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IMPROVING POWER FACTOR OF THREE-PHASE ASYNCHRONOUS MOTOR THROUGH CAPACITOR BANKS CONTROLLED WITH PROGRAMMABLE LOGIC CONTROLLER

Among the possible ways to improve the energy efficiency of three-phase asynchronous electric motors is to reduce the cost of electricity due to its more complete utilization and loss reduction. For this reason, manufacturers of electrical equipment are making more efforts to improve the efficiency of electricity in order that less of it to waste or unnecessary to provide the consumer without work. This problem is well known and therefore the improvement of the power factor or cosφ is among the main tasks of the power generators and electrical equipment manufacturers. One of the more common methods of power factor improvement is passive, using capacitor banks. In recent years there has been a demand for new methods of control of these capacitor banks. Systems are developed with microprocessor control, specialized controllers and using programmable logic controllers. In the present work is proposed an electric circuit, operating circuit and software, presented in the form of algorithm for control of capacitor banks with programmable logic controller.

Keywords: power factor, capacitor banks, programmable logic controller.

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ПОКРАЩЕННЯ КОЕФІЦІЄНТУ ПОТУЖНОСТІ ТРИФАЗНОГО АСИНХРОННОГО МОТОРУ ЗАВДЯКИ КОНДЕНСАТОРНИМ БАТАРЕЯМ, ЩО КОНТРОЛЮЮТЬСЯ ПРОГРАМНИМ ЛОГІЧНИМ КОНТРОЛЕРОМ

Серед можливих шляхів підвищення енергоефективності трифазних асинхронних електродвигунів є зниження вартості електроенергії завдяки повному її використанню та зменшенню втрат. З цієї причини виробники електрообладнання докладають більших зусиль для підвищення ефективності роботи електроенергії через зменшення втрат потужності. Ця проблема добре відома, і тому поліпшення коефіцієнта потужності є одним з головних завдань виробників електроенергії та виробників електрообладнання. Одним з найбільш поширених методів підвищення коефіцієнта потужності є пасивне використання конденсаторних батарей. Останніми роками існує попит на нові методи контролю цих конденсаторних батарей. Системи розробляються за допомогою мікропроцесорного керування, спеціалізованих контролерів та програмованих логічних контролерів. У роботі пропонується електрична схема, схема управління та програмне забезпечення, представлені у вигляді алгоритму управління конденсаторними батареями з програмованим логічним контролером.

Ключові слова: коефіцієнт потужності, конденсаторні батареї, програмований логічний контролер.

Introduction

Increasing energy efficiency by reducing energy costs is one of the ways not only to increase the competitiveness of enterprises but also to increase their environmental performance [1, 2, 8]. Among the possible ways to achieve this goal is to reduce the cost of electricity by making it more efficient and limiting losses. For this reason, manufacturers of electrical equipment are making more efforts to improve the efficiency of electricity in order that less of it to waste or unnecessary to provide the consumer without work. This problem is well known, and thus improving the power factor or cosφ is among the main tasks of the power engineers and manufacturers of electrical equipment. It is known that bringing cosφ to one leads to energy savings.

Not less is the problem of losses due to the non-sinusoidal shape of the current of the consumers, which imposes in the requirements for quality of the supplied electricity to the value of the voltage and the frequency to add the maximum closeness of its shape to the sinusoid [6, 7, 9].

Three-phase asynchronous motors are one of the largest electricity consumers in the industry, which determines the need for individual solutions related to improving their efficiency [2, 10]. One of the more common methods of power factor improvement is passive, using capacitor banks. In recent years there has been a demand for new methods of control of these capacitor banks. Systems with microprocessor control, specialized controllers and using programmable logic controllers are developed [3, 4, 8].

The purpose of this work is to design a capacitor banks control system with a programmable logic controller.

Material and methods

Selection of an electric motor. For the purpose of the study, a three-phase asynchronous electric motor (EM) with the parameters listed in Table 1 is used. Low Efficiency EMs were used to demonstrate the power factor correction capabilities.

In addition to the parameters given on the manufacturer's nameplate, we will make additional measurements for the following parameters: Resistance of windings; inductance of windings; resistance of the windings to the housing.

