Development of the reactive power compensation laboratory bench and its integration into the training simulator of dispatch control system

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Abstract

At present, the number of electrical energy consumers is growing, and they are constantly loading electrical network with reactive component of power consumption. Reactive current circulating between the generator and the consumer is converted into thermal energy in power distribution system, thus creating additional load on generators, transformers, cables and distribution device contributing to power losses and voltage drops. The application of special reactive power compensation devices can improve the reliability of power networks and increase power system capacity. The use of compensation devices reduces network interference, avoids deep voltage sags and minimizes phase asymmetry, and reduces energy consumption up to 50% of the total consumption. The application of compensation devices makes it possible to avoid penalties from electric power supplier for power factor indicators deterioration. The effectiveness of these devices largely depends on the training of personnel who will maintain them. The development of laboratory bench designed for the investigation of the impact of reactive power compensation in current consumers on voltage and energy losses in power transmission lines and its integration into the training simulator of dispatch control system is considered in this paper.

Keywords

Reactive power compensation, laboratory bench, reactive power compensation controller, software, induction motor.

1. Introduction

The functioning of the country's electricity generation and consumption system in wartime conditions results in significant power shortage and, accordingly, emergency blackouts in case of electrical network overloads. In order to avoid overloads, the electric energy consumption is rationed for all categories of consumers. Restrictions on consumption of active and reactive power are imposed for industrial enterprises.

The operation of technological facilities during the energy system peak loads hours inevitably results in emergency blackouts, which are caused by voltage drops, asymmetry of three-phase network currents, non-sinusoidal nature, reactive power deficiency. The above mentioned negative features in the operation of electrical networks are widely considered in the papers by national and foreign specialists [1, 2]. However, the application of new technical information systems and technologies in automation and control systems of energy facilities in order to increase efficiency and reduce losses, which are sensitive even to minor voltage fluctuations, demands the increase in the requirements for electric energy quality indicators and is of great importance.

In the vast majority (55-60%) of industrial enterprises, unregulated induction AC motors with 380 V voltage are used, therefore, reactive power is the part of the technological cycle of electric energy

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consumption, which affects its economic efficiency. In conditions of power shortage in order to unload the power system and uninterrupted power supply, as well as to reduce electrical energy losses, it is necessary to install compensation devices at the enterprises to ensure the reactive power balance. Excess of reactive power in energy system results in the increase of voltage in electrical network nodes due to the occurrence of active power counter-flows [3, 18].

The most effective way concerning reactive transmission parameters compensation at industrial enterprises is the use of capacitor units (CUs) - batteries of power capacitors connected in series with low specific costs for generating reactive power. For reactive power compensation, the following types of compensation are possible: individual (unregulated); group (unregulated); centralized (regulated) [3].

As a rule at industrial enterprises, the individual type of compensation is used, where CU is installed directly next to the electrical receiver and the switch of the electrical receiver is commutated simultaneously with CU, and the greatest reduction in power and electrical energy losses is reached. Such type of reactive power compensation is used for electric receivers with power of more than 20 kW [3]. The disadvantage of the given type of compensation is the requirement of adjusting CU capacity with the electrical receiver induction. While choosing CU capacities, it is necessary to compensate the part of reactive power of the enterprise (workshop) and avoid the phenomenon of reactive power transfer to the electrical network. Such situation is possible with changes the enterprise reactive load. In this case, CUs are sectioned by degrees, i. e., the sections are turned on/off depending on the specified parameters: voltage level, power factor value, period of the day. Static elements of reactive power make it possible to use the regulating link [4] while connecting capacitor batteries, i.e., CU reactive power control is carried out in stages, by dividing the batteries into parts (basic and regulating). Stepwise CU control is carried out manually or automatically. Automatic CU control is carried out as the function: by voltage, load current, reactive power direction.

Therefore, the trouble-free operation of equipment in peak load modes depends on how technically competently the problem of reactive power compensation on links up to 1 kV is solved.

