WAY OF CONNECTION OF A THREE-PHASE MOTOR TO A SINGLE-PHASE NETWORK VIA RESONANCE EFFECT

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Abstract: In this paper, we propose a method to connect a three-phase motor, with windings connected by a star and a phase-shifting capacitor as the third contact, to a single-phase network, with efficient use of electrical energy due to compensation of reactive power and due to effective distribution of the voltage in front of the motor's oscillating circuit. A resonance phenomenon in an oscillating circuit of the motor is used to compensate for reactive power, i.e. to increase the active power coefficient to the maximum value. A capacitor bank in front of the circuit is used to effectively distribute the voltage at the input of the motor circuit in order to increase the motor voltage from the mains value of 220 V to the nominal value of a three-phase motor of 380 V. A special installation was created for experimental studies. The results of experimental studies, theoretical calculations of the electrical circuit of the installation, as well as the voltage vector diagram of the motor circuit show that the case when voltages on the motor are U = 380 B (U_L= U_{C5}= 325.4 B) and U = 392 B (U_L= U_{C5}= 375.6 B) most closely corresponds to the resonant state of the motor oscillating circuit. The proposed method was introduced into the educational process as a laboratory work for students of technical specialties of the Almaty University of Energy and Communications, and can be used by designers, inventors, scientists and specialists interested in similar issues to create devices that connect a three-phase star-connected motor to a single-phase network.

Introduction

Three-phase asynchronous motors are commonly used in industry and households. Such motors are the most common, and the operation of the majority of motor-powered devices is based just on such motors. Ways to create sufficient torque include connection to the phase-shifting capacitor as the third contact, and other methods, which are offered by the service companies "Master of Cold" (2017), "Tool-Land" (2017) and the channel "Zen. yandex.ru" (2018). A three-phase motor operating in a single-phase network has practically the same rotational rate as one in a three-phase network. However, such a connection significantly reduces asynchronous motor power. This is due to a decrease in voltage between phases from 380 *V* to 220 *V* and is due to insufficient power drawn from the single-phase network. On the downside, on average, each three-phase motor connected to a single-phase network can lose up to 30 - 50 percent of its own power (Obinstrumente.ru, 2018).

This paper proposes a method to connect a three-phase motor star-connected to a single-phase network, with the electrical energy saving on account of reactive power compensation and voltage increase from 220 *V* to 380 *V*. Most modern consumers of sinusoidal electric power are presented by inductive loads with currents that lag in phase behind the supply source voltage. The active power of such consumers at a given current and voltage values still depends on the power factor $\cos\varphi$.

A near-resonance effect was used to compensate for the reactive power, and a capacitor bank in front of the three-phase motor circuit was used to save electrical energy. In a motor circuit, the load (winding) is mainly inductive. It is compensated with capacitances. This helps to increase *cosφ* to acceptable values of 0.7 to 0.9. The economic effect of the introduction of reactive power compensation devices ranges from 12 to 50% (Electrik.info, 2018).

Research Methodology

The installation for connecting a three-phase motor to a single-phase network (Fig. 1) consists of amperemeters A and A_1, a voltmeter V, capacitances C, C_5, C_6 and a three-phase motor, electric circuit of which is shown in Fig. 2. DT-830D type multimeters are used as electrical measuring instruments; the measurement limit is 10 A in the ammeter mode; the measurement limit is 600 V in the voltmeter mode. 5AY 80A4 U2 type three-phase induction motor has nominal power of 1.1 kW, rotation speed of 1400 of r/min, efficiency coefficient of 78.5%, *cosφ*=0.74. Instruments are certified by the electric measuring instruments standardization and certifications center.

