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Application of Contactless Voltage Regulators in Automatic Reactive Power Consumption Control

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ABSTRACT: This article analyzes the theoretical and practical aspects of using contactless voltage regulator devices for the automatic control of reactive power consumption. It substantiates the high efficiency of modern electronically controlled, delay-time regulated contactless regulators in eliminating power losses and equipment failures in electrical networks caused by voltage fluctuations and increased reactive power. The article thoroughly examines the structural configuration of contactless relays, their integration potential with intelligent control systems, and their economic and energy efficiency advantages.

KEYWORDS: Reactive power, contactless voltage regulator, energy efficiency, automatic control, intelligent relays, delay time, compensation, asynchronous motors, energy losses.

I. INTRODUCTION

Efficient management and accurate identification of reactive power sources are of critical importance in the generation, transmission, and consumption of electrical energy, particularly within industrial power systems. Asynchronous motors, transformers, and inductive loads are considered the primary sources of reactive power. An increase in reactive power leads to voltage drops in the power network, greater active power losses, and the potential failure of electrical equipment. Conventional electromechanical relays used to address these issues are significantly influenced by human intervention and lack the responsiveness required for modern systems. As a result, there is a growing demand for contactless voltage regulators based on electronic technologies with intelligent control systems. These devices ensure voltage stability through reflexive control, time-delay mechanisms, and digital analysis [1].

Reactive power (Q) is a crucial component in electrical power systems. Although it does not perform any useful mechanical work, it is essential for the operation of electrical equipment. Reactive power is primarily required to establish the electric and magnetic fields in transformers, inductive loads, and especially asynchronous motors. According to statistical data, 60–70% of reactive power consumption is attributed to asynchronous motors.

A high level of reactive power results in a decrease in the power factor (cosφ) of the electrical network. This leads to an increase in the total current relative to the active power being transmitted. Consequently, conductors, transformers, and other components in the network experience increased loading, energy losses rise, equipment overheats, and the risk of failure significantly increases [2]. The relationship between reactive power and active power can be expressed as follows:

$$Q = P \cdot tg\varphi$$

where, P - represents the active power (in watts), and φ - denotes the phase angle of the power factor.

Based on this formula, calculations are performed to determine the amount of reactive power present in the system, which then guides the implementation of appropriate compensation measures. Accurate management of reactive power during compensation is essential for the efficient use of electrical energy and for maintaining the stability of the power grid.

The additional active power losses that result from the flow of active and reactive power through transmission lines can be expressed by the following formula:

$$\Delta P = I^2 \cdot R_l = \left(\frac{S}{U}\right)^2 \cdot R_l = \frac{P^2 + Q^2}{U^2} \cdot R_l = \frac{P^2}{U^2} \cdot R_l + \frac{Q^2}{U^2} \cdot R_l = \Delta\mathrm{P} + \Delta\mathrm{Q}$$

where, **ΔP** refers to the active power losses resulting from the flow of active power through the network, while **ΔQ** represents the active power losses caused by the flow of reactive power through the network. As can be seen from this

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expression, the flow of reactive power through power lines contributes to additional active power losses, thereby increasing the overall share of total power losses in the system.