For installations requiring variable reactive power, permanently switched on capacitor banks are not acceptable, as this may result in undercompensation or overcompensation. In this case, the capacitor unit is equipped with specialized controller and switching and protective equipment. If the value of cosφ deviates from the set value, the controller connects or disconnects the capacitor stages.

2. Development of reactive power compensation laboratory bench

In order to improve the quality of education and introduce modern information technologies into the educational process the training laboratory bench for investigating the reactive power compensation in low-voltage electrical networks was developed at the Department of Electrical Engineering of Ternopil Ivan Puluj National Technical University [5, 19].

The basic element of the developed training laboratory bench is the reactive power controller PFC6 RS, which is designed to regulate the power factor in 50 Hz low-voltage networks with the ability to control reactive power compensation units with 6 contactor outputs (Fig. 2).

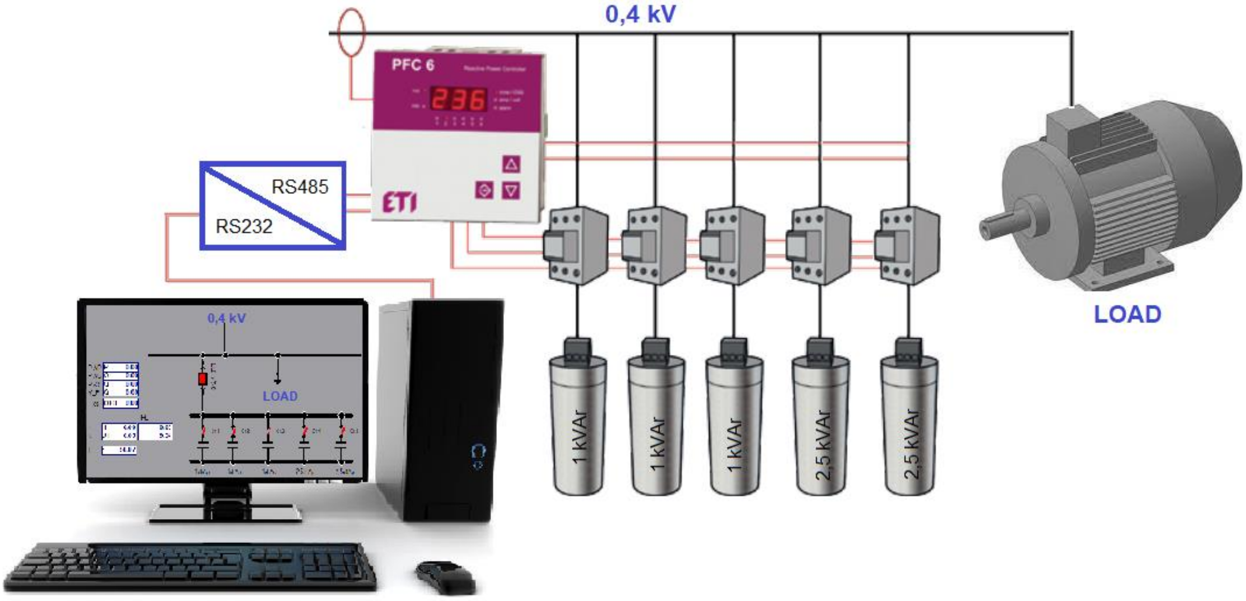


Figure 1. Functional diagram of the laboratory bench.

The reactive power controller converts linearly measured voltage and current in the measured phase into digital form. Further the device processes these values, calculates the power factor, effective voltage and current values, as well as their harmonic distortions. Calculation of the required power for compensation is carried out by comparing the set value of the reactive power factor with its current value. Based on these values, the controller will turn on or off the corresponding capacitor stages [6]. The proposed scheme for connecting the reactive power compensation controller to the load, which will be used during laboratory work is shown in Fig. 2.

