DOI: 10.2478/sbeef-2025-0012

REACTIVE POWER COMPENSATION SOLUTIONS IN THE METALLURGICAL INDUSTRY INSTALLATIONS

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Abstract. ***The metallurgical industry is one of the main branches of the global and Romanian industry. In 2023, global crude steel production was approximately 1.8 billion tons, according to the World Steel Association. It contributes approximately 5-6% to global GDP, having a significant impact on the economies of industrialized countries. It is a large consumer of electricity, being responsible for approximately 10% of global CO_2 emissions. Therefore, reducing and streamlining energy consumption is a particularly important challenge and target. Data analysis from the Târgoviste Special Steel Plant revealed poor energy efficiency and high reactive power consumption. In this sense, adequate solutions that compensate the excessive reactive power and consequently improve the power factor are to be implemented. To address this issue, this paper proposes a simple solution by implementing an automated system of controlled capacitor banks.***

Keywords: electrical energy efficiency, SCADA measurements, reactive power compensation.

1. INTRODUCTION

The metallurgical industry is one of the fundamental industries for the global economy, making a significant contribution to supporting technological progress, but also to the development of infrastructure. The steel industry is faced with many requirements worldwide: energy efficiency, reducing production costs, improving product quality, which inevitably leads to the automation and streamlining of technological processes. The latter, not only ensure more rigorous control over technological parameters but also allow for continuous and real-time monitoring of processes [1-5].

At present, both industrial and residential electrical systems face various issues related to power quality. Most of these issues stem from the nature of the consumers themselves, specifically, the characteristics of the current they draw—while only a minor portion is due to the power supplier, typically linked to the voltage properties [2-8].

A major disturbance in the network is represented by the distortion of the voltage and current waveforms. These harmonics are mainly generated by nonlinear consumers that include a variety of power electronic devices. Their high incidence in today's networks is a consequence of the requirements of application control and energy efficiency. Unfortunately, these loads produce current harmonics and cause rapid fluctuations in reactive power demand. In industrial settings, additional sources of harmonics include equipment such as welding machines, electric arc furnaces, process control systems, reheating or treatment furnaces, capacitor switching operations, and transients during the startup of large motors or transformers [1-15].

These distorted current waveforms lead to a range of adverse effects, such as overheating of transformers, motors, converters, and cables, malfunctions in digital control systems, and unexpected tripping of protective devices. Moreover, excessive distortion of the voltage waveform can significantly shorten the lifespan of many electrical devices by raising their operating temperatures [3-10]. Basically, harmonics (current and/or voltage) cause abnormal operation of all network components and ultimately affect the reliability and safety of the power supply network [4-15]. Consequently, a study on power quality is necessary to properly address harmonics-related issues.

The source of the harmonics must be identified, and appropriate corrective measures should be implemented. Passive filters are commonly used to address these issues. While they are simple, robust, and cost-effective, passive filters offer harmonic attenuation only within a specific harmonic range of the load. Furthermore, unless supplemented with additional components, they can reduce the power factor and are susceptible to resonance phenomena—particularly when the harmonic characteristics of the load or the line impedance change [7-15].

Modern Active Harmonic Filters (AHFs) are advanced power electronic devices designed to mitigate current and/or voltage harmonic distortion caused by heavy industrial loads. Their operating principles vary based on the specific technology used. In addition to harmonic mitigation, AHFs offer rapid power factor correction, load balancing, and reduction of voltage fluctuations such as flicker [6-10].

Due to their innovative design and operating principle, distortion attenuation is achieved even for loads with high dynamic characteristics (rapid changes in reactive power or harmonic content). In addition, they are not

affected by resonance phenomena or by the characteristics of the line impedance. The causes of reactive power circulation in the electrical installation are due to the following two large categories of elements: consumers and reactive power sources. The first category includes: asynchronous motors, induction and arc furnaces, welding transformers, controlled rectifiers, electric discharge lamps as well as transmission and distribution elements (transformers and power lines) [8-15].
The aim of this paper is to illustrate a simple and low-cost solution for compensating the reactive power in Targoviște Special Steel Plant. Based on a series of measurements performed during production process, a very low power factor was detected. Thus, a solution is proposed to compensate the reactive power using step-controlled capacitor banks.