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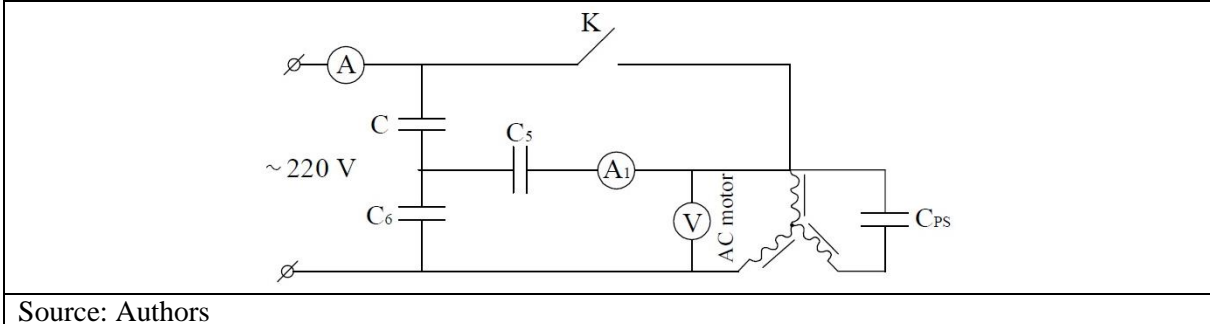
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Figure 1: The installation for connecting a three-phase motor to a single-phase network
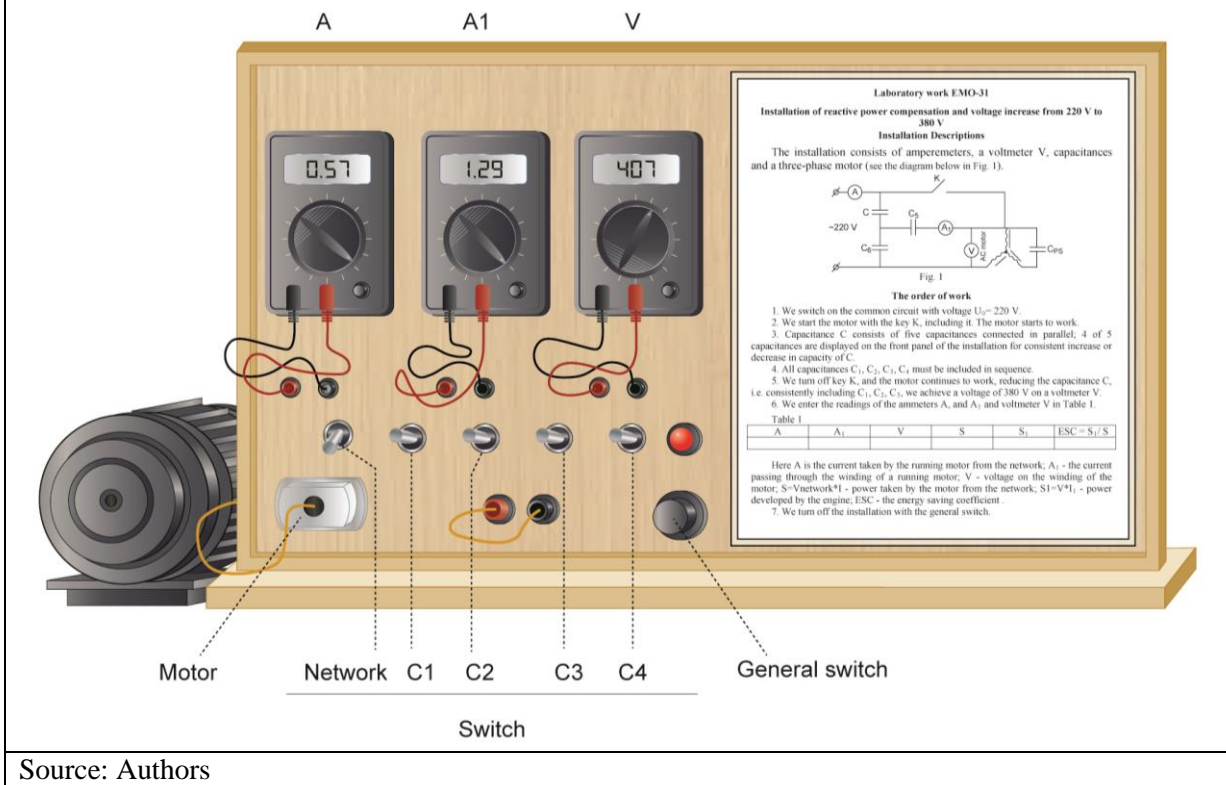
Source: Authors