Table 1

Parameters of electrical motor

Nominal power	30KW
Frequency	50Hz
Supply voltage	380V
Current	54A
Rpm	2920rpm
Cosφ	0,84
Stator poles	2

For the measurement, we use the V & A MS8201H DMM multimeter, making a duplicate measurement with another multimeter in order to reduce the possibility of a measurement error. The measurement data obtained are shown in Table 2. The second measurement confirms the received data with minor differences.

Table 2

Measured parameters

Winding	Resistance R	Inductivity L	Resistance winding-housing
L1	0,6 Ω	4,5 mH	1,5MΩ
L2	0,6 Ω	4,6 mH	1,4 MΩ
L3	0,6 Ω	4,4 mH	1,6 MΩ

Determination of the power factor against the load of the electric motor. The simulation model used is presented in [10]. Figure 1 shows a diagram of the variation of the power factor of the electric motor depending on its load.

Determining the current of the motor depending on the load. For the determination of the motor load will use a method in which the measured current of one of the phases will determine the motor load by formula (1). We assume that the load of the three phases is symmetrical.

$$I = \frac{P}{V.cos\varphi.\sqrt{3}} \quad (1)$$

Where P is the power (load), U is the voltage, I is the current, cosφ the power factor for the respective load.

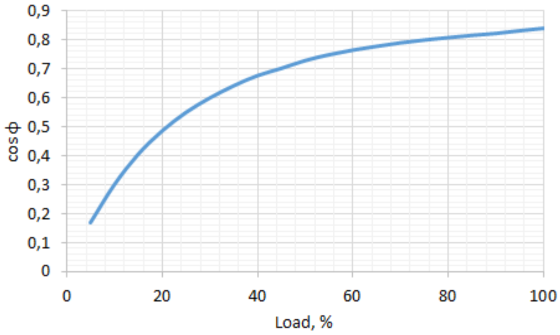

Fig. 1. Power factor versus electrical motor load

Determination of the capacitor banks power to adjust the power factor. We assume that the shape of current and voltage are sinusoidal, whereby the power factor is fully determined by cosφ. As the average power factor we are going to target, we assign cosφ=0,95. As the boundaries between which cosφ can vary – from 0,90 to 1,00, and in order to ensure the inevitable inaccuracies and errors we will narrow the cosφ limits from 0,91 to 0,99.

Determining the required power of the capacitor batteries measured in KVAR can be done in several ways. Here is a prepared table published in [2]. The data in this table are obtained using formulas (2) and (3).

$$\varphi_1 = Cos^{-1}(Cos\ \varphi_1) \quad (2)$$

$$kVAR = P\ (Tan\ \varphi_1 - Tan\ \varphi_2) \quad (3)$$

Where cosφ1 is the original power factor, cos φ2 is the desired power factor, P power of the motor in KW, KVAR is the required capacitance of the capacitor bank. The capacity of the capacitor bank in F is obtained by Formula (4).

$$C = kVAR / (2\ \pi\ f\ V^2) \quad (4)$$

Where C is the capacity of the capacitor bank in microfarade, the KVAR capacitance of the capacitor bank, f is the frequency in Hertz, V is the voltage in volts.

Selection of capacitor banks. Selected capacitor banks with power 10KVAR, model BZMJ 0.4-10-3 of manufacturer SEMO their main parameters are presented in Table 3.

Table 3

Parameters of capacitor banks

Nominal voltage	400 V
Nominal power	10 KVAR
Nominal frequency	50 Hz
Nominal capacity	199 μF
Nominal current	14,4 A
Number of phases	3
Height of the housing	140 mm

Programmable logic controller choosing, measuring and control elements. The programmable logic controller (PLC) is an essential part in the management system of capacitor banks. Its main task is to implement the control algorithm by following the introduced program. A low-level controller, the so-called microcontrollers, is sufficient for our project. The main features that we need to consider when choosing a PLC are the number of digital inputs/outputs, the number of analogue inputs/outputs, the supply voltage, the type of outputs – relay or transistor.