2. ELECTRICAL EQUIPMENT IN ROLLING MILL AND THE AUTOMATION STRUCTURE

Electrical equipment ensures efficient and adaptable operation of the rolling mill, contributes to the optimization of both the technological flow and additionally reduce operational costs. Equipment design and maintenance is crucial for reducing breakdowns, diminishing downtime and accordingly maintaining the high quality of finished products.
The entire installation contains about 792 pieces of equipment represented by DC motors, asynchronous motors, pumps of various powers and with various uses. Each device is powered either at a voltage of 400 V or 600 V, but there are also 4 stand motors that require a power supply of 800 V. The rated power of each piece of equipment varies from 1.5 kW (table roller motors) to 800 kW (stand motors), reaching an installed power of 22,333 kW for the entire installation.
Therefore, the integration of advanced technologies and continuous monitoring of equipment become essential priorities for a modern rolling mill [9, 10].
Electric motors play an essential role in this sector, being used to drive heavy equipment, handle materials and control various industrial processes. The various drives in the steel industry require motors to be able to cover wide operating ranges, especially related to the speed range and the overloads that can occur. The only motors that have been able to meet these demands have proven to be DC motors even they manifest the well-known intrinsic disadvantages caused by the mechanical rectification system and brushes contacts.
The analysis of the causes of the high and irrational consumption of reactive power in the electrical installation highlights the fact that its average power factor, even under nominal operating conditions, is below the neutral power factor value. In addition, due to the actual operating conditions, it shows an even more pronounced decrease.
Figure 1 shows a brief diagram of the industrial automated process line. The automation of the rolling line ensures precision, efficiency and control over the technological parameters. In the diagram below, the data from the rolling line are transmitted by the field sensors and processed by the programmable controller to coordinate the technological process sequences.
The production process is presented on the HMI (human-machine interface) device.
The technological parameters related to the production process are presented on the Trader Workstation (TWS level 2 automation), which is responsible for advanced process control and optimization of the production process [10-14].
The data received from the field sensors are analysed by the programmable controller and according to the production scheme and technological parameters, the programmable controller controls the electrical equipment in the field, at the same time receiving a response from it that the commands were successfully performed. There is continuous communication between the programmable controller, the field sensors and the control panel.

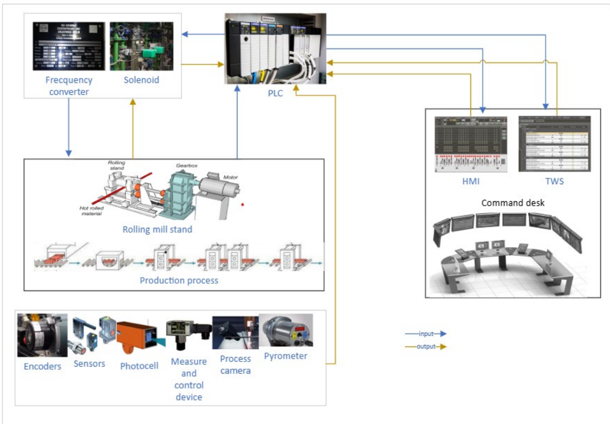


Figure 1. Automation diagram for rolling mill lines.

An automated rolling mill is a complex industrial facility that processes metals in the form of semi-finished products (round, square or strips) by reducing their cross-section and improving their mechanical and physical properties. The process takes place in several stages, each of which is monitored and controlled by an automation system.
From the point of view of automation, the general process flow in a rolling mill is assured by:
1. Power supply systems
Power supply systems must ensure:
- continuous high power required for high-power equipment
- power quality, to prevent voltage and frequency fluctuations that can negatively affect sensitive equipment, which reduces their efficiency and reliability.
2. Control of electrical machines
Frequency converters regulate the speed and torque of the motors that drive the roller groups, the drive cages for rolling the material, fans, hydraulic pumps and industrial water pumps.
3. Sensors and actuators

Sensors and actuators are very important components in the automation and control of industrial processes. This industry is characterized by complex processes, carried out under extreme conditions of temperature, pressure and vibration, continuous movement. Thus, the use of robust, reliable and precise sensors and transducers equipment is demanded. Particularly, those that monitor physical or chemical quantities are essential for the control of steelmaking processes [11]. These kinds of actuators transform electrical or electronic signals into mechanical movement, being consequentially responsible for the physical manipulation of equipment and materials in the manufacturing process [12].