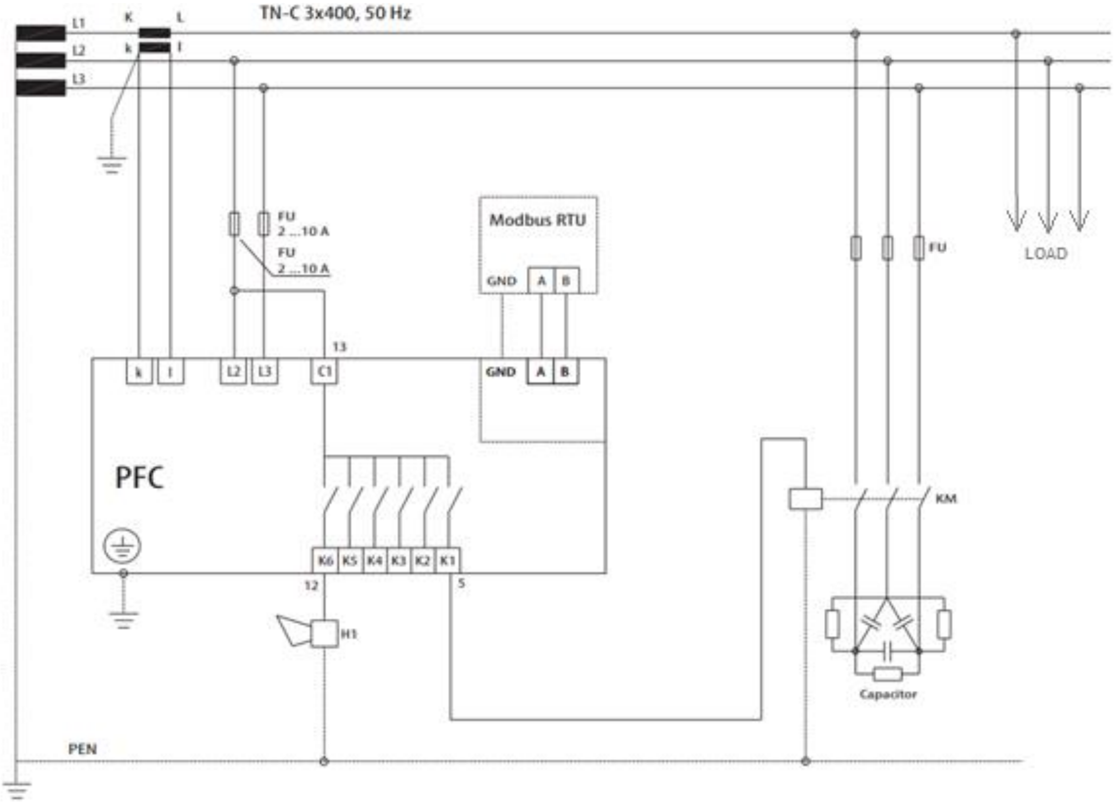


Figure 2: Connection scheme of the reactive power compensation controller

Within each power level, the regulator uses ring switching method in order to use the uniform resource of capacitor banks, where the stage disconnected for the longest time is connected in order to ensure the required power level. This makes it possible to provide the optimal level of compensation during one control cycle with minimum number of connected stages. The reactive power controller can analyze current and voltage harmonics up to the 19th harmonic and calculates THD coefficient (electric power quality index) by voltage and current [7, 19].

The main unit of the developed laboratory bench consists of the metal power cabinet with 5 capacitor banks of different ratings, 5 magnetic contactors, 5 three-phase fuses and circuit breaker (Fig. 3). All of the above listed equipment is from ETI Company[8, 20].

Figure 3: Reactive power compensation laboratory bench

PFC 6RS reactive power controller is located on the front panels of the power cabinet and is housed in the metal case, which ensures high electromagnetic protection during the installation operation. The handle of the circuit breaker is also placed on the front panel of the power cabinet (Fig. 3). The wires are connected to the terminal blocks located on the controller back side. The measuring and power terminals are connected to the regulated network and are protected by fuses. The operating voltage of the reactive power compensation laboratory bench is 380 V. The load is the induction motor. At start-up the cosϕ load is approximately 0.2.