A programmable logic controller Mitsubishi from the MELSEC FX1S series is selected, and for our needs, the FX1S-14MT-ESS/UL is suitable for use with the FX1N-2AD-BD Expansion Analog Module. In this project, the current transformer must provide information about the current (or load) of the electric motor at any moment. The range that is necessary to cover current transformer is 0-50.

Standard power transformer models reduce primary current with some standard ratio. Since the selected controller works with standard analogue levels, an additional matching scheme will be needed to convert the output from the current transformer to one of the standard analogue levels. It is much more convenient to use a current transformer with a built-in coordinate circuit, from which a standardized signal is directly received. A current transformer MBS AG model SWMU 31.51.31-5014 is selected.

The capacitive contactors will perform the switching of the capacitor banks stages. The grades are 10KVAR. The following model is selected: Capacitive contactor for reactive power compensation, 12,5 kVar at 400 VAC. 110VAC coil, manufacturer KBR GmbH, Code: K3-62K.

Support relays are required, as the controller can not directly power the contactor coils. The FINDER DPDT microrelay was used; Coil voltage: 24VDC; maximum contact load 8A/250VAC; 8A/30VDC.

Design of an electrical circuit. The design of the electrical circuits uses AutoCAD Electrical software. A diagram is designed for the stages of the capacitor banks system and a general circuit for controlling the electric motor used.

Development of a PLC control program. To develop the ladder diagram we use a Mitsubishi electric software product from the Melsoft GX Works2 program package [5].

Results and discussion

Using the tables shown in the material and methods, the required capacitance of the capacitor banks was determined first for the average value of cosφ 0,95 and then for the limit values of 0,91 and 0,99. The required power of the capacitor banks has been calculated for a load of over 30%, as in real conditions this electric machine is loaded with a minimum of 30% even at idle. This load is due to the mechanical characteristics of the electric drive system in which the motor is engaged.

From the data obtained is a diagram showing the limits in which the capacity of the capacitor banks for the respective load can vary.

It is clear from the diagram that static compensation (a constant-power capacitor banks) can not cover the entire load range of the motor. For this reason, grade compensation was used. The stages are selected so that capacitor banks of the same power or the combination thereof can be used. From economic expediency it is necessary to choose a variant with the least degree even at the price of minor inaccuracies. It is necessary to select capacitor banks with the available power on the market.

Taking into account the data received, three-stage compensation was chosen as an acceptable option.

Capacitors are rated at 10 KVAR for each individual stage. The capacitors of the individual stages are connected in parallel, which will sum their power.

The limits and power of individual ranges are as follows:

- first range from 100% to 65% load, one capacitor with 10KVAR output;
- second range from 65% to 38% load, two convoys with a total power of 20 KVAR;
- a third range less than 38% load, three capacitors with a total power of 30 KVAR.

The current of the motor and the current of one of the phases are determined (Figure 2).

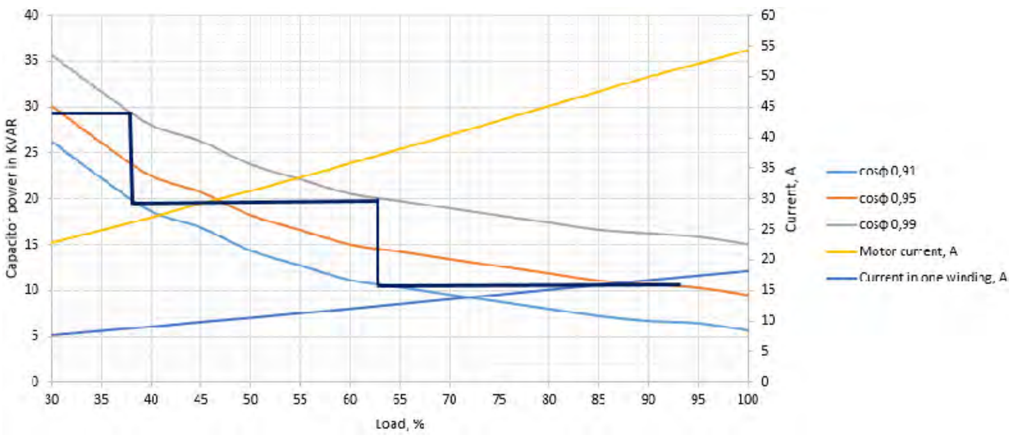

Fig. 2. Range of degrees of the capacitor bank defined by electric motor current and capacitor banks power

The electrical circuit is divided into power and operating circuits. The purpose of the power circuit is to supply a supply voltage to the power consumer, in this case the electric motor.

