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The Impact of Static Thyristor Compensators on Power Quality Loss Reduction and Energy Efficiency

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The Impact of Static Thyristor Compensators on Power Quality, Loss Reduction and Energy Efficiency

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Abstract. This article examines the impact of static var compensators (SVC) on power quality indicators, reduction of transmission network losses, and improvement of energy efficiency. SVC devices control reactive power in real-time, stabilizing network voltage, thereby improving voltage irregularities and power factor. Relevant studies have shown that when SVCs are installed in the network, they increase transmission capacity and reduce losses, as well as play an important role in optimizing active power efficiency. This work presents a comprehensive analysis of SVC focused on reducing losses and increasing overall energy efficiency, in comparison to previous studies.

INTRODUCTION

The continuous growth in electricity demand in modern power systems, combined with the geographically dispersed nature of generation resources, has led to a substantial increase in loading levels of network components. Long-distance power transmission inherently results in higher active power losses, while the presence of aging transformers and transmission lines further aggravates issues related to power quality, voltage regulation, and system reliability. Under these conditions, the expansion of existing infrastructure through the construction of new power facilities is often constrained by high capital costs, extended implementation timelines, and increasingly strict environmental and regulatory requirements. Consequently, improving the performance and utilization of existing electrical networks has become a critical objective for power system operators. In this context, Flexible AC Transmission System (FACTS) technologies, particularly Static Var Compensators (SVCs), are increasingly being adopted as an effective solution to enhance the operational efficiency of power transmission networks. FACTS devices enable fast and flexible control of power system parameters through dynamic reactive power injection or absorption, thereby improving voltage profiles, increasing transmission capacity, and enhancing system stability. Among these technologies, static thyristor compensators are especially notable for their capability to provide continuous voltage regulation and maintain reactive power balance under both steady-state and dynamic operating conditions. The application of static thyristor compensators significantly improves network reliability and reduces transmission losses by optimizing reactive power flow. Efficient utilization of electrical equipment through reactive power compensation is considerably more advantageous than operating transmission lines and transformers under high reactive loading conditions. By reducing the reactive current component, active power losses are minimized, and the available capacity of network elements is increased, allowing for either additional active power transfer or a reduction in thermal stress on system components [1-46].

Previous studies have primarily focused on the role of SVC devices in enhancing voltage stability and improving reactive power control. In contrast, the present article emphasizes the reduction of power transmission losses and the improvement of overall energy efficiency through the deployment of static thyristor compensators. The analysis extends beyond conventional voltage regulation and power factor correction by examining the combined impact of SVC operation on transmission line losses, current loading, and system-wide efficiency indicators. This integrated approach provides a more comprehensive assessment of the technical and economic benefits of static thyristor compensation in modern power transmission networks.Static thyristor compensation (STC) significantly increases the operational efficiency and controllability of power systems when implemented under a set of coordinated control conditions and system parameters. The effectiveness of this technology is determined not only by the compensator hardware itself, but also by the sophistication of its control strategies and its integration into the overall power system. One of the key conditions for improving efficiency is the limitation of voltage in both upper and lower operating ranges when predefined threshold values are exceeded. This is achieved through the rapid transition of the compensator to either full reactive power absorption or full reactive power generation modes. Such fast response prevents excessive voltage deviations and protects network equipment under abnormal or rapidly changing operating conditions. Another important operating mode is the controlled operation of transmission lines during single-phase short-circuit events. Following single-phase automatic reclosing and reconnection of the line to the power system, the static thyristor compensator operates according to a dedicated control algorithm. This algorithm supports voltage recovery, suppresses oscillations, and contributes to maintaining system stability during post-fault conditions. To achieve maximum efficiency, the control system of static thyristor compensators may implement advanced and adaptive control algorithms. These algorithms allow the compensator to respond dynamically to variations in network topology, load behavior, and system operating states, thereby improving voltage regulation accuracy and reducing response time. Efficiency is further enhanced by reducing the effective reactive power control period, which improves the voltage stabilization process in power systems with rapidly changing loads, particularly during parallel operation of multiple transmission lines or power sources. Faster reactive power control minimizes voltage fluctuations and enhances dynamic performance. In addition, the optimization of control characteristics of static thyristor compensators is achieved by flexibly adjusting the parameters of the closed-loop control system in accordance with real-time changes in power system parameters.

