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Reactive Energy Compensation Equipment Used in High Power Laboratories

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Abstract **- The power quality covers the means to conserve energy resources, such means consist in improving the power factor and judiciously managing the reactive energy in the power system. Electric grids do not have an unlimited energy transmission capacity, therefore any load on the grid with reactive energy is measured by the energy distributor/supplier and billed to the consumer. On the premise that for industrial consumers, the main consumers of reactive energy are the low-load induction motors and transformers, this paper presents a synchronization equipment for a wound-rotor induction motor with a power of 2000 kW, nominal voltage 6kV, nominal current 210A, which allows the increase of the power factor, significantly reducing the reactive energy consumption. The equipment presented was designed, built, tested and validated by tests carried out in the high-power laboratory.**

Cuvinte cheie: *motor cu inducție, energie reactivă, factor de putere, motor sincron, motor asincron, laborator de încercări de mare putere.*

Keywords: *induction motor, reactive energy, power factor, synchronous-asynchronous motor, high-power testing laboratory.*

NOMENCLATURE

"R" – "L1" phase equivalent;
"S – "L2" phase equivalent;
"T" – "L3" phase equivalent;
"URS" – voltage between phase "L1" and phase"L2";
"URT" – voltage between phase"L1" and phase"L3";
"UTR" – voltage between phase"L3" and phase"L1";
"IR" – current corresponding to phase"L1";
"IS" – current corresponding to phase "L2";
"IT" – current corresponding to phase "L3";
"UR" –voltage corresponding to phase "L1";
"US" –voltage corresponding to phase "L2";
"UT" –voltage corresponding to phase "L3"[1].

I. INTRODUCTION

Electricity consumption is characterized by two quantities: active energy and reactive energy. Active energy is consumed for useful purposes, having useful effects (examples: operation of electric motors, heating, lighting, etc.). Reactive energy only circulates between the consumer and the energy supplier and is not actually consumed.

The power quality is a complex and controversial issue. Its complexity lies in the multitude of factors influencing it, in their interdependence, the lack of methods and means of obtaining expeditious and especially precise information about certain quantities which characterize it. Due to the fact that electricity is a commodity, its quality can be incorporated into a more general concept, related to the activity of its production, and, as a result, more than a hundred definitions can be assigned to the concept of quality without identifying a unanimously accepted one among them [2].

The use of highly efficient energy entailed the creation of extensive networks of transmission lines, transformer and distribution stations, regardless of the power demand, since electricity is readily available. It's only natural for rules to be created, laying down responsibilities for producers, as well as large consumers and the smallest consumers. The European Union (EU) has urged that the transmission and distribution networks be extended, imposing common tasks, laid down by modern rules on environmentally-friendly use and maintaining the power quality.

Asynchronous electric motors exert the greatest influence on the value of the power factor of the circuit they are part of, because they always require a magnetizing current [3].

In terms of the normal operation of electric consumers in general and electric cars in particular, the consumption of active and reactive electricity coexists and is inseparable. Problems arise in the analysis of the transmission of electricity remotely because the simultaneous flow of both active and reactive energy through the transmission lines decreases the transmission capacity of the lines, which can negatively influence the power quality made available by the producer, and this influence will be felt by all energy consumers. Major drawbacks are created by the generation of the reactive electricity in the transmission lines [4].

The value of the power factor of asynchronous motors depends on their degree of loading, in case of insufficient loading, the value of the power factor is considerably reduced.

A low power factor has a number of negative consequences for the operation of the electrical network, including: increased active power losses; additional investments;

increased network voltage drops; reduction of the power equipment output.

A high power factor reduces the flow of reactive power from the power plants to the consumers, reducing the losses of electrical energy to a minimum level determined by the technological consumption. In this way, an increase in the the efficiency of the electricity transmission, transformation and distribution installations, operational safety and a better use of the electrical network is obtained by reducing the apparent power with which it is loaded.