In view of the safety requirements, a fuse switch disconnector FC1 is first installed on the power supply circuit. After that, the contactor K1, which performs the main commutation, follows the motor protection KF1, which provides overload protection of the electric motor.

To measure the current of one of the phases, a W1 current transformer (current transducer) is installed. It is powered by a 24VDC operating voltage from the PLC, its V+ and VI- terminals are connected to the PLC analogue block. The capacitor banks C1, C2, C3 are connected in parallel to the motor and switched via the capacitive contactors KC1, KC2, KC3 (Figure 3).

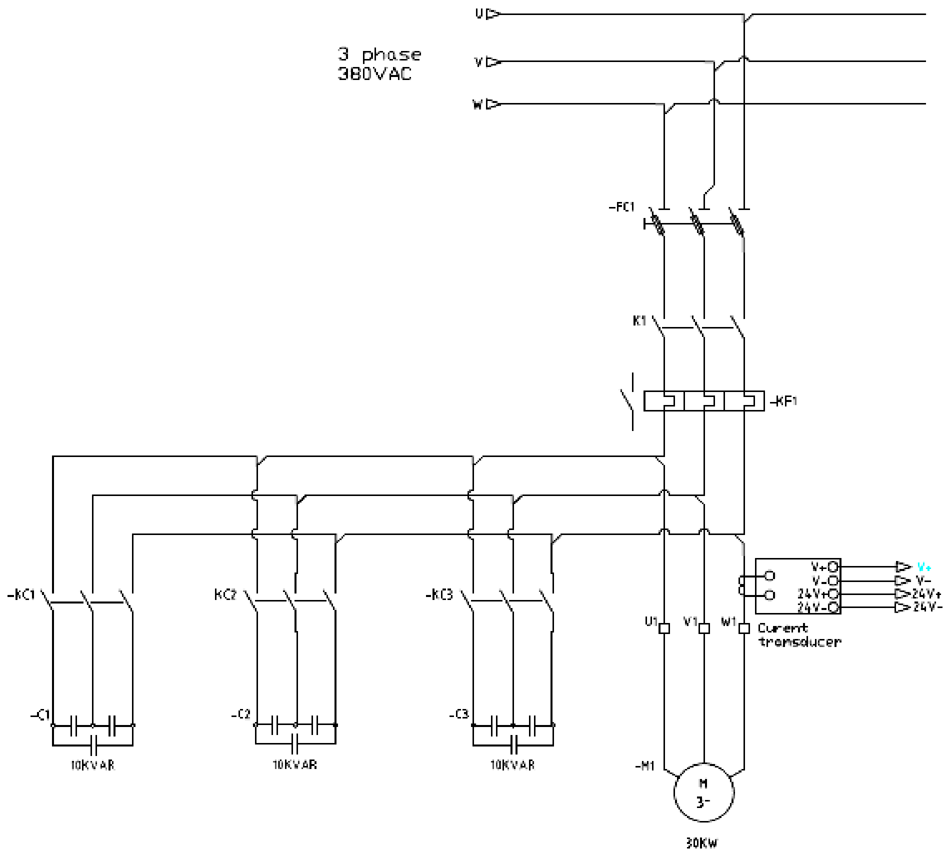

Fig. 3. Power circuit of an electric motor with three-stage capacitor bank

The operating circuit (Figure 4) transmits the control signals between the different components of the circuit diagram. From a safety point of view, it has a voltage lower than 110VAC, 24VAC or 24VDC.

The outputs of the controller can not directly power the contactors coils due to their inconsistent power. For this purpose, auxiliary relays K1.0, KC1.0, KC2.0, KC3.0 are used, this will extend the life of the controller and provide additional separation of the power circuit from the PLC operating circuit.