4. Automated decisions

The programmable logic controller processes the data received from the sensors and runs a predefined program to control industrial processes through commands to the actuators.

5. SCADA systems

In the modern steelmaking industry, all the sensors and actuators are integrated into a complex automated system, controlled by a SCADA (Supervisory Control and Data Acquisition) system. This system allows:

- Continuous monitoring of process parameters.
- Real-time control of critical equipment.
- Data analysis for performance optimization [13,14].

Figure 2 summarizes the production line within Targoviște Special Steel Plant.

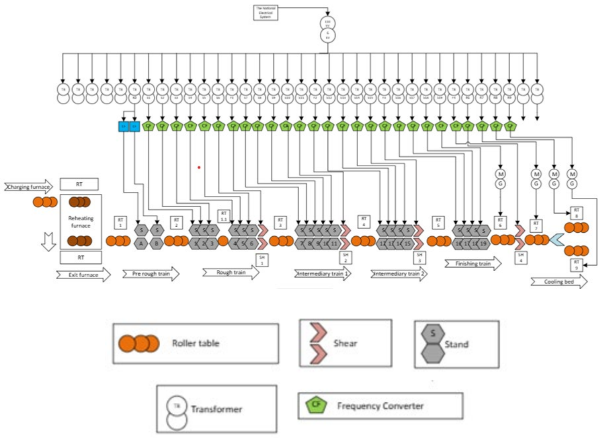


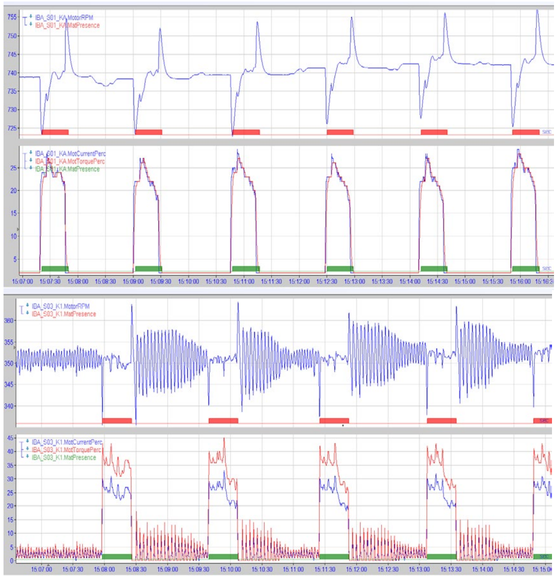
Figure 2. Electrical equipments diagrams for rolling mill.

3. MECHANICAL AND ELECTRICAL MEASUREMENTS IN THE PLANT

The experimental data were collected from the operation of the essential machines of the production flow, with a special focus on high-power electric motors. These motors, being critical equipment in the industrial process, are among the largest consumers of electricity in the entire system.

A. Analysis of rotation speed, current and torque for cage drive motors

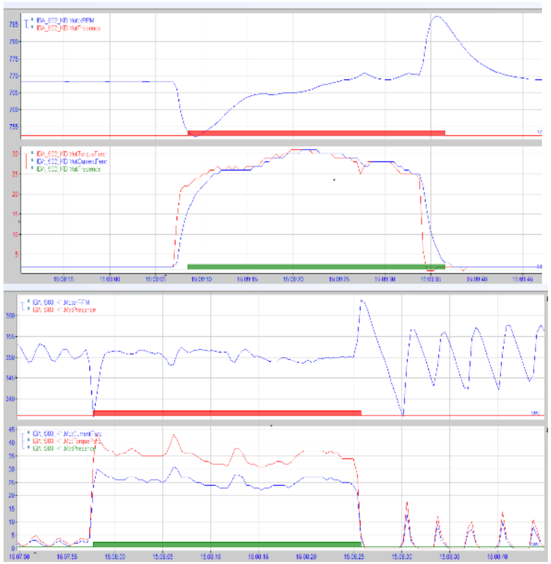
The following graphs show the rotation speed of the motor, current and torque for multiple material passes, respectively a single pass. The measurements were carried out for a 500 kW SMS GH 355SK motor, driven with a ABB frequency converter (Fig. 3a and 4a) and a GMFW 1413-32 (Figure 3b and 4b) motor with thyristor frequency converter (year of manufacture 1978).



a)

b)

Figure 3. Variation of motor rotation speed, current and torque over multiple passes of the material.



a)

b)

Figure 4. Variation of the rotational speed, current, and motor torque during a single pass of the material.