In the case of industrial consumers, the main consumers of reactive energy are induction motors and low-load transformers. Induction electric motors exert the greatest influence on the value of the power factor of the circuit to which they are connected. The value of the power factor depends on the load level of induction motors, in case of insufficient loading, the value of the power factor decreases considerably [5].

The main types of equipment used for the compensation of the power factor are:

- The use of capacitor banks;
- The use of reactors;
- Synchronous compensators;
- Synchronization of induction motors.

This paper presents the synchronization equipment for a wound-rotor induction motor with a power of 2000 kW, powered at a voltage of 6kV, which allows the increase of the power factor from 0.86 to 0.99, mainly aiming to reduce the transfer of reactive energy.

The reduction of the power factor (when transmitting the same active power) leads to the need to increase the apparent power of the generators in the power plants and the transformers of the energy system, due to the increase in current caused by the reduction of the power factor [6].

The diagram in fig.1. shows the change in the apparent power (in kVA) of the transformers, depending on the change in the power factor, when transmitting the same active power of 1000 kW.

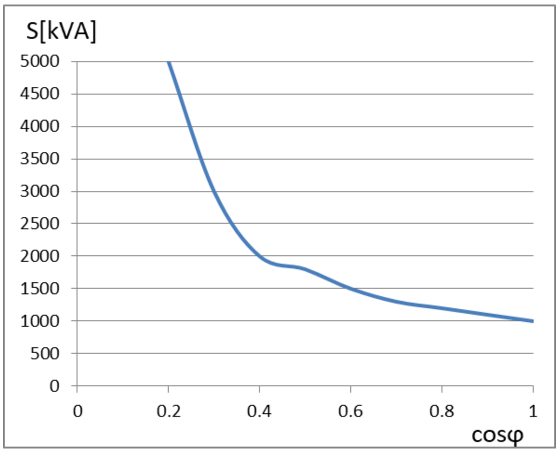

Fig.1 The graph of the power variation of the transformers in the power stations depending on the power factor.

In the case of a decrease in the power factor of the consumers, the capacity of active power transmission the transformers decreases, as a result of the increase in the reactive power. For the transmission to consumers of an active power of l000 kW, to a power factor equal to unity, a transformer of l000 kVA is required [7].

But if the power factor in the circuit decreases to 0.5, then a transformer with a power of 2000 kVA is needed to transmit the same active power (P=1000 kW).

The deterioration of the power factor also leads to the incomplete loading of the primary motors of the generators in power plants (the power of the primary motors is chosen based on the active power of the generators within the power stations).

Through this, the efficiency of the engines decreases and the operating characteristic of the entire installation worsens, leading to an increase in fuel consumption in the power plants.

The rest of the paper is structured as follows: Section II shows the overload behavior of wound-rotor induction motors, and Section III presents the equipment intended to reduce the transfer of reactive energy. The experimental results obtained using the synchronization equipment are presented in Section IV, while the conclusions are presented in the final section.

II. Overload Behavior of Wound-Rotor Induction Motors

Among the shortcomings specific to a synchronous motor, the insufficiency of overload resistance is very important, which represents the ratio between the maximum torque (for synchronous mode) and the nominal torque that corresponds to the catalog power of the motor.

The overload resistance depends on the intensity of the excitation current Iex and the relative value of the idle current (Io/In ratio) of the motor, for asynchronous mode.

The higher the Io/In ratio and also the higher the excitation current Iex, the higher the overload resistance of a synchronous motor [8].

Since the calculated excitation current Iex is limited due to the admissible heating of the rotor, it appears that it is practically not possible to increase the overload resistance by increasing the excitation current Iex.

Under these conditions, the overload resistance for synchronous mode is conditioned by the constructive qualities of the motor, which determine the internal magnetic resistance or the "Io/In" ratio.

$$u_{kr} = \frac{I_0}{I_n}\sqrt{1+\left(\frac{I_n}{I_0}\right)^2} = 1.04 \ldots\ldots 1.1$$

The "Io/In" ratio usually varies between 0.3 ......0.45.