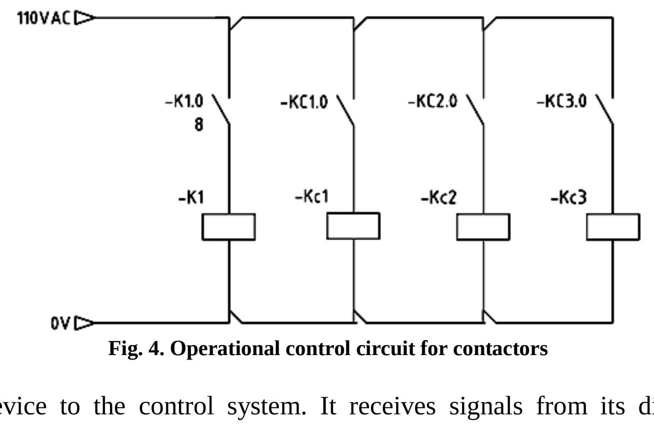

Fig. 4. Operational control circuit for contactors

PLC is central device to the control system. It receives signals from its digital and analogue inputs, processes them via rules set by the control program and triggers the corresponding outputs (Figure 5). In this case, the PLC is powered by a 230VAC main voltage supplied to terminals L and N and grounded to the GND terminal.

For supplying the input and output circuits, the controller has an internal power module. It converts the main voltage to a stabilized operating voltage of 24VDC.

The input circuit needs to be configured via a S/S (sink / source) terminal. It is supplied with 0V or 24V, depending on whether sensors with NPN or PNP logic are used. In this case, no such sensors are used, so it does not matter.

To the S/S terminal is supplied to 0V, and to the inputs 24V is passed, which will pass through fuse F2, 200mA.

The output circuit is powered by +V0, +V1, +V2 terminals with 24V, and the power supply also goes through the normally closed contact of an emergency stop button. Pressing the button will stop the power supply from the outputs and from there the switched relays.

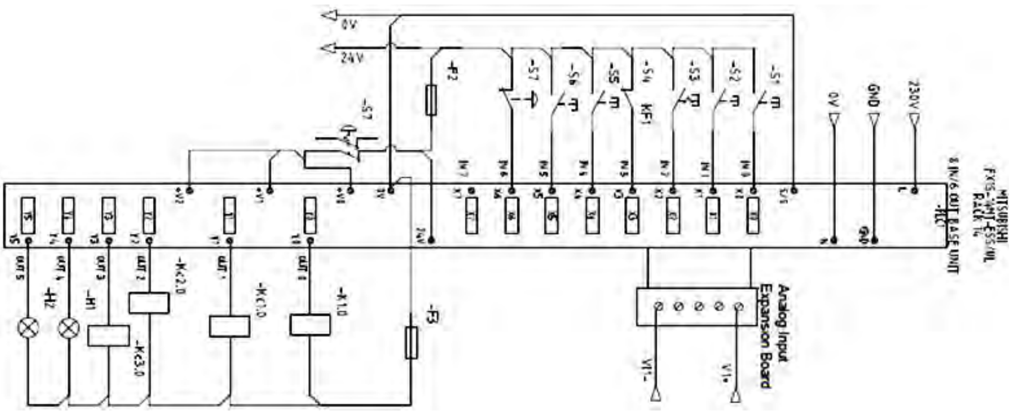

Fig. 5. Input and output circuits of PLC

Process data points are defined, which are controlled from PLC inputs and outputs. Table 4 lists these points with their corresponding inputs and outputs.

Table 4

Process information points

Inputs		Outputs	
Name	Address	Name	Address
Button start S1	X0	K1.0 Additional relay for contact K1	Y0
Button stop S2	X1	KC1.0 Additional relay for contact KC1	Y1
On/off switch for capacitor bank S3	X2	KC2.0 Additional relay for contact KC2	Y2
Additional contact for motor protection S4	X3	KC3.0 Additional relay for contact KC3	Y3
Restart button for capacitor bank timer S5	X4	H1 Signal lamp for control time KБ	Y4
Reset button for switching counter S6	X5	H2 Termal protection signal lamp	Y5
Emergency stop S7	X6	-	-

The purpose of the control algorithm is to set the conditions for switching the different levels of the capacitor banks (CB). Some additional features have been added to increase the capacitors life of the capacitor banks and make it easier to diagnose it.

