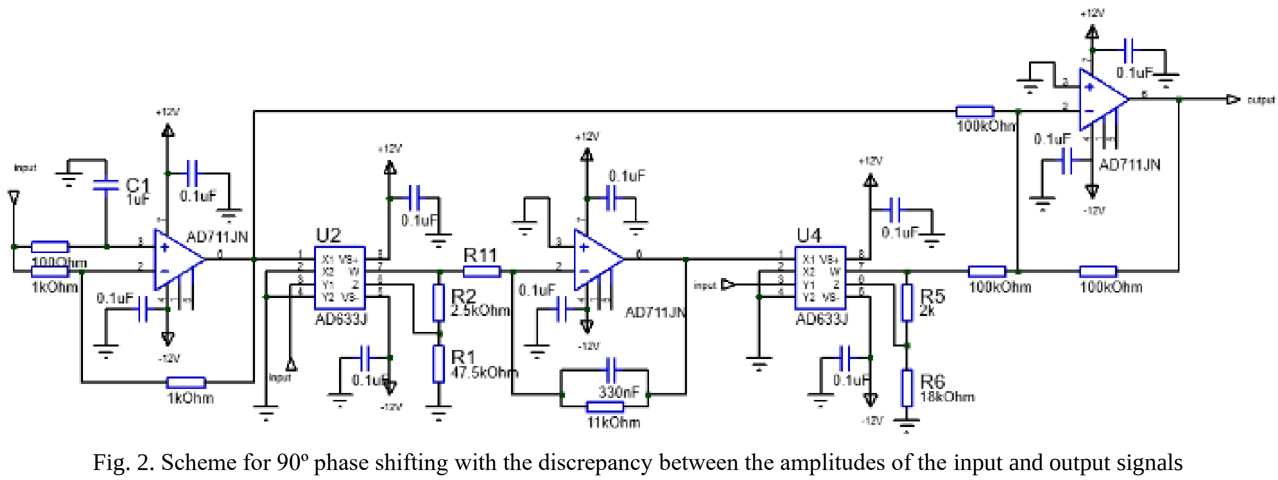

Fig. 2. Scheme for 90º phase shifting with the discrepancy between the amplitudes of the input and output signals

The analog multiplier U_2 is followed by the inverting low pass filter built on operational amplifier AD711. The low pass filter allows to suppress the alternating component of voltage on the output of the analog multiplier. For the selected values of R_1 and R_2 and the amplitude of the input sine voltage equal to 1 volt the absolute value of voltage on the output of the low pass filter will be equal to cos(φ). This voltage is multiplied by the input signal by using the second analog multiplier (designated as U_4 in Fig. 2). For this multiplier the selected values of resistors R_5 and R_6 allow to obtain the total gain equal to 10. This gain is necessary in order to offset the default division of the output signal by 10. The sum of the output voltage of the multiplier U_4 and the preliminary shifted by using the inverting voltage summing amplifier allows to obtain the output signal with the value of phase shift 90º with respect to the input harmonic signal.

Quadtature phase shifter without the loss of amplitude. The disadvantage of the presented in Fig. 1 principle of phase shifting is the decreasing of amplitude of the output voltage. Since according to the trigonometric equality (1) the amplitude of the output voltage depends on the multiplier: -sin(φ) this decreasing of amplitude also will be dependent on frequency of the input signal. Mentioned frequency dependence is caused by the determined according to the relation (2) affect of frequency of the input voltage on the value of phase shift between the input harmonic signal and sine signal on the output of the input phase shifter. Since this mitigation of the output signal should be taken into account during the design of measurement systems it can be objectionable for some schematic solutions.

The block-diagram of the improved circuit, which allows to avoid the described mitigation of amplitude, is presented in Fig. 3.

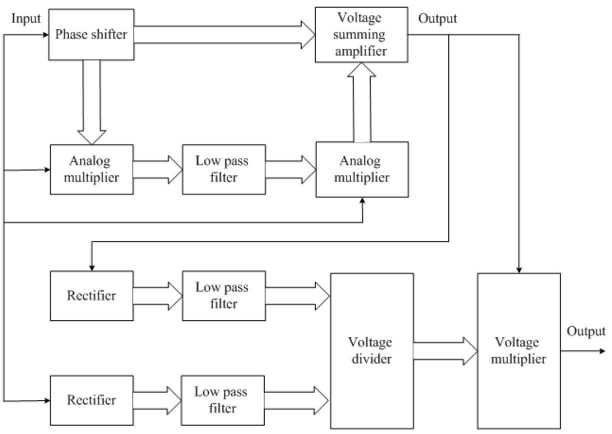

Fig. 3. Block diagram of the analog phase shifting circuit without amplitude loss