The maximum torque of the synchronized motor differs very little from the nominal torque. If, in order to create the necessary stability, we start from the reserve coefficient, kreserve=1.5, the limit load coefficient of the synchronized motor, depending on stability, must be:

$$l_{engine\ limit} = \frac{u_{kr}}{k_{rezerve}} = \frac{1.04 \ldots\ldots .1.1}{1.5} = 0.7 \ldots\ldots .0.75$$

The power factor (PF) of an AC electricity system is defined in electrical engineering as the ratio of the actual power flowing towards the load to the apparent power in the circuit, and is a dimensionless number in the range [-1,1];

The expression of the power factor is written as (1) :

$$PF = \frac{P}{S} \quad (1)$$

where: P - active power, S - apparent power.

In the sinusoidal mode, in the case of balanced three-phase circuits, the expression of the power factor can also be written as:

$$PF = cos\varphi \quad (2)$$

The low power factor causes additional losses in the system: increases the current absorbed from the network to the same active power, increases losses in conductors, causes the increase of losses in transmission lines, reduces the available power in the system, decreases the stability of the energy distribution system. To deter a low-load power factor, most electricity suppliers impose certain forms of penalty [9].

According to national and international energy regulatory authorities, the rules applied in Romania have set a neutral power factor of 0.9 for both the inductive and capacitive mode

In order to comply with the regulations in force, to increase the power factor and minimize the transfer of reactive energy, a synchronization piece of equipment was achieved for a wound-rotor induction motor.

Induction motors exert the greatest influence on the value of the power factor of the circuit to which they are connected, due to the fact that they always require a magnetizing current, operating with a sub unitary power factor [10].

The value of the PF in induction motors depends on the load level, hence, if there is insufficient loading of the motors, there will be a considerable reduction in the power factor. This is due to the following main reasons:

- The magnetizing current of the induction motor, and respectively the reactive power varies in the case of load changes;
- The active power changes proportionally with the mechanical load in the shaft.

A low PF has the following consequences:

- Increased electricity losses due to the heating of cables and conductors of networks and windings of electric machines, because the heat losses are proportional to the square of the current (Joule-Lentz effect);
- Increased section and weight of cables and conductors;
- Increased apparent power of generators in power plants, incomplete use of prime movers, increased apparent power of transformers;
- The reduction of the power factor leads, in the case of the same active power, to the increase of the current and therefore to the increase of the voltage losses, which causes the reduction of the voltage to the consumers [11].

In this way, a low power factor has a negative effect, both for electricity supply companies and for industrial companies Among the specific drawbacks of a synchronized motor, the overload resistance is very important; it represents the ratio of the maximum torque (for the synchronous mode) to the nominal torque corresponding to the list power of the wound-rotor induction motor [12].

When the motor is out-of-step (in case of sudden drops of the power supply voltage or shocks of the load), alternating current begins to flow through the rotor winding with slip frequency, which causes an asynchronous torque. Variations in speed and current variation that occur in this case are undoubtedly damaging for both the motor and the conductors, but the use of automatic circuits for switching the motor to normal asynchronous mode at the time of overload and for returning to synchronous mode when the load has decreased removes these drawbacks [13].

III. Functional Description of a Reactive Energy Transfer Reduction Equipment

The periods of loading to nominal load of induction motors operating in the testing laboratories are intermittent, with a value of less than 1 minute, corresponding to the duration when the impulse generator, with a power of 2500MVA is brought to a state of energization, and the sample itself has a time range between 50ms÷3s, followed by pauses between two consecutive tests lasting between 10 minutes ÷ 30 minutes.

The method used by the test laboratory is intended for the production of equipment for the synchronization of low-load wound-rotor induction motors. This method is applied in situations where it is necessary to increase the power factor in order to reduce energy consumption [14].

The induction motors in the laboratory operate for a long time at low load, triggering shock generators with a power of 2500 MVA; these generators operate most of the time in de-energized state, so the driving motors of these generators operate at low load, generating a high consumption of reactive energy.