Figure 2: Electrical diagram of installation

Source: Authors

In the system, three windings of a three-phase motor star-connected to one common point, are connected to a single-phase circuit in the following way. The second ends of the first and second windings are connected to each other through a phase-shift capacitance $Cps = 5 \ \mu F$ "Tool-Land" (2017), from the other side the second end of the first winding is connected simultaneously to the key path K and the second end of the third winding is connected to the internal circuit of a single-phase circuit. When the C capacitor is off and the K key is turned on, a mains voltage of 220 V is applied to the second ends of the first and third windings and together with the phase shifting capacitor Cps provide voltage drops between adjacent phases equal to 220 V with phase shifts equal to 120^0 "Tool-Land"(2017). If we consider that usually the voltage between the phases of the motor windings in a three-phase circuit is 380 V, then when a three-phase motor is connected to a single-phase network, a significant reduction in the total power consumed by the motor due to a decrease in the voltage between phases from 380 V to 220 V is understandable. It is necessary to increase the voltage from 220 V to 380 V and higher values which is possible by creating a resonance condition in the motor circuit with an active resistance R, windings inductance L and capacity C_5, to eliminate deficiency in total power consumed by the motor and to increase the total power more. Under conditions of resonance, the voltage applied to the motor considerably exceeds the mains voltage, the reactive power at the inductive impedance of the motor winding is compensated with the reactive power at

capacitance of the capacitor C_5. Then the motor power coefficient approaches its limit value and the power supplied from the mains to the motor circuit will be approximately equal to the active power at the active resistance of the motor windings. Therefore, the purpose of this study is to design a system and its electrical circuit ensuring the achievement of resonance in the motor circuit with a voltage at the ends of the neighboring windings equal to 380 V or more, to increase the total power consumed by the motor significantly higher than the mains power. Experimental and theoretical studies were carried out to implement this.

Results and its Discussion

An experimental investigation was carried to the following procedure. Ammeter A measures the current in the mains, A_1 measures the current in the motor, V measures the motor neighboring windings voltage. Capacitance C consists of five capacitances connected in parallel; 4 of 5 capacitances are displayed on the front panel of the installation. The work is performed in the following order. Switch on the common circuit with voltage $U_0 = 220 \ V$. When switch on the key K, obtaining $U_0 = 220 \ V$, $I = 0.48 \ A$, $I_1 = 0.29 \ A$. Power in the mains is $S_1 = U_0 I$, full rotor power is $S_2 = U \ I_1$. All capacitances C must be included in sequence; $C_6 = 10 \ \mu F$. Turn off key K, and the motor continues to work. While reducing the capacitance, change the voltage U_2 on the capacitor C_6.

With an increase in the capacitance of the capacitor C_6, its capacitance X_C decreases and, accordingly, the voltage U_1 is dropping on it, due to this the voltage U_2 on the capacitor C_6 increases, i.e. the voltage applied to the oscillating circuit of the motor and the motor voltage U also increase. The current strength in the motor circuit I_1 is greater than the current strength of the mains I, and it also increases. The voltage U becomes significantly greater than U_2 and, accordingly, the voltage of the mains U_0 for the account of the reactive component U on the inductive resistance of the motor windings U_L, which at resonance is compensated with voltage U_{C5} on the capacitance X_{C5} of the capacitor C_5.

Enter measurement results in Table 1.