Analysing graphs 3a and 4a on the one hand, and graphs 3b and 4b on the other, it is clearly seen the superiority of the modern motors implemented in cages A and B, compared to solutions over 40 years old in the other cages. This aspect confirms once again the need to modernize the entire rolling line soon to increase the energy efficiency of the entire enterprise.

The solid line represents the presence of material in the cage. The blue line in the upper graph represents the motor rotation speed (rpm). The blue and red lines in the lower graph represent the motor current and torque in percentages of load (0-100%).

Current and voltage fluctuations after an electric motor is unloaded can be attributed to several factors and components specific to the equipment:

Effect of mechanical inertia. Electric motors have a mechanical inertia caused by their rotating components (shaft, rotor, reducer, etc.). With the sudden decrease in load, the rotor continues to rotate at a variable speed until it stabilizes. At the same time, the change in rotation speed affects the magnetic flux inside the motor, generating temporary fluctuations in the absorbed current and in the voltage in the network.

Effect of the residual magnetic field. Electric motors can resonate with the natural frequencies of the power system, especially when the load is removed, this resonance is caused by temporary oscillations of the current and voltage. For example, in asynchronous motors, the removal of the load can lead to rapid variations in slip, which is reflected in fluctuations in the absorbed current.

Power supply network reaction. When the load suddenly drops, the current at the motor terminals is reduced, this change causing a reaction of the power supply network, especially in high impedance networks, this decrease causes voltage fluctuations at the terminals, until the motor stabilizes.

Behaviour of control and protection elements. Modern motors are connected to control and protection systems, which monitor the current, voltage and load on the motor in real time, and can introduce delays and temporary oscillations to stabilize the motor parameters.

Loss of natural damping. The motor under load has a natural damping, due to the mechanical load, which limits voltage and current fluctuations. When the load is removed, this damping disappears, and the system oscillates until the system stabilizes.

These phenomena can be reduced by:

- Installing electrical and mechanical dampers to reduce temporary fluctuations.
- Installing a Soft Starter or a VFD (Variable Frequency Drive).
- Improving grid stability.

Reducing grid impedance or installing correction capacitors that can limit voltage fluctuations [15, 16].

B. Analysis of electrical quantities

In Fig. 5 can be depicted the variation active, reactive power and the power factor, respectively, during the metallurgic process over 30 minutes. The solid lines in the upper graph represent the presence of material in the rolling mill cages (from 1 to 19). The red and blue lines in the middle graph represent the active power and reactive power, respectively. The blue line in the lower graph represents the power factor.

One can notice that when the material passes through several cages, the power factor decreases significantly, reaching values up to 0.525. This difference in the no-load and load of the power factor value is due to the ratio between active and reactive energy. This problem highlights the importance of operating electrical devices and equipment at optimal loads (the equipment should be adapted to the load) to maintain a high-power factor and the energy efficiency of the system.

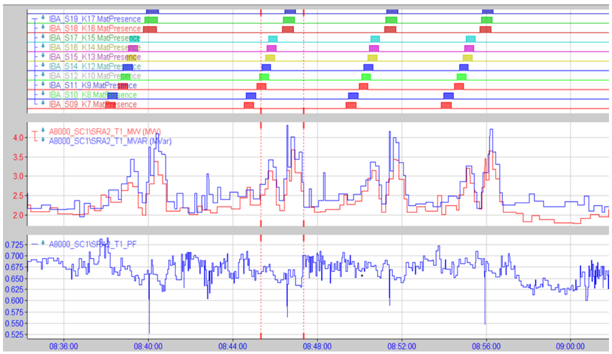


Figure 5. Active/Reactive Power vs. Power Factor.

The graph below represents the current A, B, C phases in the primary of the transformer (110kV), respectively in the secondary of the transformer (6kV).