The motor actuates the rotor of a 2500MVA synchronous shock generator. Such equipment has been implemented in the testing laboratory for the synchronization of low-load wound-rotor induction motors, hence the optimal conditions are met for laboratory tests for electrical equipment [15].

Fig. 2 shows the diagram of operation of the synchronization equipment. This equipment is used for an induction 2000 kW power motor, 6 kV rated voltage, 2980 rpm rated speed [16].

The equipment for the synchronization of low-load wound-rotor power induction motors consists of a three-phase transformer, a three-phase rectifier with semiconductor diodes and RC filters, closing switches, switches, safety fuses. It is also equipped with control, measuring and signaling devices.

The TTA 20kVA transformer is powered by the 400V AC network via fusible fuses F1, F2, F3, Cs closing switch and RT thermal relay.

The parameters of the transformer, rectifier and devices of the power circuit have been determined according to the power of the wound-rotor induction motor, which is 2000kW.

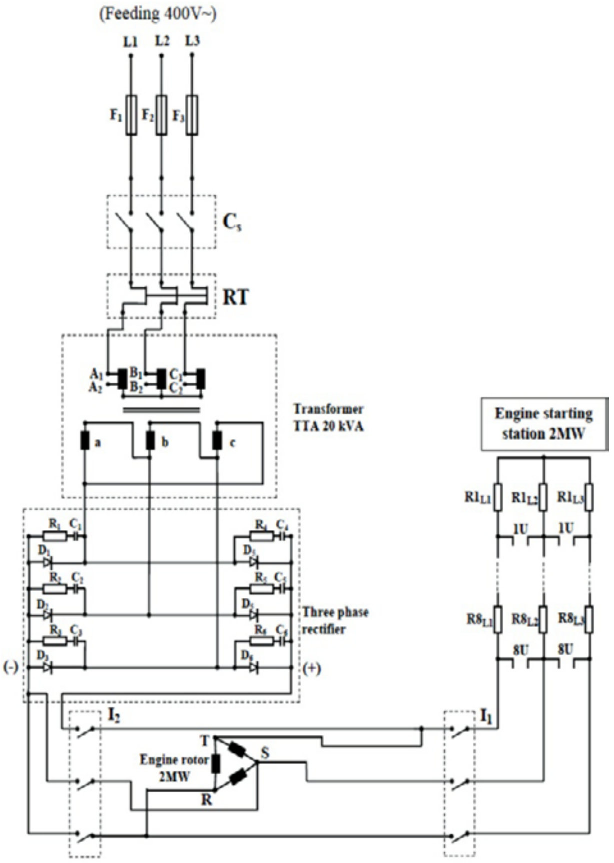

Fig. 2. Synchronization equipment diagram.

In the asynchronous mode, the setting of the devices is as follows: switch I_1 – closed, switch I_2 – open and closing switch C_s – open. In the synchronous mode, the setting of the devices is: switch I_1 – open, contacts $U_1 \div U_8$ related to the closing switches for short-circuiting the resistance steps used to start the wound-rotor induction motor– closed, switch I_2 – closed, closing switch C_s – closed.

The motor starts in the asynchronous mode with the rheostatic feature, using a starting station which consists of 8 resistance steps. As the motor accelerates, one resistance step is short-circuited at a time, until all eight resistance steps are short-circuited, and the motor reaches the rated speed.

In fig.3, the starting current is oscillographed as a function of time, and the time instant and the current value to which each resistance stage is short-circuited can be noted.

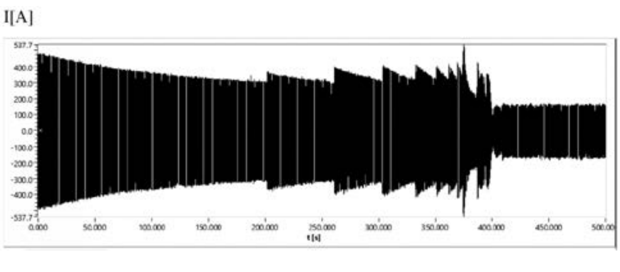

Fig. 3 Starting the asynchronous motor

After the motor has reached the rated speed, the synchronization circuit is automatically powered by the normal open auxiliary contact 8U of the closing switch which short-circuits the last resistance step of the rheostatic starting station, as well as by the normal closed auxiliary contact of the compressed-air operating switch, with high breaking capacity (12kV rated voltage, 120kA RMS breaking current), which is part of the power circuit of the high power laboratory.