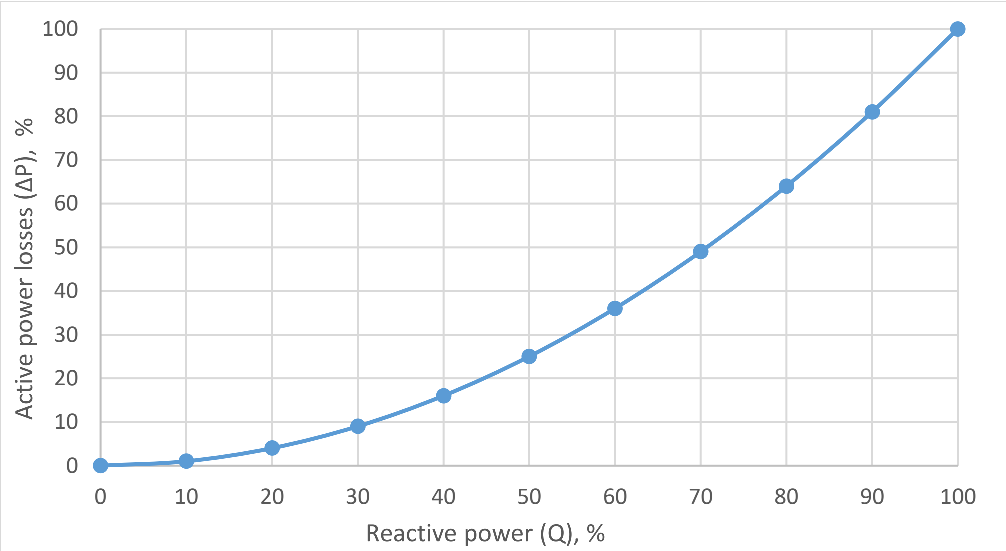

Figure 1. Load graph illustrating the relationship between reactive power demand and active power losses.

Figure 1 illustrates the relationship between the variation in the share of reactive power consumption (Q) by industrial enterprises and the corresponding share of active power losses (ΔP) caused by the reactive power demand in the transmission lines supplying electricity to these enterprises.

As the graph shows, an increase in reactive power leads to a corresponding rise in active power losses. The waste of active power increases in direct proportion to the square of the reactive power demand. In other words, as reactive power increases, active power losses grow at an accelerated rate [4]. This clearly highlights the importance of efficient reactive power management in power networks and the necessity of minimizing losses across the grid. The following expression presents the additional voltage drop losses resulting from the flow of both active and reactive power through the transmission lines:

$$\Delta U = IR_l cos\varphi + IX_l sin\varphi = \frac{IUcos\varphi}{U} R_l + \frac{IUsin\varphi}{U} = \frac{P}{U} R_l + \frac{Q}{U} X_l = \Delta U_P + \Delta U_Q$$

where, ΔU denotes the voltage drop losses caused by the flow of active power in the network, while ΔU represents the voltage drop losses resulting from the flow of reactive power. As seen from this expression, the additional voltage losses caused by reactive power flow contributes to an increased share of the total voltage losses in the power network.

Figure 2 depicts the relationship between the variation in the share of reactive power consumption (Q) and the corresponding share of voltage losses (ΔU) arising from the reactive power demand in the transmission lines supplying electricity to the enterprise. The graph clearly shows that a 10% increase in reactive power demand leads to an approximately 1% rise in voltage losses. This indicates the negative impact of reactive power on voltage stability in power networks. Therefore, efficient reactive power management is essential for reducing voltage losses and enhancing the overall performance of the electrical grid.

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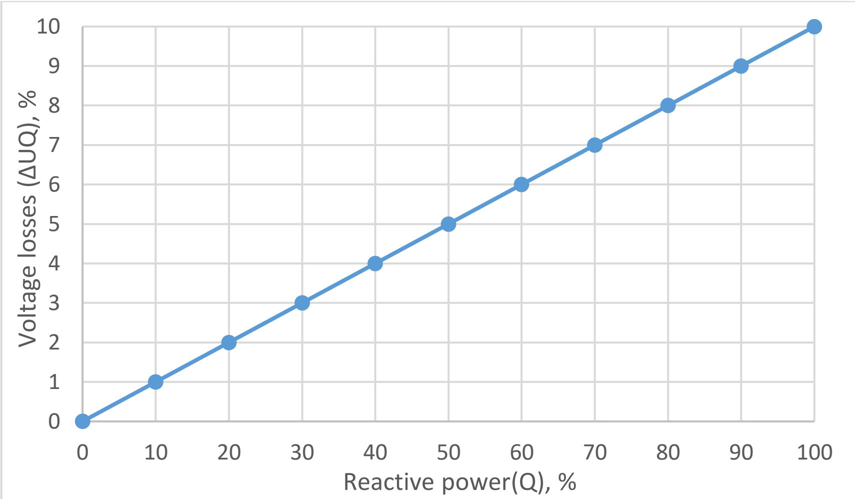

Figure 2. Load graph illustrating the relationship between reactive power demand and voltage drop losses.