When starting the electric motor, the load is 100%, this means that the first stage will be switched on simultaneously. When the load is reduced to 65%, the second range is turned on. If the load continues to decrease to 38%, a third range is turned on, but if it increases back to 65%, the second range is excluded.

- first range (CB 1) will be turned on at a load of 65%-100% (12,7A-18,1A);
- second range (CB 1+2) will be turned on at a load of 65%-38% (12,7A-8,8A);
- third range (CB 1+2+3) will be turned on at a load <38% (8,8A).

In order to prevent frequent switching in intermediate zones, hysteresis must be determined.

The larger hysteresis will make the system more stable but less accurate, but the smaller backwards – more accurate but less stable. Therefore, the possibility of changing the parameters defining hysteresis should be provided.

When the switching points are reached at a higher or lower range, the load has to go through the 1% (0,2A) point of the switching point to make the switch. This will give us a hysteresis of 2% at the switching points.

Another possibility of occurrence of unwanted frequent switching are the disturbances. These are sharp short-term changes in the measured value, in our case current (load). To prevent the disturbance effect, a filter element is introduced. For the purposes of this algorithm, it is sufficient to determine the time T1 for which the switching point has to be reached in order to switch to a higher or lower degree. This is an disturbance filter with a time less than T1. This time is set to T1=0,5s, and it must also be possible to change this parameter.

The first additional function is rotating the capacitor banks (KB) for the individual ranges. During work, the CBs of the individual range are loaded for different periods of time (first range is constantly loaded, second range in a bit and at least a third), this will lead to uneven drainage of the CB and decrease the life of the capacitors. The purpose of the function is to change the positions of the CB in relation to the individual ranges. This will be done every time the electric motor is started to avoid unnecessary switching under load during operation.

A second additional function is a timer that measures the operating time of the capacitors and a signal lamp will be switched on when a part of the service life set by the manufacturer is reached. It will indicate that a prophylactic measurement of the CB capacity should be made to avoid ineffective work.

A third extra function is a counter that measures the number of turnouts in one hour. The role of this function is to determine whether the system is working normally during the system start-up or subsequent diagnostics. Too many activations of capacitor banks will mean that hysteresis or T1 time has to be increased. If switchings are few in number, can be reduced hysteresis or time of filtration in order to increase accuracy.

The number of switching is also judged for the life of the capacitive contactors.

The control algorithm for switching the capacitor battery is presented in Table 5.