The closing of switch I_2 triggers the automatic opening of switch I_1.

Using an auxiliary conditioning circuit, the closing of switch I_2 is initiated when the current crosses zero; this circuit is shown in Fig. 4.

This module is used to limit the maximum currents in the stator when switching from asynchronous to synchronous mode. Basically the transition from one mode to another is performed when the current measured in the stator on phase R crosses zero.

Before performing tests in the high-power laboratory, the closing of the operating switch with high breaking capacity of the laboratory's power circuit triggers the opening of switch I_2, this triggers in turn the closing of switch I_1, hence switching from synchronous mode to asynchronous mode, to protect the induction motor during the tests.

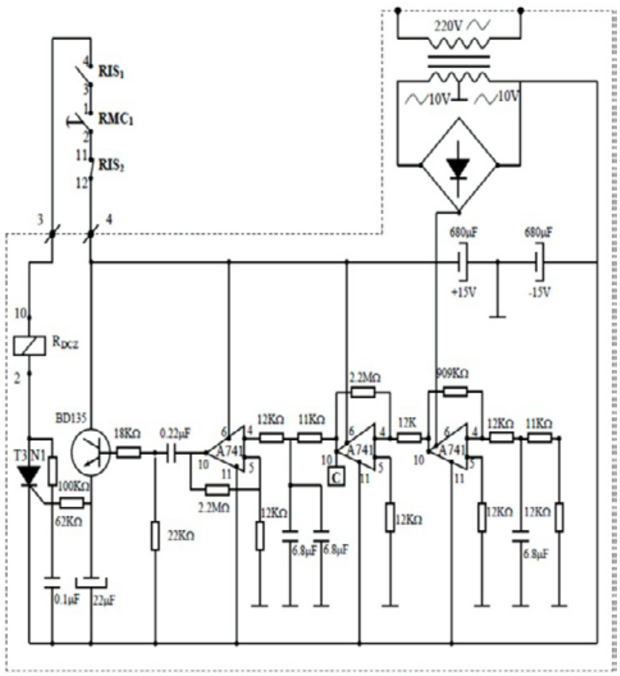

Fig.4. I2 switch conditioning module when the current crosses zero.

Moreover, the transition from synchronous to asynchronous mode is performed automatically when disconnecting the motor from the network as well as during the operation of the induction motor protection (See fig.4).

When the engine is out-of-step (in case of voltage drops or load shocks), alternating current flows through the rotor winding with slip frequency that causes asynchronous torque. Variations in speed and current variation that occur in this case are damaging for both the motor and the conductors.

The implementation of automatic circuits for switching the motor to normal asynchronous mode at the time of overload and for returning to synchronous mode when the load has decreased removes these drawbacks [16].

IV. EXPERIMENTAL RESULTS OBTAINED USING THE DISMAP SYNCHRONIZATION EQUIPMENT

Nominal data of the drive motor 2 MW type ATM 2500-2

- Nominal power	- 2 MW;
- Nominal voltage	- 6 kV;
- Stator current	- 210 A;
- Speed	- 2980 rpm;
- Engine performance	- 95.1%;
- Power factory	- cos φ 0.86;
- Rotor voltage	- 1330 V;
- Rotor current	- 920 A;
- Rotor weight	- 3650 kg;
- Total engine weight	- 15865 kg;
- Air consumption	- 3 m3/second;
- Oil flow through the bearing	- 25 liters/minute.

Fig. 5. Asynchronous motor with wound rotor, type ATM 2500 -2

To obtain the experimental data, the high-performance, 8-channel, 16-bit, fiber optic acquisition system *Transient Recorder Tras Mobile* was used, with a sampling rate of 100kS/s (10μs between 2 points), (see Fig. 5).