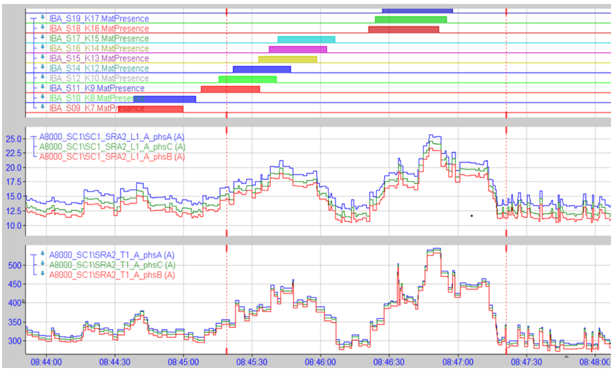


Figure 6. Transformer primary/secondary current.

The solid lines in the top graph represent the presence of material in the rolling mills (from 1 to 19). The blue/red/green line in the middle graph represents the current A/B/C phases on the primary of the laminar power transformer. The blue/red/green line in the bottom graph represents the current A/B/C phases on the secondary of the laminar power transformer.

Increasing the current from 300 A to 500 A on the secondary part of the transformer and correspondingly from 12.5 A to 25A on its primary part within 10 seconds in a continuous working mode can have a significant impact on the power network and associated equipment. Although these current differences may seem smaller than in the case of very high currents, the impact of this type of constant fluctuation is notable, especially in the long term.

Because of these current fluctuations, the following phenomena occur: the overheating of conductors and aging of the power line equipment; (due to additional Joule effect): The energy dissipated in the form of heat is directly proportional to the square of the current. When increasing from 300 A to 500 A, the dissipated energy increases by 2.78 times (500/300)2=2.78). These come with some consequences: premature aging of the insulation, electrical equipment can reach thermal operating limits, affecting their lifespan, Temporary increase in current leads to temporary increase in voltage drop on conductors and transformers.

The graph in Fig. 7 represents the voltage between phases A, B, C in the primary of the transformer (110kV) and in the secondary of the transformer (6kV), respectively.

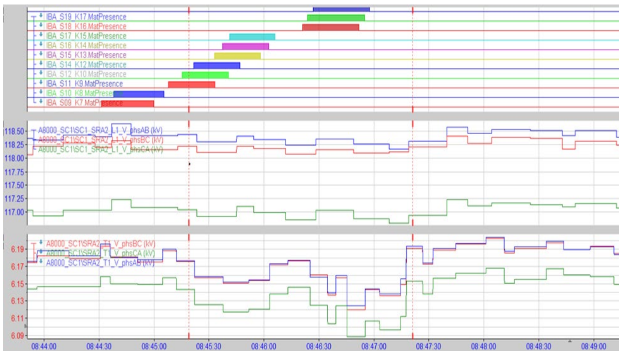


Figure 7. Transformer primary/secondary voltage/phase.

The solid lines in the top graph represent the presence of material in the rolling cages (from 1 to 19). The blue/red/green line in the middle graph represents the voltages on phases A/B/C on the primary of the laminar power transformer. The blue/red/green line in the bottom graph represents the voltages on phases A/B/C on the secondary of the laminar power transformer.

An imbalance between phases of approximately 1 kV can be observed in the graph above. This voltage imbalance between phases can lead to much higher losses, but also to the non-compliant operation of the equipment. That voltage power quality issues can also lead to an increase in imbalance currents. Consequently, the losses increases in all the electric installation components (transformers, power cable line etc), which shortens the life time expectancy of the equipment.

4. PROPOSED SOLUTIONS FOR IMPROVING THE POWER FACTOR (REACTIVE POWER COMPENSATION)

A solution that can still be used in technology up to 6 kV voltage is that of reactive power compensation through special capacitor banks [17, 18]. For a correct dimensioning of the components of the capacitor bank, the following aspects must be considered: evaluation of the power required for the battery, calculation of the discharge resistances of the capacitors, determination of the circuit for the capacitor bank.

The placement of medium-voltage capacitor banks in an installation can be done at various points of it. The following compensation methods can be highlighted: global (placement at a single point for the entire installation – usually in the secondary of the distribution transformer), sectoral (upstream of a group of consumers or a sector of loads), local or individual (at each consumer), mixed – a combination of the last two [15-19].

