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AUTOMATED REACTIVE POWER CONTROL SYSTEMS AND FREQUENCY-CONTROLLED ELECTRIC DRIVES AS TOOLS FOR ENHANCING ENERGY EFFICIENCY IN POWER SUPPLY SYSTEMS

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Abstract: The article discusses modern technical solutions aimed at improving the energy efficiency of power supply systems through the introduction of automated reactive power control systems and frequency-controlled electric drives. The reasons for inefficient consumption of electricity in the traditional control of electric drives and the lack of reactive power compensation are analyzed. The principles of operation of frequency converters and automatic compensating devices, their architecture and algorithms of functioning are described. Examples of practical application of these technologies in public utilities and industry are given, their economic and technical efficiency is shown. The presented data confirm that the integrated use of frequency control and adaptive reactive power compensation can significantly reduce energy losses, increase equipment life and reduce operating costs.

Keywords: energy efficiency, frequency converter, electric drive, reactive power compensation, automation, energy management, FACTS, STATCOM, smart grids, energy saving, automated process control system

Introduction. Enhancing the energy efficiency of power supply systems is one of the key challenges in modern energy engineering. A significant portion of generated electricity is consumed by electric drives and distribution networks, with losses due to mismatched operating conditions. For instance, electric motors account for over 65% of total electricity consumption, making improvements in their operating conditions highly impactful.

Two critical areas of energy saving are reactive power compensation in electrical networks and the use of frequency-controlled drives (frequency converters) to optimize electric motor performance. This review examines the operating principles of automated reactive power control systems and frequency converters, as well as their impact on improving the energy efficiency of power supply systems. Examples of technical solutions and modern approaches to implementing these systems are provided. The discussion employs precise scientific and technical terminology.

The Problem of Reactive Power and Its Compensation. In AC power networks, the presence of reactive power (e.g., when supplying inductive loads such as motors or transformers) leads to energy circulation between the source and the load without performing useful work. This circulation increases the total current in circuits, causing additional losses and reducing energy transmission efficiency. Excessive reactive power results in several adverse effects: transformer overloading, cable overheating, increased power losses, significant voltage drops, and higher electricity costs. Consequently, a low power factor (cos φ) leads to energy overuse and reduced power supply quality.

One effective way to optimize electricity use and improve the technical and economic performance of electrical equipment is through reactive power compensation. The essence of compensation lies in introducing reactive power sources that generate the necessary reactive current directly within the consumer's network, reducing reactive energy exchange with the source. Typically, capacitor banks (for inductive reactive power consumption) or synchronous compensators are used for this purpose. Properly implemented compensation reduces power losses in conductors by lowering the current flow and maintains the required voltage level in the network. As a result, active power is transmitted more efficiently, and equipment operates under more favorable conditions.

Since the amount of consumed reactive power varies with the load, effective compensation must be adaptive. An automated reactive power control system monitors the power factor (cos φ or tan φ) in the network and adjusts the degree of compensation in real time. Its operation typically relies on a controller linked to current and voltage transformers. For example, the controller receives a signal from a current transformer, calculates the power factor, and connects the required number of capacitor bank stages to achieve the target cos φ value. When the load decreases and overcompensation occurs, excess capacitors are automatically disconnected. Thus, the system maintains an optimal reactive power balance, avoiding both under compensation and overcompensation.

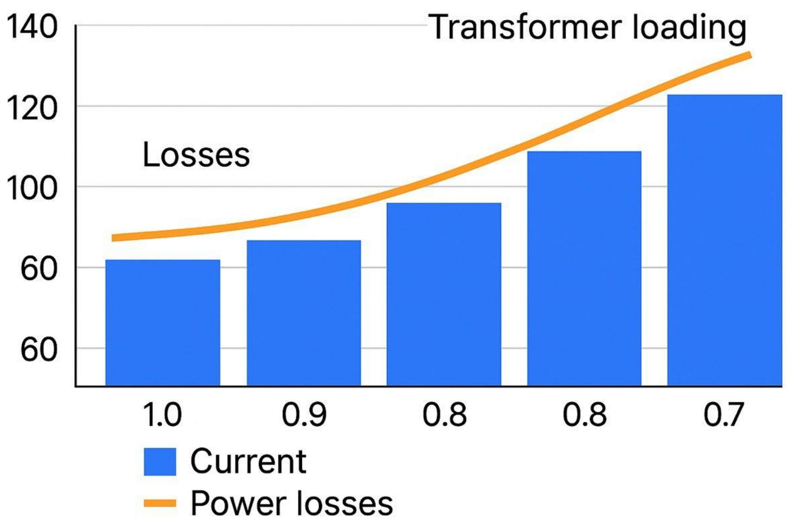

Fig. 1 Changes in System Parameters with a Decrease in cos φ.