Fig. 6. TRAS Mobile acquisition system.

HVT 50 RCR 50kV/50V voltage dividers were used for voltage measurement, and CWT15R (500A/V) 3000 A peak Rogowski belts were used for current measurement (see Fig. 6).

Fig. 6. Current and voltage measurement acquisition system.

By closing switch I_2, which is conditioned by the conditioning module shown in Fig. 2 to close when the current crosses zero, the rotor winding of the induction motor is supplied by direct current, obtained from the rectifier of the DISMAP synchronization equipment, and, after several current steps, considered harmless to the motor, the transition from asynchronous mode to synchronous mode is performed.

Fig. 7 shows the currents in the stator of the 2000-kW power induction motor, corresponding to the phases IR, IS, IT when switching from asynchronous to synchronous mode.

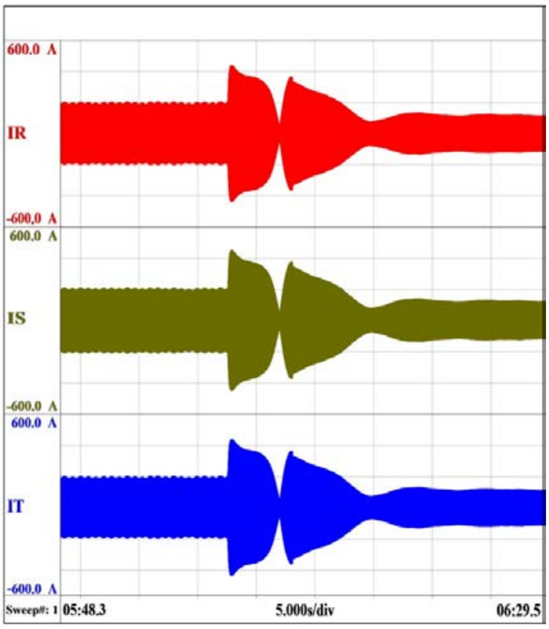

Fig.7. Transition from asynchronous to synchronous mode.

The values of the currents measured in the stator of the motor in asynchronous and respectively synchronous mode are presented in Table I:

TABLE I.
VALUES OF PHASE CURRENTS

	Phase currents in asynchronous mode	**Phase currents in synchronous mode**
IR_RMS	136.589 A	76.6227 A
IS_RMS	142.537 A	80.1198 A
IT_RMS	135.720 A	75.0794 A

The 142.537A peak current in the stator of the motor in asynchronous mode is recorded on phase S. After achieving the synchronism conditions, the peak current value in the stator of the motor is of 80.1198A. This decrease in currents occurs on the three phases, as evidenced by the data in Table I. There is a substantial decrease in the currents measured in the stator of the induction motor when using the DISMAP synchronization equipment.[16]

The values of the average power factor recorded for the asynchronous and synchronous modes are presented in table II.

TABLE II.
POWER FACTOR VALUES

	PF in asynchronous mode	PF in synchronous mode
Phase R	0.65	0.99
Phase S	0.65	0.99
Phase T	0.65	0.99

Fig. 8 and Fig. 9 shows the oscillograms which reveal the phase shift between voltage and current in asynchronous/synchronous mode on the three phases.

Once the synchronization is achieved by using the synchronization equipment, there is an increase in the power factor, from 0.65 (asynchronous mode) to 0.99 (synchronous mode), thus reaching the value imposed by the Romanian energy regulatory authority (0.9).

The use of synchronization equipment for low-load wound-rotor induction motors leads to a substantial reduction of monthly costs. The performance of this DISMAP synchronization equipment led to a reduction of almost 50% in the active energy consumption and also a reduction of almost 60% in the reactive energy consumption, which was determined by comparing monthly invoices before and after the implementation of the equipment.

