The Evolution of Flexible Alternative Current Transmission Systems Design from Thyristors to Modular Multilevel

Jialiang Wang

Dalian Jiaotong University, School of Electrical Engineering, Dalian, Liaoning, China

jialiangwangeric@outlook.com

Abstract. This article systematically reviews the technological evolution of power circuit topology in Flexible AC Transmission System (FACTS) devices, from thyristor semi controlled circuits to IGBT fully controlled architectures, and then to the distributed structure of modular multilevel converters (MMC), revealing the changes in circuit design concepts during technological iterations. This article compares the topological characteristics of each stage and finds that thyristor circuits have simple driving but limited dynamic performance due to passive commutation. IGBT circuits improve response speed through PWM control but face switching losses and electromagnetic interference problems. Although MMC structures achieve high voltage and low harmonic output, they need to solve problems such as capacitor balancing and isolation control. The evolution of key aspects in circuit design is closely related to device characteristics. The driving circuit has evolved from pulse triggering to multi-level active driving, the protection mechanism has been upgraded from fuses to multi-level locking, the voltage balancing technology has developed from passive balancing to dynamic algorithms, and the heat dissipation scheme has shifted to liquid cooling systems due to the increase in power density. In summary, the current technological bottlenecks mainly focus on high losses and electromagnetic compatibility issues. The future breakthrough direction should integrate wide bandgap semiconductor devices, artificial intelligence optimization control algorithms, and multi physics field collaborative design to improve system economy and reliability and meet the needs of new power system construction.

Keywords: Flexible ac transmission system (FACTS); thyristors; insulated gate bipolar transistor (IGBT); modular multilevel converter (MMC).

1. Introduction

With the continuous expansion of the power system and the large-scale integration of renewable energy, the stable operation of the power grid is facing unprecedented challenges. Flexible AC Transmission System (FACTS), as a product of the combination of modern power electronics technology and traditional transmission technology, has become one of the key technologies for improving power grid stability due to its flexible reactive power compensation, precise voltage control, and fast current regulation capability. Since its proposal in the 1970s, FACTS technology has undergone an evolution from early thyristor-based half-controlled devices to today's modular multilevel converters (MMC) structure, gradually achieving a leap from single function to multifunctional collaborative control. However, there are still issues with dynamic response matching, harmonic suppression, and system oscillation suppression in the interaction between FACTS devices and the power grid. The integration between their functional positioning and the stability requirements of the power grid has always been a core issue in technological development. How to optimize the control strategy of FACTS in complex power grid environments, so that it can play a greater role in maintaining voltage stability, suppressing power oscillations, and improving transmission capacity is still the focus of current research.

As the core of FACTS devices, the topology of power circuits directly determines the performance boundary of the power grid, including applicable voltage levels, dynamic response speed, and operational reliability. Early thyristor-controlled reactors (TCR) and thyristor switched capacitors (TSC) used semi-controlled devices. New topologies such as MMC based on fully controlled devices have significantly improved the voltage level and response performance of the device, making it widely used in high-voltage power grids.

This article aims to systematically review the development of FACTS technology, analyze the impact of power circuit topology evolution on power grid performance, and extract future technological routes based on this. With the development of the power system, FACTS technology needs to achieve breakthroughs in the combination of wide bandgap devices, artificial intelligence, and multi physics field collaborative design [1,2]. This study can not only provide theoretical support for the optimization of existing FACTS devices, but also provide assistance and technical reference for the stable and efficient operation of future power grids.

2. Overview of FACTS Technology

Flexible AC Transmission System (FACTS) equipment achieves flexible control of grid parameters through power electronics technology, and its core function is closely related to circuit topology. In parallel compensation devices, the Static Var Compensator (SVC) uses a thyristor-controlled reactor (TCR) combined with a fixed capacitor (FC) to achieve dynamic reactive power compensation by adjusting the equivalent reactance. It is mainly used for voltage stability and flicker suppression [3]. The Static Synchronous Compensator (STATCOM) is based on the Voltage Source Converter (VSC) topology, which regulates reactive power by outputting controllable AC voltage [4]. It responds faster without the need for large capacity energy storage components and is suitable for dynamic voltage support and oscillation damping. In the series compensation device, thyristor-controlled series compensator (TCSC) adjusts the equivalent reactance of the line through variable impedance to achieve power flow control and sub synchronous oscillation suppression [5]. The Static Synchronous Series Compensator (SSSC) adopts a VSC structure to inject controllable compensation voltage, which can accurately control active power flow and enhance system stability. As the most complex combination device, the Unified Power Flow Controller (UPFC) integrates the parallel series structure of STATCOM and SSSC, and achieves independent regulation of active and reactive power flow of the line through collaborative control, which is suitable for power optimization of hub nodes [6]. The circuit topology of these devices directly determines the output characteristics and control degrees of freedom, and the subsequent evolution of topology further enhances the capacity and response performance of FACTS, promoting its deep application in the power system.

3. Circuit Design Based on Thyristor Semi-Control Devices

3.1 Mainstream Topology Structure

In the early days, FACTS used thyristors as devices, and there were two mainstream topologies for thyristor semiconductor circuits.