In order to investigate reactive power compensation in laboratory conditions, the model of power transmission line with active resistance, active-inductive load R, XL (the stationary induction electric motor switched on according to the triangle scheme), and capacitor bank with adjustable capacity were used. The scheme shown in Fig. 2 is best suited for real demonstration experiment in laboratory conditions.

3. Bench integration into the training simulator of the dispatch control system

PFC reactive power controller has data transfer interface according to Modbus RTU protocol, as well as configurable discrete inputs and outputs. The display shows the installation status and main parameters (Fig. 4). Due to the display and buttons on the front panel, by means of the menu, you can perform all necessary settings and view diagnostic information. The presence of data transfer interface makes it possible to receive information about the controller status, adjust the operation parameters and send control commands remotely. This provides the possibility of including reactive power compensation with PFC 6RS control unit into the monitoring and dispatching system

Figure 4: The control panel of the reactive power compensation laboratory bench

Therefore, the decision to integrate the developed laboratory bench into the training SCADA system "Energy" of the software and hardware complex "Strila" was made [9, 18]. This system is the simulator of the automated dispatch control system for investigating and controlling the electric power system modes [10]. The simulator is the hardware and software complex and is used in the educational process to deliver classes on emergency training exercises with the reflection of operational situation in electric power system. The simulator makes it possible to simulate the electrical network operation modes during the classes, as well as to connect various executive mechanisms and equipment and to control them remotely The developed laboratory bench based on the reactive power controller, together with the developed software, will become a part of the laboratory complex for the construction of TVcontrol and dispatch control systems in electric power industry [11].

In order for the hardware and software complex to be able to exchange data with PFC 6 RS reactive power controller, it is necessary to write the exchange program based on Modbus RTU protocol [12]. Below is given the text of the developed data exchange program based on this protocol, i.e. Modbus RTU device card file containing the main commands from the available list which will be used by "Strila" hardware and software complex. Only part of the available commands of PFC 6 RS reactive power compensation controller register are used here, if necessary, these commands can be added to the developed laboratory bench software.

Modbus RTU device card file

```
[GENERAL]
AddressDecrement=0
[REQWEST]
;Start address, number of registers, Modbus command, group 101, whether included in the general protocol
reqwest01=58,14,3,1,1
reqwest02=150,15,3,1,1
reqwest03=166,11,3,1,1
reqwest04=250,3,3,1,1
[TVLIST]
;Start address, offset (for a bit), data type, scale (coefficient), start of scale
;Data types   0: ui16     1: i16      2: ui32     3: i32      4: float32
;                    5: float48  6: Int64      7: float64  8: float80
```

```
; Start address, offset (for a bit), data type, scale
;Step1 – Selection of the 1st stage capacitor (1 kVAr, 400 V)
tv001=21,0,1,1
;Step2 – Selection of the 2nd stage capacitor (1 kVAr, 400 V)
tv002=22,0,1,1
;Step3– Selection of the 3rd stage capacitor (1 kVAr, 400 V)
tv003=23,0,1,1
;Step4– Selection of the 4th stage capacitor (2,5 kVAr, 400 V)
tv004=24,0,1,1
;Step5– Selection of the 5th stage capacitor (2,5 kVAr, 400 V)
tv005=25,0,1,1
;Step6– Selection of the 6th stage capacitor (reserve)
tv006=26,0,1,1
;SHtd – Control delay during overcompensation
tv013=33,0,1,1
;CoSF(phi) (32-bit float0) - Current cosφ value
tv014=50,0,4,1
;I_AP(A) (32-bit float0) – Phase current, A
tv015=60,0,4,1
;THD_i() (32-bit float0) - Emergency alarm by current
tv016=62,0,4,1
;U_EF(V) (32-bit float0) – Phase voltage, V
tv017=82,0,4,1
;THD_U() (32-bit float0) - Emergency alarm by voltage
tv018=84,0,4,1
;P_AP(BA) (32-bit float0) – Complete three-phase power, VA
tv019=104,0,4,1
;P_AC(Bт) (32-bit float0) – Active three-phase power, W
tv020=106,0,4,1
;P_rC(BAP) (32-bit float0) – Reactive three-phase power, VAr
tv021=108,0,4,1
;rC_P(BAP) (32-bit float0) – Reactive power that is insufficient to reach the
                                   established cosφ, VAr
tv022=110,0,4,1
;F() – Network frequency, Hz
tv023=160,0,4,1

[OK]
ok=ok
```