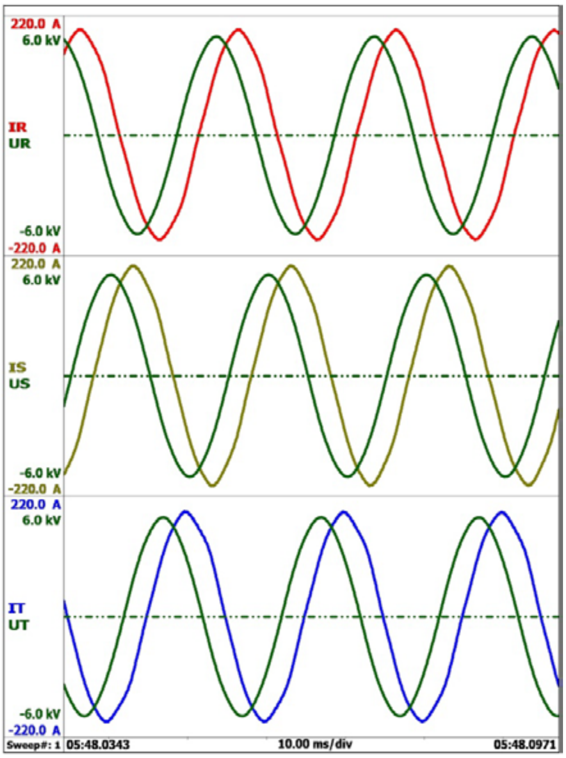

Fig. 8 Voltage – current phase shift in the stator in asynchronous mode.

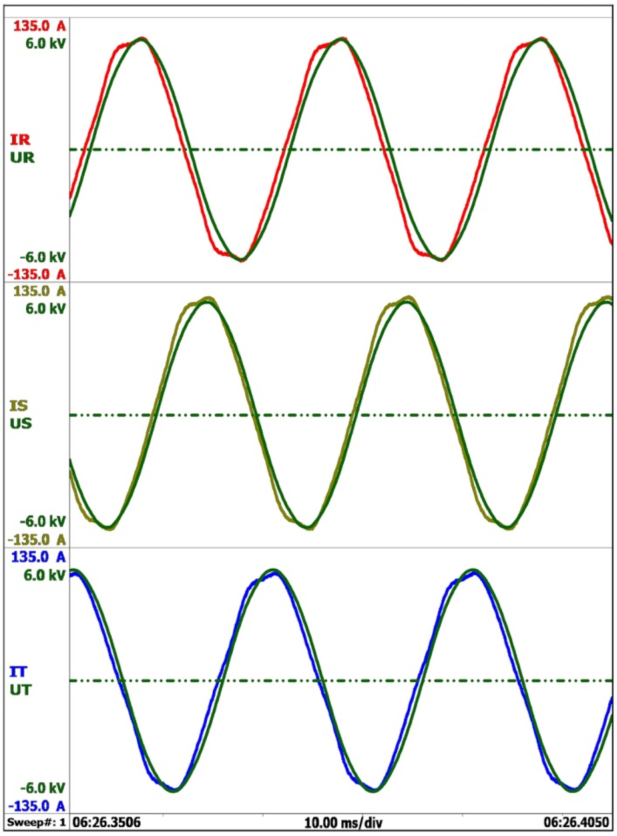

Fig. 9. Voltage – current phase shift in the stator in synchronous mode.

V. CONCLUSIONS

This paper presents the synchronization equipment and its performance, which led to a reduction of almost 50% in the active energy consumption and also a reduction of almost 60% in the reactive energy consumption, and this was determined by comparing monthly invoices before and after the implementation of the equipment.

The implementation of this synchronization equipment for the low-load wound-rotor induction motors allows the increase of the average power factor from 0.65 in asynchronous mode to 0.99 in synchronous mode, substantially reducing both the active energy consumption and the reactive energy consumption.

The equipment has shown high performance in reducing the reactive energy consumption and increasing the power factor, and it was incorporated into the laboratory test circuit for high-power equipment [16].

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First author – 50%;
First coauthor – 10%;
Second coauthor – 10%;
Third coauthor – 10%;

Fourth coauthor – 10%;
Fifth coauthor – 10%.

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