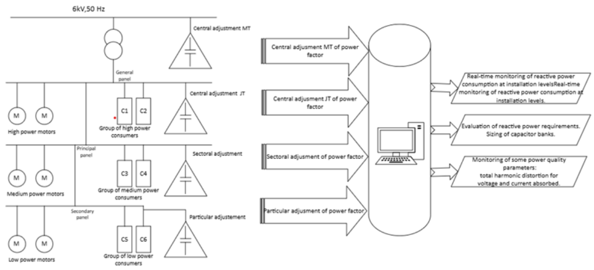


Figure 8. Location of capacitors batteries.

Centralized compensation can be achieved by connecting the capacitor bank to the bars of the general distribution board in the transformer station. The bank is executed in steps with switching, usually automatic (equipped with switching devices for coupling-decoupling to the electrical network), depending on the reactive power to be compensated, corresponding to the operation of the powered receivers [15-20].

The bank can also be connected to the medium voltage side of the transformer station. In this case, the positive technical effects are not felt on the consumer's low voltage installations (downstream of the installation site). However, large consumers, supplied directly at medium voltage, use this type of compensation (with the bank mounted on the medium voltage side) which ensures a general power factor (PF) above the neutral power factor value, so that electricity consumption is charged only for the active energy [21-23].

Analysis of the data measured over a 24-hour operating period highlighted the following values of the main quantities of interest.

Table 1. Values for the main quantities.

Quantity	PF [-]	P [MW]	Q [MVAr]	S [MVA]
Minimum	0.399	8.94	21	22.83
Maximum	0.795	8.24	6.52	10.516
Average	0.583	9.93	14.08	17.283

Starting from the minimum values from the table above we can identify the reactive power necessary to increase the power factor to a value of 0.8. It is important not to set a power factor that is too high because if compensation leads to a surplus of reactive power, we will have an increase in voltage in installations that can cause more damage.

The following simple calculation will lead us to the reactive power necessary to improve the power factor:

$$cos\varphi_1 = 0.399 \Longrightarrow tan\varphi_1 = 2.995 \text{ (minimum PF)} \quad (1)$$

$$cos\varphi_2 = 0.8 \Longrightarrow tan\varphi_2 = 0.75 \text{ (intended PF)} \quad (2)$$

$$Q_C = P|_{cos\varphi_1} \cdot \left(tan\varphi_1 - tan\varphi_2\right) = \\ = 8.94 \cdot (2.995 - 0.75) = 13.81\ (kVAr) \quad (3)$$

$$C_Y = \frac{Q_C}{\omega \cdot \left(U/\sqrt{3}\right)^2} = \frac{13.081 \cdot 10^3}{2 \cdot \pi \cdot 50 \cdot \left(6000/\sqrt{3}\right)^2} \quad (4)$$

$$C_Y = 1.22 \text{ mF}$$

Considering the result from equation (4) an equivalent capacitor of 1.22 mF is necessary for wye (Y) connection of, by correspondence a 3.66 mF for delta (Δ) connection.

Capacitor manufacturers offer solutions for such situations. The most suitable solution would be to choose the 150 kVAr solution [41], therefore 90 pieces are needed to obtain a 13.5 MVAr compensation of reactive power. Therefore, we propose a 3-step solution for automatic connection of these capacitors according to the following scheme:

- Step 1 – 3.0 MVAr (20 x 150 kVAr),
- Step 2 – 4.5 MVAr (30 x 150 kVAr),
- Step 3 – 6.0 MVAr (40 x 150 kVAr).

The use of capacitor banks connected in parallel is used to obtain a higher total capacity and to adapt the system to power factor correction needs.

The time variation curve of the reactive power consumption *Q* in an electrical installation is not, in general, a constant one. The reactive power requirement depends on the way in which electrical energy is used in various technological processes, a fact illustrated by the load variation. The reactive power absorbed can, therefore, vary slowly or very quickly, within very wide limits. The adoption in this situation of fixed value capacitor banks can determine over- or under-compensation regimes. [24, 25].

The selection of the number and value of the steps of a capacitor bank must consider the fact that the efficiency of the regulation increases with the number of steps, making it possible to follow the reactive power load curve as faithfully as possible. On the other hand, an excessive fraction of the bank becomes, at some point, uneconomical because it requires the use of a complex switching scheme [26, 27].