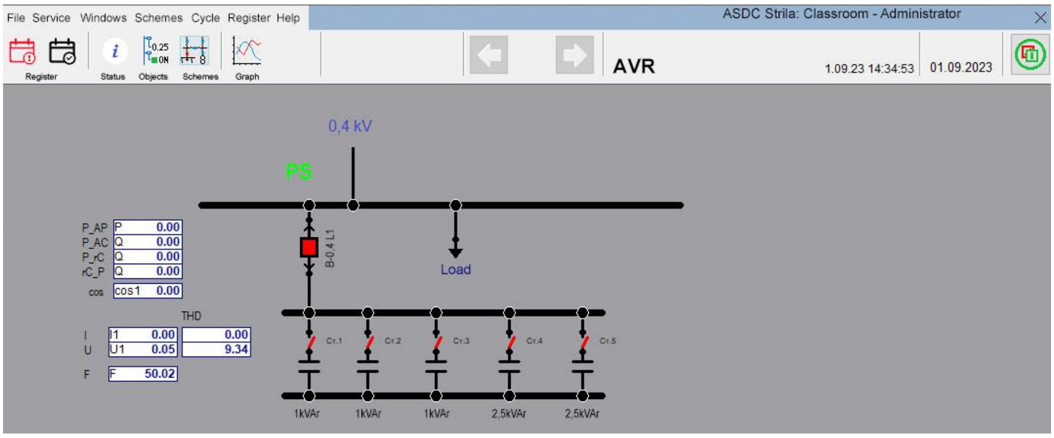
The developed program file of the device Modbus RTU card and PFC 6 RS reactive power compensation controller itself are real model of “Energy” training SCADA system. In order to integrate this model into SCADA system environment, graphical model (Fig. 5) and configuration file containing the following data are created.

Configuration file

[GENERAL]
ObjectCount=1 – the number of substations
ChannelsCount=1 – the number of communication channels
DisableCrashLog=1 — disable automatic creation of logs (by default, log data are written to the Logs directory, or the program startup directory)
CheckInterval=1000 – control survey period in msec.
CommonRequestInterval=30000 — total background survey period in msec.
; Modbus
[Channel1] - 1 communication channel is used
Type=1 - channel type (2 – TCP-IP, 1 – RS232)
Thread=1 – flow number
Port=7 – port number
Prm=19200-8-N-1 – RS232 connection parameters (19200 - frequency, 8 - 8 bits, N - pairing, 1 - stop bit))
ByteTimeOut=200 – waiting time for the next byte (0.2 sec)
DataReadTimeOut=3500 - Connection to the port, the program waits for data from the equipment for 3.5 seconds.
DeffaultTimeout=2000 - While starting the equipment from the command line, the default standby time is 2 seconds
Description=Modbus – Description of the messaging structure for establishing chief-subordinate communication between intelligent devices