In the simplest automatic reactive power compensation systems, capacitor banks are connected in steps via contactors controlled by a power factor regulator relay. More advanced systems use thyristor switches (TSC – Thyristor-Switched Capacitor, TCR – Thyristor-Controlled Reactor) for smooth and rapid regulation of reactive current, which is necessary for rapidly changing loads (e.g., arc furnaces or large drive systems). A modern, highly dynamic solution is the use of static compensators like STATCOM, based on power transistors (IGBT). Studies show that implementing STATCOM in medium-voltage distribution networks (e.g., 10 kV) combined with transformer tap regulation enables highly adaptive reactive power flow management with significant economic efficiency [1]. Such devices belong to the family of FACTS (Flexible AC Transmission Systems) and can automatically maintain the required voltage level and power factor at network nodes. The implementation of automated reactive power compensation systems yields significant energy-saving benefits. Reducing current flow directly decreases thermal losses in cables and busbars. Rational reactive power compensation in industrial networks reduces energy losses by 10–15% due to lower load currents [3,4].

Additionally, voltage quality improves for consumers, especially under significant load fluctuations, which positively affects the operation of sensitive equipment. The economic benefit is also evident in reduced payments for reactive energy. In many power systems, fees for reactive power consumption can account for 12–50% of active energy costs. Automatic compensators help avoid these penalties by maintaining a power factor close to unity. Ready-made technical solutions are widely used to implement these measures. For example, low-voltage automatic capacitor units (ACUs) installed at the main distribution boards of enterprises can adjust the power factor for an entire facility. For instance, the AUKRM-0.4 series (automatic reactive power compensation units for 0.4 kV) with capacities ranging from 5 to 3000 kVar enable step-by-step reactive power regulation in three-phase networks of 0.23–0.69 kV at 50 Hz. The controller in such units automatically maintains the set operating mode by connecting or disconnecting capacitor groups. In high- and medium-voltage networks, static capacitor banks are installed at substations, along with synchronous compensators (special synchronous machines operating in idle mode). In recent years, industrial-grade static var generators (STATCOM, SVC) have become available, particularly effective for facilities with rapidly changing loads and high-power quality requirements.

As a result of using reactive power compensation tools, total energy transmission in the network occurs with fewer losses and a higher efficiency coefficient. The load on transformers and generators decreases, extending their lifespan due to reduced winding heating. Additional network capacity is freed up, as a reactive-power-free network can transmit more active power at the same current levels. Thus, automated reactive power control systems significantly enhance the energy efficiency of power supply systems by optimizing operating conditions and eliminating inefficient losses.

The Problem of Inefficient Electric Drive Regulation and the Use of Frequency Converters.
AC electric motors have traditionally operated at a fixed network frequency (50 Hz), with technological parameters (flow, pressure, mechanism speed) adjusted mechanically. Throttling liquid flow with valves or dampers and periodic on-off switching of pumps are examples of “old methods” of regulation characterized by low efficiency. During throttling, excess fluid energy is dissipated uselessly, heating the valve without contributing to useful work.

Frequent starts and stops cause shock loads and accelerated equipment wear. As a result, a significant portion of consumed electrical energy is wasted. This is particularly critical for water supply, heating, and ventilation systems, where loads fluctuate daily and seasonally. Amid rising electricity tariffs, industries are compelled to seek ways to reduce costs for electric drives, which, as noted, account for over half of total energy consumption.

To improve the efficiency of electric motors, frequency-controlled electric drives are used, based on controlling the frequency of the supply voltage. A frequency converter is an electronic device that adjusts the frequency and amplitude of the voltage supplied to the motor, thereby regulating its rotational speed.

Modern frequency converters operate on the principle of double energy conversion. First, the AC voltage from the industrial network is rectified by a diode bridge into DC. The DC circuit smooths out ripples using capacitors or an LC filter. Then, an inverter unit based on IGBT power transistors generates AC voltage of the desired frequency and magnitude using pulse-width modulation. The inverter’s output consists of rectangular pulses, which, due to filtering or the motor’s inductive properties, approximate a sinusoidal voltage. Thus, the network AC voltage is first converted to DC and then back to AC with the required parameters. The power section of a typical frequency converter includes three components: a rectifier, a DC link, and an inverter bridge, each performing a specific energy conversion function. The operation of power switches is managed by an integrated microprocessor controller, implementing a specified control law (scalar V/f or vector algorithm) to achieve the desired dynamic characteristics of the drive.

Using a frequency converter allows the supply frequency of an asynchronous motor to be adjusted based on process requirements, enabling precise control of rotational speed. This is particularly important for equipment with variable loads, such as pumps, which can operate at the required flow rate without excessive energy consumption. According to the affinity laws for hydraulic machines, power consumption decreases proportionally to the cube of the frequency, so even a slight reduction in speed results in significant energy savings.