By implementing automatic regulation of reactive power near consumers—without transmitting it over long distances through power lines—it is possible to reduce additional active power and voltage losses. This, in turn, improves both the efficiency and reliability of the power system [5]. Moreover, variations in reactive power demand can be explained by seasonal consumption patterns, such as reduced energy use during summer and increased demand in the autumn. These fluctuations can affect the continuity of technological processes, emphasizing the need for efficient reactive power management systems, energy-saving measures, and improved forecasting of energy consumption. Ultimately, this leads to reduced production costs and enhanced operational efficiency.

Today, contactless voltage regulators play a crucial role in the automatic control of reactive power consumption. These regulators are built using high-precision electronic components and are designed to continuously analyze the voltage in real time and maintain it within nominal limits through automatic adjustments.

The internal structure of such a device includes several critical modules:

- A voltage sensor continuously measures the voltage level in the network.
- An ADC (Analog-to-Digital Converter) digitizes the analog signals from the sensor and sends them to the controller.
- The controller analyzes the incoming data and, using a delay-time mechanism, determines the required output action.
- A triac-based output module adjusts the output voltage by altering the phase angle according to the controller's command.
- A special timer introduces delayed responses to short-term voltage fluctuations, preventing frequent switching.
- Filter and protection elements are used to suppress high-frequency noise and other harmful effects.

This design ensures the device is highly reliable, responsive, and safe for managing voltage fluctuations.

In automatic control systems, intelligent solutions, including fuzzy logic and artificial neural networks, allow for effective and adaptive reactive power management. A fuzzy logic-based device evaluates input parameters such as voltage variation (ΔU) and reactive power variation (ΔQ). These values are divided into nominal ranges using membership functions, usually triangular in shape.

Using fuzzy inference rules in the form of "If...then..." conditions, the controller makes control decisions. In the final stage, the defuzzification process is performed using the Center of Gravity (COG) method to generate a precise output signal—such as "connect the device," "disconnect," or "take no action." This system ensures reliable control even under uncertain or dynamic conditions, contributing to more efficient energy use [6].

Contactless voltage regulators are widely used across various sectors and provide specific advantages for each application:

- In the oil and gas industry, they ensure the stable operation of pump units, guaranteeing continuous production.
- In metallurgy, where loads are heavy, these devices stabilize voltage fluctuations, allowing uninterrupted equipment operation.
- In the textile industry, accurate and continuous voltage regulation ensures the smooth and synchronous operation of automated conveyor lines.

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- In the food industry, where synchronized operation of preparation and compliance-related equipment is essential, voltage stability is critically important.
- In household electrical networks, these regulators provide effective protection for home appliances and electronic devices against high or low voltage conditions.

Finally, it is assessed the performance of traditional contact-based voltage regulators and the newer contactless types—now entering industrial use—based on key criteria such as sensitivity, operational longevity, energy efficiency, and reliability.