[Object1]
Type=7
ModbusTCP=0 - The applied protocol is not classic Modbus TCP, but specialized one
Modbus RTU
Address=41 –model address
Channel=1 – the 1st communication channel
Paused=0 – survey delay time
// Modbus RTU card file name of the device
Map=PFC6 – object model
Description=KRP(PFC6) – model description
[MainForm] - parameters of the main window for viewing data exchange logs (is filled automatically).
Top=179
Left=738
Width=890
Height=627
LVHeight=150
[ModelState] - parameters of the window for placing the model graphical scheme
Top=17
Left=247
Width=887
Height=974
[LogForm0]
Top=182
Left=182
Width=698
Height=316

```
[LogForm1]
Top=500
Left=32
Width=698
Height=316
```



P_AP P 0.00
P_AC Q 0.00
P_rC Q 0.00
rC_P Q 0.00
cos cos1 0.00
I I1 0.00 0.00
U U1 0.05 9.34
F F 50.02

Figure 5: Graphical model of the laboratory bench for the investigation of reactive power compensation

The program communicates with the equipment via communication channel, which is RS232-RS485 communication channel connection. Then the data are transferred to the equipment model, where messages are processed. From the equipment model, the data are transferred to the real model, where the final processing is carried out.

In the real model, the message is fixed in database, the emergency situation is analyzed, and all information about the current model status is stored. During the work, the student uses the graphic model which requests data from the real model and displays it in the form common to the user - mnemonic circuits (Fig. 5).

B-0.4 switch, which is in the off state (red color) is shown in the graphic model. 5 cosine capacitors of different capacities: three of 1 kVAr and two of 2.5 kVAr are also shown. The laboratory installation can compensate maximum up to 8 kVAr, and such capacitors set makes it possible to obtain different values of the compensated power. Each capacitor is equipped with the key (Page 1 - Page 5). During the laboratory installation operation, the keys on mnemonic circuit are closed, i.e., they show which capacitors participate in reactive power compensation.

Also, for the data analysis convenience, the mnemonic circuit shows the value of the total three-phase power P_AP (kVA), the value of active three-phase power P_AC (kW), the value of reactive three-phase power P_rC (kVAr), the value of the reactive power that is insufficient to achieve the set cosφrC_P (kVA), the value of power factor cosφ, current I (A), voltage U (V) and network frequency F (Hz).

4. Investigation of the laboratory bench operation

Reactive power has two types: inductive, which is generated by electromagnetic devices, and capacitive, produced by differently polarized wires separated by insulator [13]. Both types of reactive power occurs and disappear in counter-phase to each other and can mutually cancel each other (compensate) if they are equal in magnitude. However, their mutual equality is a rare phenomenon, as inductive power often prevails. Equality can be achieved artificially by connecting capacitor banks with adjustable capacity.

The traditional theoretical approach in the electric power industry assumes that inductance is perceived as a consumer of reactive power (Q_L), and capacity as its generator (Q_C).

Reactive power is measured in volt-ampere-reactive (VAR) or kilovolt-ampere reactive (kVAr). The ratio of all components of the total power S is shown by the following formulas [14]:

$$S = \sqrt{P^2 + (Q_L - Q_C)^2}; \quad I_\Sigma = \sqrt{I^2_{Active} + (I_L - I_C)^2}\,. \tag{1}$$

Q_L and Q_C values can be determined by the following formulas:

$$Q_L = I^2 \cdot X_L; \quad Q_C = I^2 \cdot X_C, \tag{2}$$

where X_L and X_C are inductive and capacitive resistance, respectively.

The indicator of reactive power compensation efficiency is $\cos\varphi$ value:

$$\cos\varphi = \frac{P}{S} = \frac{I_{Active}}{I_\Sigma}. \tag{3}$$

With inductive power, $\cos\varphi$ is positive, with capacitive power, it is negative. At complete compensation (or purely active load), $\cos\varphi = 1$.