	C [μF]	7.5	8.5	9.5	10.5	11.5	
	U_2 [V]	94.6	101.2	107.8	112.2	117.7	
	U_2/U_0	0.43	0.46	0.49	0.51	0.53	
	I [A]	0.65	0.63	0.62	0.61	0.59	
	I_1 [A]	0.88	1.03	1.12	1.19	1.26	
	U [V]	346	370	380	392	400	
	S_1 [V*A]	143	138.6	136.4	134.2	129.8	
	S_2 [V*A]	304.5	381.1	425.6	466.5	504	
	S_2/ S_1	2.13	2.75	3.12	3.48	3.88	

Table 1: Experimental Data

Source: Authors

The energy saving coefficient (ESC) is characterized by S_2 / S_1. With rated linear voltage on the motor, U=380 V (see Table 1), ESC is 3.12. The efficiency coefficient of the motor circuit is $P_2 / P_1 \approx 0.89$.

We carry out the substantiation of the above assumption and the results of experimental investigations. Power dependence on $\cos \varphi$ must be considered when designing an AC power transmission circuit. If the supplied loads have a large reactance $X = X_L - X_C$, then $\cos \varphi$ can be noticeably less than one.

In these cases, to transfer the required power to the consumer (with such mains voltage), I should be increased, which leads to an increase in useless energy losses in the supply lines. Therefore, attempts must be always made to distribute the load, inductance and capacitance so that $\cos \varphi$ is as close to one as possible. To do this, it is enough to make the reactance X as small as possible, i.e. ensure

equality of inductive and capacitive impedances: $X_L = X_C$, i.e. to create a condition in the circuit close to resonance (Irodov, 2013).

Additionally, inductance voltage

$$U_{Lr} = \omega L I_1 \qquad (1)$$

and capacitance voltage

$$U_{Cr} = \frac{1}{\omega C_5} I_1 \qquad (2)$$

are equal to each other:

$$U_{Lr} = U_{C5r} = \sqrt{\frac{L}{C_5}} I_1 = \frac{1}{R} \sqrt{\frac{L}{C_5}} U_2. \qquad (3)$$

If the characteristic wave impedance of the circuit is greater than its active resistance (of motor winding) (Atabekov, 2009)

$$\rho = \sqrt{\frac{L}{C_5}} \succ R, \qquad (4)$$

then inductance voltage U_{Lr} and capacitance voltage U_{Cr} will exceed the voltage applied to the motor circuit $U_2 = U_{C_6}$ (Savelyev, 2012):

$$U_{Lr} = U_{C5r} \succ U_2 = U_{C_6}. \qquad (5)$$

Reactance of a motor circuit containing a winding inductance L and capacitance C_5 is proportional to the difference of the effectual values of the power stored in the magnetic and electric fields (Atabekov, 2009)

$$X = \frac{4\pi}{I^2} \left(P_L - P_C \right). \qquad (6)$$

The condition of resonance ($X = 0$) corresponds to the equality

$$P_L - P_C = 0. \qquad (7)$$

The quality of inductance L of the motor winding $Q_L = \omega L / R$ and capacitance C_5 of the capacitor $Q_C = \omega C_5 R$ can be expressed through the maximum power P_{Lm} that periodically stores inductance L and the maximum power P_{Cm} that periodically stores capacitance C_5, respectively.

$$Q_L = 2\pi \frac{P_{L\max}}{P},$$
$$Q_C = 2\pi \frac{P_{C\max}}{P}. \qquad (8)$$

Where, P is the active power consumed in the motor winding resistances R at the amplitude of current I_m or at the amplitude of capacitance voltage U_{C5m}.