In comparison with the presented in Fig. 1 approach for phase shifting, the presented in Fig. 3 block diagram of the analog phase shifting circuit is complemented by two rectifiers, followed by the low pass filters, analog voltage divider and analog voltage multiplier. In order to emphasise that these elements are complementary with respect to the presented in Fig. 1 approach for phase shifting the diagram in Fig. 3 is presented with two outputs. The output which directly follows the voltage summing amplifier allows to obtain the quadrature signal according to the presented in Fig. 1 principle of phase shifting. The amplitude of the corresponding output signal will be lower than the amplitude of the input signal. The second output, which directly follows the analog voltage multiplier, allows to obtain the quadrature signal with its amplitude equal to the amplitude of the input signal. This alignment of amplitudes is attained by using two additional voltage rectifiers, two low pass filters and the analog voltage divider and multiplier. According to the trigonometric equality (1), after the removal of term $A\sin(\omega t)\cos(\varphi)$ by using the voltage summing amplifier, the decline of amplitude of the remaining term with 90º phase shift with respect to the input signal will be determined by the multiplier: sin(φ). Since the decline of the amplitude of the output signal is affected by the multiplier sin(φ) the same very multiplier will determine the ratio of the r.m.s value of the input voltage to the r.m.s value of the output voltage, as well as the ratio of their average rectified values. This affect has been used in order to align the amplitudes of the input and output signals. The developed approach implies the detection of the average rectified values of the input signal and signal on the output of the voltage summing amplifier with further evaluation of their ratio. This ratio is equal to 1/sin(φ). The multiplication of this ratio by the signal on the output of the voltage summing amplifier allows to remove the described mitigation of amplitude and to align the amplitudes of the input and the output signal. The complementary part of the circuit, which allows to remove the decline of the amplitude of the output signal is presented in Fig. 4. For the presented in Fig. 4 complementary part of the phase shifting circuit the voltage rectifiers are built on operational amplifiers AD711 and followed by the *RC* circuits which are used as the low pass filters with time constant equal to 0.235 s. The analog voltage divider is built on analog multiplier AD633 and operational amplifier AD711. The input no.1 of the presented in Fig. 4 electrical circuit is intended for the signal from the output of the voltage summing amplifier of the presented in Fig. 2 circuit. The input no.2 is intended for the overall input signal of the circuit generated by the external *AC* generator of testing voltage. Taking into account the default multiplication of the result of voltage division by 10 the absolute value of voltage on the output of this voltage divider is equal to 10/sin(φ) volt. The multiplication of this voltage by the signal from the output of voltage summing amplifier (input no.1) yields the quadrature signal with the amplitude equal to the amplitude of the input signal. The default division by 10 of the AD633 analog multiplier allows to offset the increased value of voltage on pin no. 1 due to the multiplied by 10 value of voltage on the output of voltage divider.

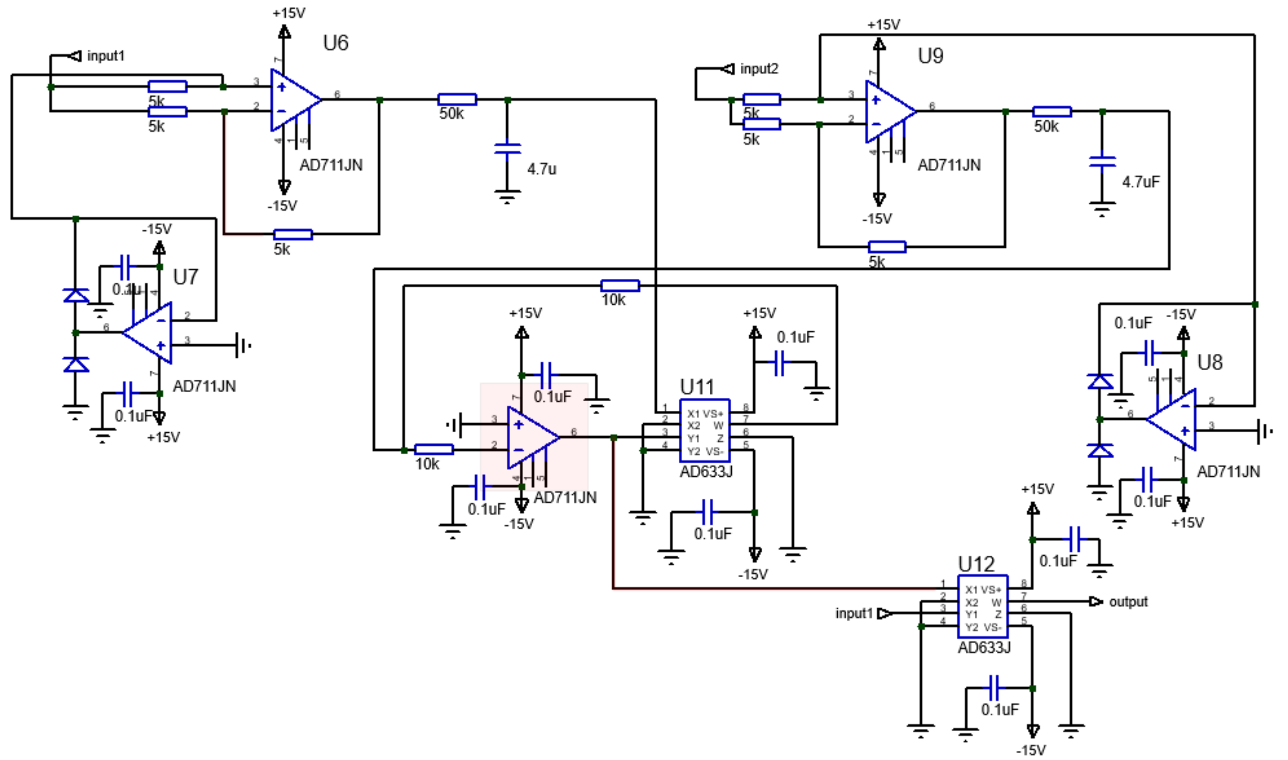

Fig. 4. Complementary part of the phase shifting circuit with the aligned amplitudes of the input and output signals

Conclusions. The designed electrical circuits are intended for the generation of harmonic quadrature signals. The implemented approach for their development implies adding of the preliminary shifted harmonic signal to the signal with the same initial phase as the input signal of the phase shifting circuit. The schematic implementation of this approach leads to the decline of amplitude of the output signal. The alignment of amplitudes of the input and output signals can be attained by using supplementary detectors of the average rectified values of the input and output signals, voltage divider and voltage multiplier.

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