During the transmission of electrical energy by electrical lines, voltage and power losses occur, their values depend on the magnitude of the transmitted current (power) and wires resistance according to the following equation:

$$\Delta U = \frac{P_{Active} \cdot P + Q \cdot X}{U} = \frac{P_{Active} \cdot R}{U} + \frac{Q \cdot X}{U} = \Delta U_{Active} + \Delta U_X\,, \tag{4}$$

where ΔU_X – additional voltage losses generated by reactive power consumed from the network.

$$\Delta P = \frac{P_{Active} \cdot Q^2}{U} \cdot R = \frac{P^2_{Active}}{U^2} \cdot R + \frac{Q^2}{U^2} \cdot R = \Delta P_{Active} + \Delta P_Q, \tag{5}$$

where ΔP_Q– additional active voltage losses produced by reactive power transmission Q^2.

The above-mentioned theoretical investigations and formulas served as the basis for the object model construction during the software development. Reactive power compensation affects the most important indicators of electrical energy quality - voltage deviation and fluctuation in the load nodes. Therefore, the task of reactive power compensation should be solved in conjunction with the task of maintaining the voltage within the limits set by the state standards [15].

In order to carry out real demonstration experiment in laboratory conditions, the connection scheme shown in Fig. 6 is the best one. The selection of capacitor banks as compensating devices is determined by the ease of installation and operation, the ability of changing the generated reactive power within wide range with step control, small specific losses of active power for the reactive component production, which is an order of magnitude less than for other sources of reactive power [16].

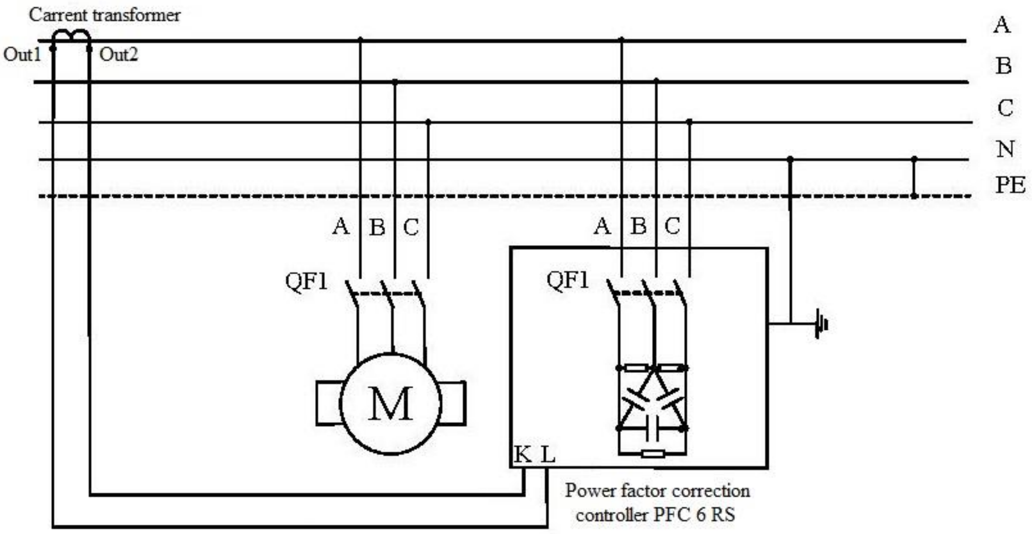
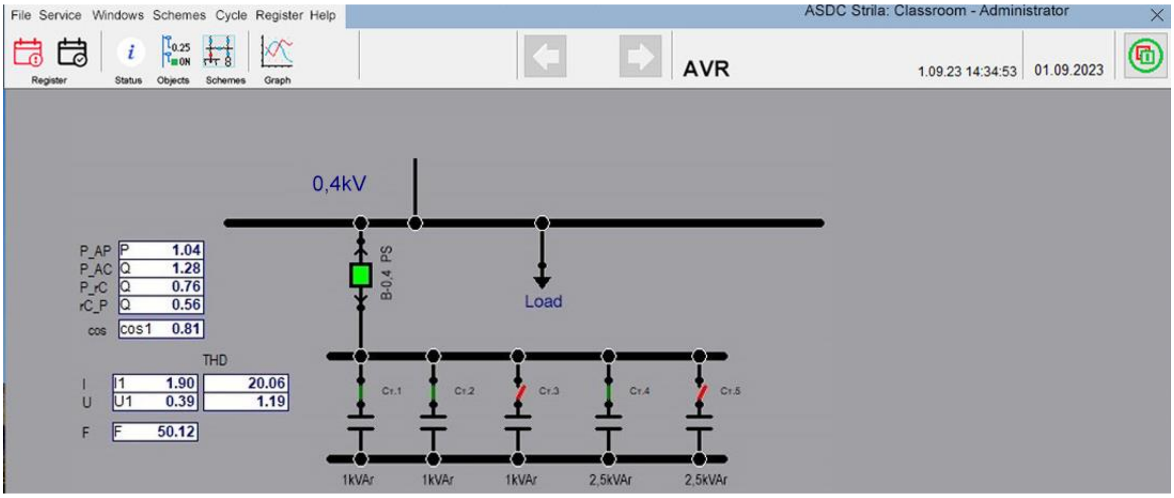