Moreover, frequency control ensures smooth motor starts and stops, eliminating shock loads and reducing starting currents. This reduces mechanical wear, extends the lifespan of the motor and associated equipment, and improves overall system reliability.

Controlling electric motors with frequency converters provides substantial energy-saving benefits. By precisely matching power to the actual load, energy consumption can be reduced by 20–50% [2]. Practical applications show that implementing frequency control in pump and fan systems can achieve energy savings of several tens of percent. For example, in water and heat supply facilities in the Leningrad Region, installing frequency converters reduced electricity costs by 35–40%, with equipment payback periods of less than one year [5].

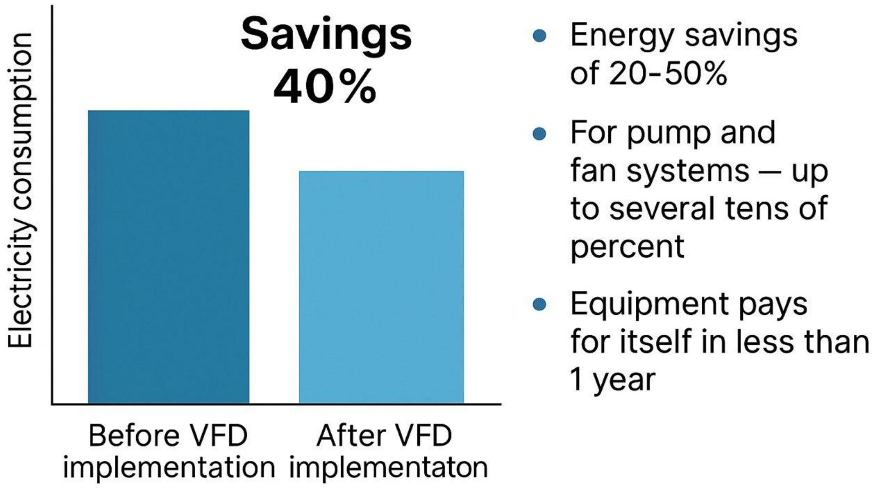

Fig. 2 Energy Savings in Motor Control with Frequency Converters

A similar effect is observed in ventilation and air conditioning systems. Frequency drives enable precise regulation of climate parameters in buildings, reducing energy consumption during partial load periods. In addition to lowering electricity costs, frequency-controlled drives reduce equipment wear. Smooth starts decrease the likelihood of hydraulic shocks in pump systems, reducing breakdowns and extending maintenance intervals. The risk of winding overheating and bearing failure is also reduced, lowering maintenance costs.

Precise parameter regulation also improves the quality of technological processes, such as maintaining stable pressure, flow, or temperature, which can prevent resource overuse (e.g., water or heat). Frequency converters easily integrate into automated control systems, enabling data exchange and process optimization. An additional efficiency boost comes from energy regeneration functions—during motor braking, excess energy can be returned to the network or DC link, increasing overall system efficiency.

Today, frequency-controlled drives are widely used across various industries. In water supply and sewage systems, they maintain set pressure with minimal energy consumption. They are installed in pumping stations, blowers, and exhaust fans in boiler rooms. This not only reduces energy costs but also decreases the need for maintenance personnel. In buildings with variable loads, such as shopping malls or offices, frequency drives manage ventilation based on time of day and occupancy, saving energy during off-peak hours.

In industry, such drives are used in machine tools, conveyors, compressors, centrifuges, and other mechanisms requiring speed and torque control. Manufacturers offer a wide range of frequency converters, from low-power models to robust industrial solutions compliant with international energy efficiency standards, such as Danfoss VLT, Siemens Sinamics, and ABB ACS. Overall, frequency-controlled electric drives are considered one of the most effective energy-saving tools in modern electrical installations.

Conclusion. Automated reactive power compensation systems and frequency converters are two powerful tools for enhancing the energy efficiency of electrical networks and installations. The former eliminates inefficient losses in networks related to reactive energy transmission and optimizes the operating conditions of power grid equipment. The latter ensures economical electricity use on the consumer side by adapting motor operation to actual needs. Implementing these technologies delivers a comprehensive effect: reducing losses and penalties for reactive energy, lowering electricity consumption by drives under partial loads, improving power quality, and increasing equipment reliability. Modern technical solutions (intelligent controllers, power electronics, monitoring systems) make these control tools accessible and cost-effective. Many enterprises have already confirmed that investments in capacitor units and frequency converters pay off quickly through reduced electricity bills. In the future, further automation and integration of these systems into unified "smart" grids (Smart Grid) and industrial complexes will enable even greater optimization and energy savings. In conclusion, the integrated application of automated reactive power compensation and frequency-controlled electric drives is a critical direction for enhancing the energy efficiency of power supply systems across various economic sectors.

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