On the other hand, the quality of the motor circuit is as follows:

$$Q = \frac{\rho}{R}. \qquad (9)$$

Comparing two expressions (8) and (9) of the circuit quality, we can say that the greater the characteristic wave impedance ρ of the motor circuit, as compared to the active resistance of the windings R, the greater the maximum power P_{Lm} that periodically stores inductance L or maximum

power P_{Cm} that periodically stores capacity C_5 compared to the active power consumed in the motor windings P, i.e.

$$P_{Lm} \succ P, P_{Cm} \succ P. \tag{10}$$

The total power of the oscillating circuit of the motor is

$$S = \sqrt{P^2 + \left(P_L - P_C\right)^2}. \tag{11}$$

In the case of resonance, taking into account (7), we obtain

$$S = P. \tag{12}$$

Total power applied to the motor is

$$S_2 = \sqrt{P^2 + P_L^2}. \tag{13}$$

If we take into account the experimental results of Table 1: $I_1 \succ I, U_2 \succ U_0$, and that mains power S_1 is practically active (12), then taking into account inequalities (10), we can be sure that

$$S_2 \succ S_1 \tag{14}$$

or power saving coefficient

$$S_2/S_1 \succ 1. \tag{15}$$

For the theoretical calculation of the electrical circuit in Figure 2, we use the symbolic (complex) method (Bessonov, 1996; Bondarenko, 2004). Network voltage $\dot{U}_0$ according to complex Kirchhoff's second law is

$$\dot{U}_0 = \dot{I}\dot{X}_C + \dot{I}\dot{Z}_r = \dot{I}\left\{ \frac{R}{1+\left(\omega C_6 R\right)^2} - j\left[\frac{\omega C_6 R^2}{1+\left(\omega C_6 R\right)^2} + \frac{1}{\omega C_5} \right] \right\}. \tag{16}$$

Where $\dot{X}_C = -j\dfrac{1}{\omega C}$ is capacitive resistance of capacitor banks;

$\dot{Z}_r = \dfrac{1/R}{\left(1/R\right)^2 + \left(\omega C_6\right)^2} - j\dfrac{\omega C_6}{\left(1/R\right)^2 + \left(\omega C_6\right)^2}$ is impedance of the resonant circuit.

Hence, the network current $\dot{I}$ according to Ohm's law in an integrated form is as follows.

$$\dot{I} = \frac{\dot{U}_0}{\dfrac{R}{1+\left(\omega C_6 R\right)^2} - j\left[\dfrac{\omega C_6 R^2}{1+\left(\omega C_6 R\right)^2} + \dfrac{1}{\omega C_5} \right]}. \tag{17}$$

The full circuit impedance is as follows

$$\dot{Z} = \frac{R}{1+\left(\omega C_6 R\right)^2} - j\left[\frac{\omega C_6 R^2}{1+\left(\omega C_6 R\right)^2} + \frac{1}{\omega C_5} \right]. \tag{18}$$

Its module is as follows

$$Z = \sqrt{ \left[\frac{R}{1+\left(\omega C_6 R\right)^2} \right]^2 + \left[\frac{\omega C_6 R^2}{1+\left(\omega C_6 R\right)^2} + \frac{1}{\omega C_5} \right]^2 }. \tag{19}$$

Argument φ of full circuit impedance can be determined by the formula

$$tan\varphi = \frac{\omega C_6 R + X_{C5}\left[1+\left(\omega C_6 R\right)^2 \right]}{R}. \tag{20}$$

Then, the complex impedance can be represented as follows.

$$\dot{Z} = Z e^{-j\varphi}. \tag{21}$$

The mains current is as follows.

$$\dot{I} = \frac{U_0 e^{j\omega t}}{Z e^{-j\varphi}} = \frac{U_0}{Z} e^{j(\omega t + \varphi)} = I e^{j(\omega t + \varphi)}. \tag{22}$$

According to this formula, we can see that the mains current is ahead of the mains voltage in phase, which means the predominance of capacitive resistance of the circuit. This is explained by the fact that in the case of the motor circuit resonance, the inductive resistance X_L of the windings is compensated by the capacitance resistance of the circuit X_{C5}: $X_L - X_{C5} = 0$ and only the active resistance of the windings R and the prevailing capacitances X_C, X_{C6} of the capacitors C and C_6 will practically act in the circuit.