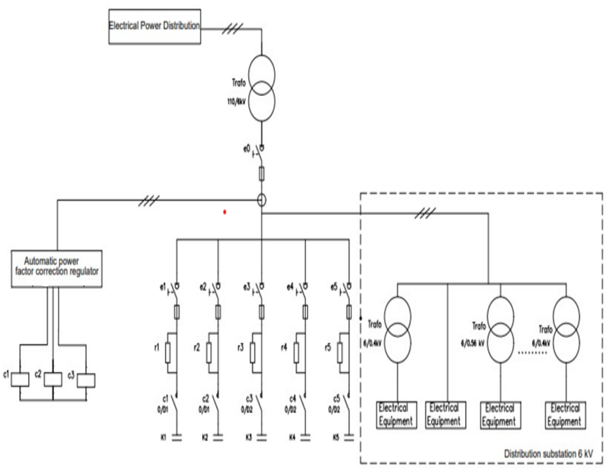


Figure 9. The components of the automatic power factor reduction system.

In Fig. 9 the operational schematic is presented to compensate the reactive power (legend: e1-e5 represents fuses, c1-c5 – contactors and r1-r5- discharge resistors).

The automatic power factor control system allows the power of a capacitor bank to be regulated according to the variations in reactive power. The automatic regulators control the circuit breakers or contactors of the steps according to the reactive power or the power factor measured at the connection point of the capacitor bank.

Implementing this solution, in Fig. 10 there is presented a comparison between the measured PF (with blue) and the estimated PF (orange).

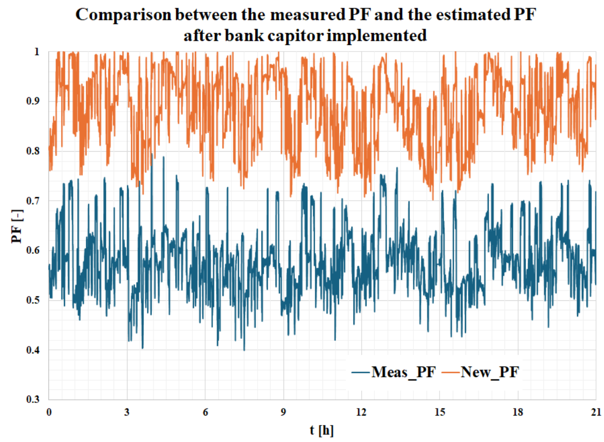


Figure 10. The comparison between measured PF and estimated PF.

In table 2 a comparison is presented between the minimum, maximum and the average power factor before and after implementing the bank capacitor solution.

Table 1. Values for the main quantities.

Quantity	PF_meas [-]	PF_new [-]
Minimum	0.399	0.706
Maximum	0.795	0.99
Average	0.583	0.889

5. CONCLUSIONS

The selection of the power factor correction method at low-voltage installation must simultaneously consider technical aspects regarding the proper functioning of the network and the economic aspects related to the investment in the compensation system. Also, the duration of the investment recovery (return on investments indicators) are to be regarded.

A classical power factor compensation systems, although expensive, have a number of advantages, which have led to their widespread use: immediate adaptation to power factor fluctuations (response time 2 s or 40 ms, depending on the controller options), elimination of transient phenomena in the network when switching capacitors through controlled selection of the switching moment, practically unlimited number of on/off cycles and, last but not least, silent operation.

Real-time collection of experimental data from sensors and equipment is necessary for continuous monitoring of the production process. This allows for rapid detection of deviations from normal operating parameters, thus ensuring precise control of the technological flow and prevention of incidents.

The use of automatic control systems, such as PLCs and SCADA, contributes to efficient management of the rolling process. These systems allow not only monitoring, but also automatic adjustment of operating parameters, reducing manual intervention and optimizing energy consumption and product quality.

Statistical analysis and mathematical modeling of experimental data provide valuable information on the correlations between process parameters and the quality of the finished product. This approach allows for precise adjustment of operational parameters to minimize variations and improve the consistency of the final product.

Efficient processing of experimental data allows for the identification of opportunities for optimizing energy consumption. Continuous adjustment of process parameters reduces energy losses, thus contributing to lower production costs and increasing the sustainability of steel operations.

Monitoring and analysis of field data are essential to assess energy efficiency, identify potential losses and implement consumption optimization measures. This data reflects the operational characteristics of the equipment, such as energy consumption, operating mode and load behavior, providing a solid basis for performance analysis and for adopting appropriate technical decisions.

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