Table 5

Algorithm of program for PLC control of capacitor bank

Stage	Process	Description
1	2	3
A	Protection circuit	When executing the conditions X6=1 AND X3=1 AND M8004=1, the program relay M1=1
B	Definition of setup parameters	Switching point for range 2, register D12 Switching point for range 3, register D15 Hysteresis zone in switching points, register D18 Time T of filter function, register D17 The converting values are: D12=1270 (12,7A) D15=880 (8,8A) D17=5 (0,5 sec) D18=20 (1%) A M8002 program relay is used which is only included when the program first scans The transformations are performed once when the controller is started in RUN mode
C	Analog signal processing	The current transformer range is 0-50A and converted to an analog 0-10V signal from there, the analog to digital converter of the controller converts them to a digital value with a range of 0-4000 stored in register D8112 A coefficient for the measured value to the value of the register k=1/80 is defined The value of the analog register is moved to register D0. With the MUL function the register value is multiplied by 5, the resulting result is recorded in D19 The value of D19 is divided by 4 and the result is recorded in register D1
D	Electric motor control	The conditions are to be pressed the START X0 relay M1 that the STOP X2 or X0=1 AND X1=0 AND M1=1 pushbutton is not active. After the conditions are fulfilled, the output Y0=1 that triggers the start of the electric motor To deactivate the output, it is sufficient to activate the stop button (X1=1) or switch off the safety relay (M1=0). Upon activation of the output, the relay M2, which is responsible for the startup of the capacitor bank range 1
E	Capacitor bank ranges control	Three values need to switch to range 2. Switching point - D12, lower and upper limit of the hysteresis zone D11 and D12. Comparison function *inline comparisons* has been used When the recorded analog value in register D1 is less than D11, the auxiliary relay M2 is switched on. When the value D1 is greater than D13, an auxiliary relay M3 is switched on. When D1 is less than D12, the timer T1 is switched on When D1 is greater than D12, the timer T2 (T1 and T2 timers for the D17 filter time) is switched on. The conditions for the inclusion of range 2 are T1 and M2 to be active, the auxiliary relay M4 (stopping the degree) is not active and the output Y0 is active When switching on the auxiliary relay for step two, T1 and M2 maintenance is triggered. When T1 and M3 are activated, the range is turned off. The dependencies for starting and stopping stage 3 with auxiliary relay M9 are similar
F	Ranges rotation control function	From the parts of the program, we have built-in auxiliary relays M2, M8 and M9 to start, respectively, the first, second and third stages of the condenser system Outputs Y1, Y2 and Y3 trigger the capacitor banks, respectively C1, C2 and C3. In the first cycle M1 triggers Y1, M8-Y2 and M9-Y3 (variant 1) In the second cycle M2-Y3, M8-Y1 and M9-Y2 (variant 2). In the third cycle M2-Y2, M8-Y3 and M9-Y1 (variant 3). For this purpose, connections of each relay (M2, M8 and M9) are made with each output separately, between them are mounted auxiliary relays M400, M401 and M402, so that the inclusion of each of these relays determines one of the three variants. The relays are of a special type that maintains their states in registers in the PLC's permanent memory. Thus, even when the clamping stops, the order of range shifting will be maintained. In the next part of the program, one of the relays M400, M401 and M402 will be activated every time Y0 is triggered. Here is used the rising edge pulse (PLS) function. When relay Y0 is triggered, the relay contact is active for only one scanning cycle of the controller. In this case, this means that the circuit will work one time at electrical motor start. The SET function includes the relays to remain constant until they are switched off by the RESET function

Table 1 continued

1	2	3
G	Function for working time measurement	Thanks to the rotation function, the working time of the individual capacitor bank is approximately equal, so it is enough to measure the time of only one. In this case, the operating time of Y1 was measured. The control time that is set is 30000 h. The controller does not have a timer with such a long memory. The solution is to use a combination of timer and counters. A retain timer is used, which, even when the input is interrupted, retains the value. In this case, a T25 timer is used At each 10-minute count, the timer outputs a C16 counter to the K6 constant, which will activate it at any one hour C16 sends a signal to C17 with the K30000 constant, which will be activated every 30000 hours. EEPROM backed ups are used, they retain the numbered value after the power supply C17 switches on a M10 auxiliary relay, which through the special M8113 (1S pulse) relay includes output Y4 (signal lamp - time of capacitor bank). When the reset button (X4) is pressed, the circuit stops and the maintenance stop, stopping the signal lamp (Y4)
H	Counter for cycles of inclusion	For counting the number of loop cycles of one of KB (Y1), three registers D128, D129 and D130 are used. The registers used are EEPROM backed up At each run of Y1 through the ADD function, the value in register D128 is incremented by one, thus counting the number of inclusions In register D129, the number of cycles of a C16 counter is measured, which in this case are the hours of operation. In D130 through the DIV function, we calculate the number of shifts per hour When triggered at input X5 (Reset Cycles button), the values in the three registers are multiplied by zero, which practically zeroes them
I	Alarm for thermal protection	When X3 is triggered (auxiliary motor protection contact), output Y5 is activated (signal lamp-activated motor protection) An M8013 (1S pulse) relay is also used to allow the signal lamp to flash at a frequency of one second

Conclusion

The choice of reactive energy compensation method depends on:

- Cost of equipment for power factor correction;
- Time for efficient operation of the apparatus;
- Need for service;
- Expected economic effect of power factor improvement;
- Expected indirect benefits.

The chosen method of controlling passive power factor correction apparatuses with a programmable logic controller has the advantage of having the flexibility of the microelectronic devices and the efficiency of the dedicated controllers for capacitor banks control.

The proposed hardware and software tools can be easily adapted to electric motors, and it is necessary to determine a conversion factor for the numerical values obtained in the controller register in specific values of the motor current measured.

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