On the other hand, according to the Kirchhoff's first law, the mains current is equal to the sum of currents in the branches:

$$\dot{I} = \dot{I}_1 + \dot{I}_2. \tag{23}$$

Table 2 presents some results of theoretical calculations based on the results of experimental work. Here the voltage U_1 on distribution capacitance $X_C = \dfrac{1}{2\pi f C}$ is calculated by the formula

$$U_1 = I \cdot X_C, \tag{24}$$

active resistance of motor windings by expression

$$R = \frac{U_2}{I_1}. \tag{25}$$

Voltage U_L on inductive resistance X_L of motor windings or voltage U_{C5} on capacitance X_{C5} of the oscillatory circuit are found according to the formula

$$U_L = U_{C5} = \sqrt{U^2 - U_2^2}. \tag{26}$$

Reactive resistances X_L and X_{C5} are calculated by the formula

$$X_L = X_{C5} = \frac{U_L}{I_1} = \frac{U_{C5}}{I_1}. \tag{27}$$

Calculations of inductance L, capacity C_5 of the oscillatory circuit are found according to the formula

$$L = \frac{X_L}{2\pi f}, C_5 = \frac{1}{2\pi f X_{C5}}. \tag{28}$$

Wave resistance ρ of the oscillatory circuit is found by the formula (4).

Table 2: The results of theoretical calculations

U_1 [V]	$U_L = U_{C5}$ [V]	R [O]	$X_L = X_{C5}$ [O]	L [H]	C_5 [μF]	ρ [O]
276	333	107.5	378.2	1.20	8.42	377.5
236	356	98.3	345.5	1.10	9.22	345.4
208	364	96.3	325.4	1.04	9.79	325.9
185	376	94.3	315.6	1.01	10.10	316.2
163	382	93.4	303.4	0.97	10.50	303.9
Source: Authors						

We can observe from Table 2 that $\rho \succ R$.

Let's get a vector diagram of voltages (Fig.3) according to the data of Tables 1 and 2 using the following method. According to the vector sum $\dot{U}_0 = \dot{U}_1 + \dot{U}_2$, we construct the voltage triangle U_0, U_1 and U_2.. Under resonance conditions, the voltage U_2 is equal to U_R, i.e. $U_2 = U_R$, and the vectors $\dot{U}_L$ and $\dot{U}_{C5}$ are equal in value and perpendicular to the vector $\dot{U}_R$.