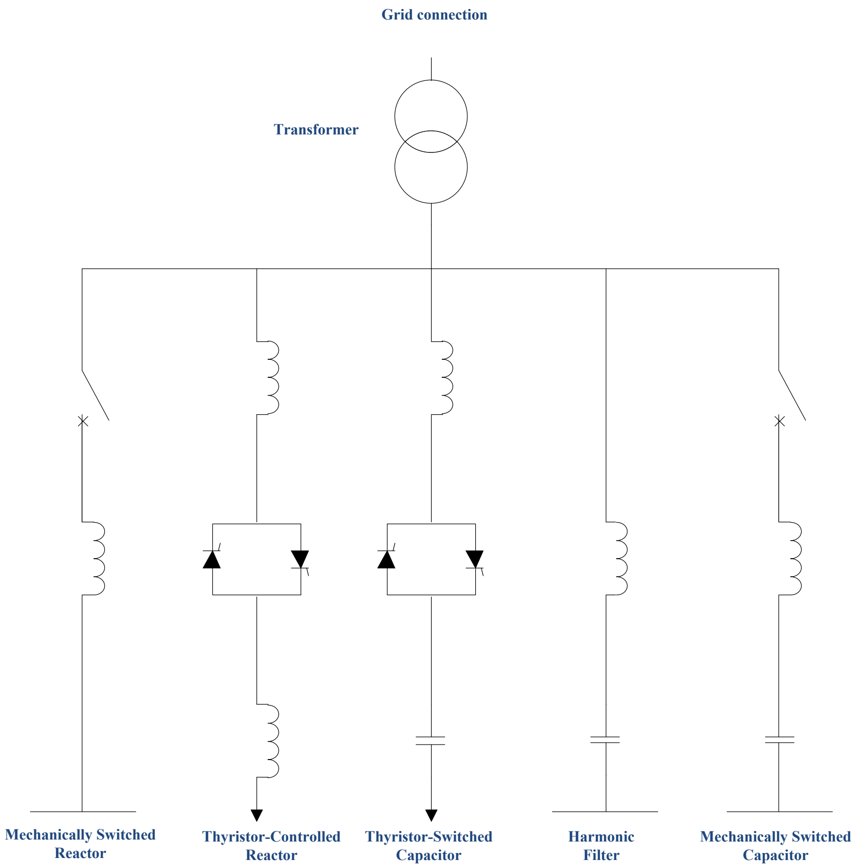

Figure 1. Single-line diagram of a static thyristor compensator

Such adaptive tuning ensures stable operation across a wide range of loading and fault conditions, while maintaining optimal compensator performance. Finally, the coordinated use of external switching devices for individual substation equipment, including transmission lines, power transformers, shunt reactors, and capacitor banks, enables an active and synergistic influence of static thyristor compensators on the power system. This coordination reduces switching disturbances, minimizes transient impacts, and enhances overall system reliability. In summary, the application of static thyristor compensation with advanced control strategies and coordinated equipment interaction provides a robust solution for improving voltage stability, reactive power management, and overall efficiency of modern power systems. A Static VAR Compensator (SVC) is a set of devices connected in shunt to the transmission network, capable of supplying or absorbing reactive current to control the network voltage. The device dynamically regulates reactive power using high-power thyristors. A basic SVC circuit (Figure 1) primarily consists of a thyristor-controlled reactor (TCR) and a thyristor-switched capacitor (TSC), which are utilized to supply or absorb the required reactive power.

The SVC is distinguished by its ability to respond rapidly, as it lacks mechanically moving parts and its operation relies entirely on semiconductor elements (thyristors). The device's control system provides reactive power in any desired direction by adjusting the firing angle of the thyristors, connecting or disconnecting the reactor or capacitors to the network. According to the operating principle, if the reactive component in the network load is inductive, the SVC absorbs reactive power and reduces voltage by connecting the thyristor-controlled reactor; if the reactive load is capacitive, the capacitor is automatically engaged, increasing the system voltage. The traditional method of regulating reactive power from high to low levels in electrical transmission involves replacing voltage-linear shunts with reactors mounted on high-voltage busbars and connecting synchronous (previously) or static compensators to the windings of high-voltage or intermediate substations or to the windings of network autotransformers.

Power factor improvement formulas are widely used in reactive power compensation. For example, if the active power P of the load and the initial power factor need to be improved from $\cos\varphi_1$ to the target $\cos\varphi_2$, the required compensating reactive power Q_c is calculated as follows

$$Q_c = P(\tan\varphi_1 - \tan\varphi_2) \quad (1)$$

This formula clearly shows what capacitor power is necessary to improve the power factor. Additionally, losses in transmission lines are related to the square of the current flow.

$$P_{loss} = \sum I_i^2 R_i \quad (2)$$

That is, as the distributed current I increases, losses increase sharply. Therefore, if the power factor of the network improves as a result of SVC intervention, the load flow decreases and losses are reduced according to the I^2R equation.