Figure 6: Connection scheme of PFC 6 RS reactive power compensation controller

It should be taken into account that the excessive capacity of the capacitors not only compensates the inductive component of consumer's current, but also produces excessive capacitive current component, which is also undesirable as it generates voltage and power losses in the line.

Achievement of the set goal in this work is based on the basic laws of electrical engineering and is performed due to the application of modern digital devices. The task of the tests is to determine the compensation effect (capacitor bank connection) on the magnitude of power and voltage losses in the line. For this purpose, current, voltage and power are measured at the beginning of the line and the same parameters are measured in the consumer circuit (the windings of induction motor connected at the end of the line are used as inductive load), and cosφ value is determined. These measurements can be carried out at different values of the line active resistance (R) and the number of connected capacitors ($C1$, $C2$, ...).

Graphical model of the laboratory bench for the investigation of reactive power compensation with connected load is shown in Fig. 7.



1.09.23 14:34:53

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P_AP P 1.04
P_AC Q 1.28
P_rC Q 0.76
rC_P Q 0.56
cos cos1 0.81

I I1 1.90 20.06
U U1 0.39 1.19
F F 50.12

Figure 7: Graphical model of the laboratory bench for the investigation of reactive power compensation with connected load

It is obvious from Fig. 7 that after the load connection (switch B-0.4 is green), the system selects the necessary combination of capacitors to provide reactive power compensation. In this case, the first, the second and the fourth capacitors are connected: 1 kVAr, 1 kVAr, and 2,5 kVAr, respectively. For convenience, the keys by which these capacitors are connected, are closed and are represented in green colour.

On the instrument panel, you can see that active power is $P = 1,04$ kW, reactive power is $Q = 0,76$ kVAr. Hence, according to the well-known formula [13, 21]:

$$\cos\varphi = \frac{P}{\sqrt{P^2 + Q^2}} = \frac{1,04}{\sqrt{1,04^2 + 0,76^2}} = 0,81 \cdot \qquad (6)$$

On the instrument panel, the power factor is also equal to 0,81.

The same value is shown on the control panel display of the reactive power compensation laboratory bench (Fig. 8).

Figure 8. Reactive power compensator panel with the performed compensation results

This confirms the verification of power factor values obtained by means of reactive power compensation laboratory bench and the proposed software package.

Also , it can be seen from Fig. 8, that 1, 2 and 4 indicators glow, indicating which capacitors are connected at the moment.

The application of reactive power compensation means makes it possible to reduce significantly the electricity losses during its transportation by reducing power transmission lines heating. The use of special reactive power compensation devices has a number of advantages, the main ones among them are: improvement of power supply quality, increase of the equipment service life, savings in costs for power supply networks arrangement, absence of fines, energy consumption savings [17, 22].

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