№	Parameter	Contact Relay	Contactless Relay
1.	Reaction Time	Seconds	Milliseconds
2.	Service Life	50,000 cycles	500,000+ cycles
3.	Power Factor (cosφ)	0.7 – 0.85	0.95 – 1.0
4.	Power Losses	Average	10–20% lower
5.	Reliability	Mechanical	Electronic

The table above compares the key technical parameters of contact-based and contactless voltage relays. In terms of reaction time, contactless relays respond within milliseconds, whereas contact-based relays have a delayed response measured in seconds. Regarding operational lifespan, contact-based relays can typically endure up to 50,000 cycles, while contactless relays are capable of operating beyond 500,000 cycles. The power factor (cosφ) for contact-based relays ranges between 0.7 and 0.85, which is considered inefficient for optimal energy use. In contrast, contactless relays achieve a high utilization factor, with cosφ values ranging from 0.95 to 1.0. In terms of power losses, contact-based relays exhibit average losses, whereas contactless relays reduce losses by approximately 10–20%. From the reliability perspective, contact-based relays, due to their mechanical components, are prone to wear and have a shorter service life. Contactless relays, on the other hand, have an electronic structure that ensures long-term durability and operational safety. Overall, contactless relays demonstrate superior efficiency across all technical parameters [7].

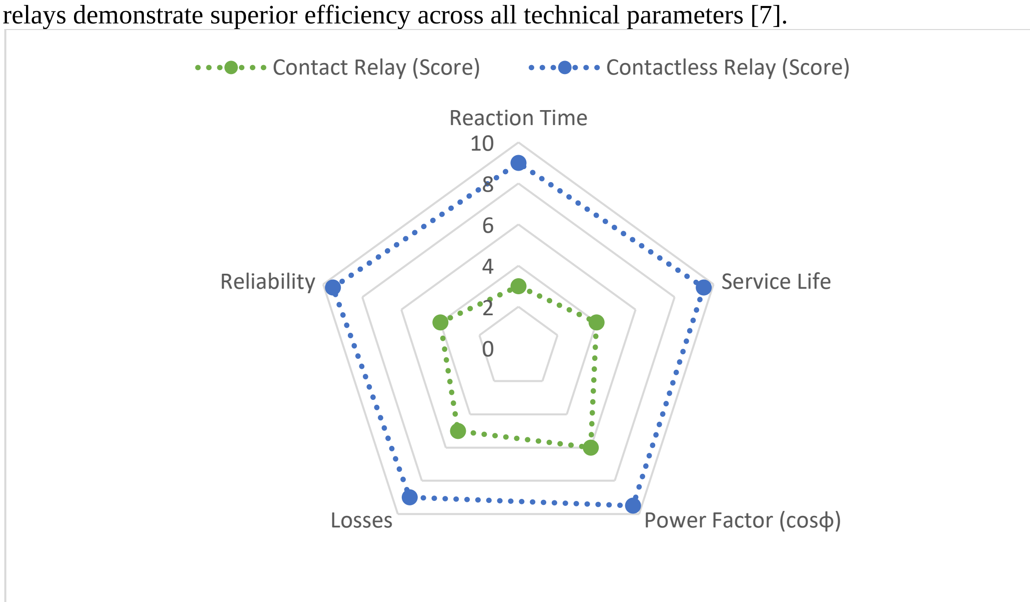

Figure 3. Without contact and contact effort Radar diagram for evaluation of relays

In this radar chart, the key technical parameters of contact-based and contactless voltage relays are visually compared using a 10-point rating scale. As the chart clearly illustrates, contactless relays demonstrate a distinct advantage across all technical indicators. They outperform traditional contact-based relays in terms of reaction time, reliability, lower power losses, and longer operational lifespan. Such radar charts are highly useful for visual comparisons and informed decision-making.

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II.CONCLUSION

In conclusion, contactless voltage regulator devices play a crucial role in enhancing energy efficiency by enabling real-time voltage analysis and automatic compensation of reactive power in electrical networks. Their integration with intelligent algorithms such as fuzzy logic and IoT-based systems allows for faster, more accurate, and reliable control. The industrial implementation of such devices not only contributes to energy savings but also improves equipment reliability and reduces maintenance costs. Therefore, the gradual adoption of contactless regulators, the localization of their production, the widespread use of intelligent control systems, and the strengthening of collaboration between science and industry are among the most pressing priorities.

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