Static thyristor compensators are an important tool for improving power quality. They are effective in reducing load harmonics, ensuring voltage and current stability, and eliminating three-phase imbalances. Experimental studies show that when using SVC (Static Var Compensator), the network voltage becomes more stable, and the reactive power flow is significantly reduced. For example, an article in ISS Energies analyzed an SVC installed in a metallurgical plant and found that with the SVC present, voltage fluctuations decreased and reactive power consumption reduced[2].

Additionally, SVC also serves to improve the power factor. The improvement in power factor theoretically reduces network current, which leads to a reduction in losses in transformers and transmission lines. Furthermore, since SVC can quickly respond to various load conditions, it has an advantage in maintaining voltage stability in industrial settings with frequently changing loads. Thus, SVC improves power quality, mitigates harmonic distortions and voltage fluctuations arising from the load, and enhances network stability[2].

The application of static thyristor compensators directly impacts the reduction of energy losses and improvement of energy efficiency. As mentioned above, SVC enhances the power factor and reduces current flow by controlling reactive power, which decreases I^2R losses in transmission lines. According to ABB, installing SVCs at appropriate locations increases transmission capacity and reduces losses while maintaining a stable voltage profile. Practical studies confirm that when an SVC is installed, the active power efficiency in the network increases, the current required for the power drawn from the network decreases, resulting in reduced losses.

Furthermore, the installation of SVCs improves the quality of power input to the network and helps optimize future energy production needs. The obtained results indicate that systems with SVCs increase the energy efficiency of the electrical grid, as they eliminate network oscillations and voltage drops, which reduces disruptions in production processes and optimizes overall energy consumption.

Undoubtedly, the need to use a special step-down transformer for the application of thyristors in high-voltage networks leads to additional compensatory losses and an increase in the installation area.

The implementation of the proposed measures enables the controlled reactor to ensure reliable regulation of power flows in high-voltage transmission networks while maintaining the required level of active power transmitted through the lines. As a result of these measures, a number of important technical and operational improvements are achieved.

First, the voltage level on the busbars of substations is increased by up to 11%, allowing it to reach the rated value of 220 kV. This voltage stabilization contributes to improved power quality, reduces voltage deviations under varying load conditions, and ensures compliance with grid operation standards. Second, the nominal current in power transmission lines is reduced by approximately 15%, which directly leads to a decrease in Joule losses, reduced thermal stress on conductors, and an extension of the service life of transmission equipment. Lower current levels also enhance the overall energy efficiency of the power system. In addition, the application of controlled reactor regulation significantly increases both the static and dynamic stability limits of the power system. This improvement enhances the system's ability to withstand steady-state disturbances as well as transient events, such as sudden load changes, switching operations, or short-term faults. Furthermore, the stability of the power transmission line is improved due to an increase in its effective transmission capacity. By optimizing reactive power compensation and voltage profiles, the line operates closer to its optimal loading conditions without violating stability or thermal constraints.

The analyzed case study demonstrates that, beyond compensating for the charging (capacitive) power of long power transmission lines, voltage stabilization within the proposed control strategy effectively reduces both the reactor voltage and the switching overvoltages. This reduction mitigates electrical stress on switching equipment and insulation systems, thereby enhancing operational safety and reliability.

Moreover, the proposed control approach prevents system failures during emergency load shedding scenarios. By maintaining voltage stability and limiting transient overvoltages, the system remains stable even under severe operating conditions, reducing the risk of cascading failures and large-scale outages. Overall, the results confirm that the proposed control measures provide a comprehensive solution for improving voltage regulation, power system stability, and operational reliability in high-voltage transmission networks.

CONCLUSIONS

This article examines the significance of static VAR compensators (SVCs) in improving power quality, reducing losses, and enhancing energy efficiency. Research shows that SVCs stabilize network voltage, improve power factor, and reduce harmonics, thereby enhancing overall power quality. Furthermore, when SVCs are installed, transmission line losses are significantly reduced as SVCs decrease current flow and prevent increased I^2R losses in the lines.

During the analysis of electrical network operation, the operating modes of existing electrical networks and transformers were examined, and the power in overhead transmission lines was analyzed. The existing parameters of power (active and reactive) in overhead power transmission lines were studied and mathematically substantiated. The feasibility of measures aimed at reducing reactive and active power losses and their implementation were considered, and recommendations were provided to minimize their impact on power transmission networks.

As a recommendation, it is necessary to widely implement SVC technology in electrical engineering practice. Specifically, power quality and energy efficiency can be improved through the strategic placement of SVCs in heavily loaded networks and industrial facilities. For future work, it is recommended to conduct detailed modeling and testing of SVC design and control, as the optimization of reactive power distribution in real networks may yield results that differ from initial calculations.

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