Figure 3: Vector diagram of voltages at resonance

Source: Authors
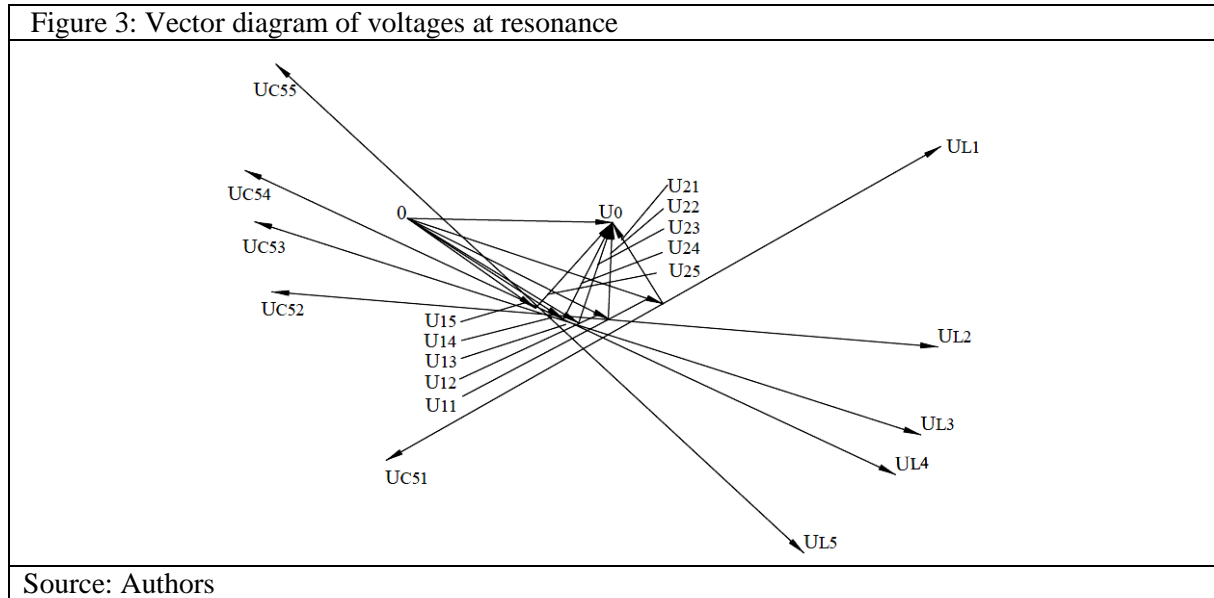
We can observe from Figure 3 that in the cases with the voltages $U = 380\ V\ (U_L = U_{C5} = 325.4\ V)$ and $U = 392\ V\ (U_L = U_{C5} = 375.6\ V)$ the vector of voltage $\dot{U}_1$ on the capacitance X_C and the vector of voltage $\dot{U}_2 = \dot{U}_R$ on the active resistance R of the motor windings is practically mutually perpendicular, which should be at the resonance, and the direction of the values of voltages U_{L3} and U_{L4}, U_{C3} and U_{C4} proved to be mutually close in comparison with the directions of other voltages values. The power savings and efficiency coefficients of the motor circuit are $(S_2 / S_1)_3 = 3.12$; $(P_2 / P_1)_3 \approx 0.89$ and $(S_2 / S_1)_4 = 3.48$; $(P_2 / P_1)_4 \approx 0.99$, respectively. The values of efficiency coefficient are very close to one. This means that the loss of mains power in the motor circuit is insignificant at resonance. Therefore, the theoretical justification and calculation formulas (4), (24) - (28) are most appropriate for these cases of the resonant state of the motor circuit.

Conclusion

An experimental setup was created, and a method was proposed to connect a three-phase motor with the star-connected windings and a third contact, a phase-shifting capacitor, to a single-phase network with the effect of electrical energy saving for the account of reactive power compensation and voltage increase from 220 V to 380 V. A near-resonance phenomenon is used to compensate for reactive power, and a capacitor bank with adjustable capacitance is used in front of a three-phase motor's circuit for efficient use of electrical energy. Experimental studies, theoretical calculations of the electrical circuit of the installation and the justification of their results were carried out. According to the study results, the voltage diagram of the motor circuit was built. It is revealed that the case with voltages on the motor $U = 380\ V\ (U_L = U_{C5} = 325,4\ V)$ and $U = 392\ V\ (U_L = U_{C5} = 375.6\ V)$ is the closest to the resonant state of the motor circuit. In these cases, the energy saving and efficiency coefficients of the motor circuit are $(S_2 / S_1)_3 = 3.12$; $(P_2 / P_1)_3 = 0.89$ and $(S_2 / S_1)_4 = 3.48$; $(P_2 / P_1)_4 = 0.99$, respectively. The loss of mains power decreases from 11% to 1% in the motor circuit. The proposed method to connect a three-phase motor star-connected to single-phase network was introduced into the educational process as a laboratory work for students of technical specialties of the Almaty University of Energy and Communications, and it can be used in electric machine industry to create single-phase induction motors and by designers, inventors and scientists interested in similar issues.

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