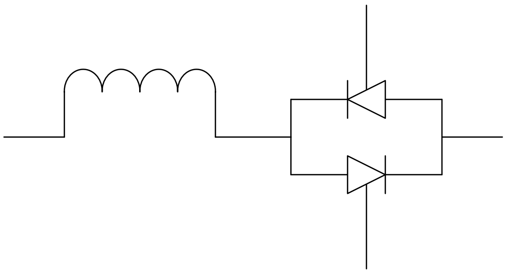

Fig. 1 Thyristor controlled reactor (TCR)

Fig. 1 shows the structure of TCR. The typical structure of a TCR is a pair of antiparallel thyristors connected in series with a linear hollow reactor. TCR continuously regulates the current flowing through linear hollow reactors by controlling the triggering angle of anti-parallel thyristor pairs, thereby providing continuously adjustable inductive reactive power for compensating line capacitive reactive power and stabilizing bus voltage [7]. Fig. 2 shows the structure of TSC. The typical structure of TSC is a pair of anti-parallel thyristors connected in series with a capacitor. TSC dynamically adjusts the reactive power of the system by controlling the conduction and turn-off of the thyristor, but its response speed is limited by the turn-off time of the thyristor. TCR and TSC are two mainstreams static var compensator topology structures in thyristor semi-control device circuits. These two topological structures were widely used in the 1980s.

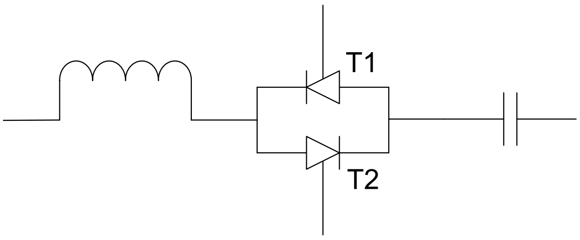

Fig. 2 Thyristor switched capacitors (TSC)

3.2 Typical Circuit Design Features

The typical circuit of thyristor semi-controlled devices mainly includes a driving circuit, a protection circuit, and a current-sharing circuit during design. Due to the limitations of the semi-controlled characteristics of thyristors, it is necessary to design gate drive circuits with strong triggering capabilities, usually using pulse transformers or optocoupler isolation schemes. Energy storage capacitors are also required to ensure sufficient triggering pulse width to maintain reliable conduction. In the design process, a high triggering pulse current is also required to ensure reliable conduction. However, the drive circuit of thyristor devices is susceptible to electromagnetic interference. When designing protection circuits, fast fuses are usually used for overcurrent protection, and RC buffer circuits are also required to suppress switch overvoltage. When designing a current sharing circuit, it is necessary to achieve static current sharing when multiple thyristors are connected in parallel through gate signal synchronization and current sharing reactors. Dynamic current sharing also relies on device parameter matching and layout optimization. These designs together achieve a reliable operation mode of thyristor circuits, but there are also some inherent limitations and disadvantages due to the characteristics of the devices.

3.3 Technical Bottleneck in Design

There are three main technical bottlenecks when designing circuits based on thyristor semiconductor devices. Firstly, due to the switching characteristics of thyristors, the current waveform will be distorted, generating a large number of harmonic components, causing serious harmonic pollution to the power grid, affecting power quality, and interfering with the normal operation of other equipment. Secondly, the turn-off of thyristors depends on external commutation circuits or natural zero crossings. If the frequency of the switch is limited, the dynamic response speed will slow down, making it difficult to meet the application requirements for rapid adjustment. In addition, thyristors and their supporting heat dissipation and protection circuits are usually bulky, resulting in low system integration, especially in the trend of modern power electronic equipment developing towards miniaturization and lightweight. This disadvantage is even more prominent.

4. FACTS Topology Evolution Based on Fully Controlled Devices: from Two-Level to Multi-Level

4.1 The Evolution of Typical Topological Structures

The topology structure based on IGBT devices is divided into two types: two-level and three-level. Fig. 3 shows the IGBT-based two-level structure. The typical two-level topology structures include half-bridge and full-bridge circuits, whose bridge arms are composed of upper and lower IGBTs. The switching action is achieved through the alternating conduction of the upper and lower bridge arm IGBTs. The two-level topology structure can output high and low electrical levels. Fig. 4 shows the

IGBT-based three-level structure. The neutral point clamp (NPC) and T-type topologies are the most common three-level topologies, which extend the output level to high, zero, and low levels by using clamp diodes or capacitors [8].

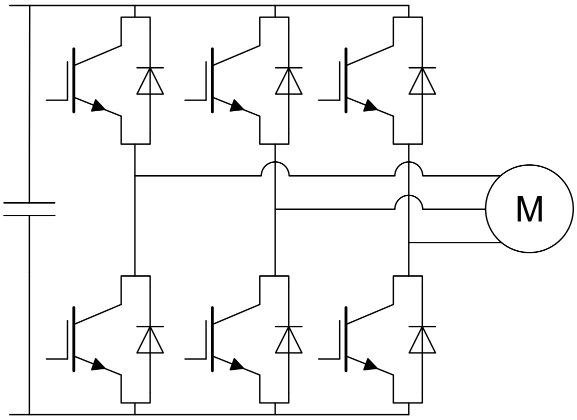

Fig. 3 IGBT-based two-level structure

The two-level and three-level topologies based on IGBT devices have their own advantages and are usually used in different scenarios in practical applications. The advantages of two-level topology include simple circuit structure, mature technology, and low manufacturing cost, which are usually used for low-power circuits or systems with less stringent requirements. Although the three-level topology structure increases the complexity and cost of the system, due to its multi-level output characteristics, the three-level topology structure can significantly improve the waveform quality of the output voltage, have lower harmonic distortion rates, reduce interference, improve the overall efficiency of the system, and make the system have better dynamic performance, making it more suitable for high-voltage and high-power fields.

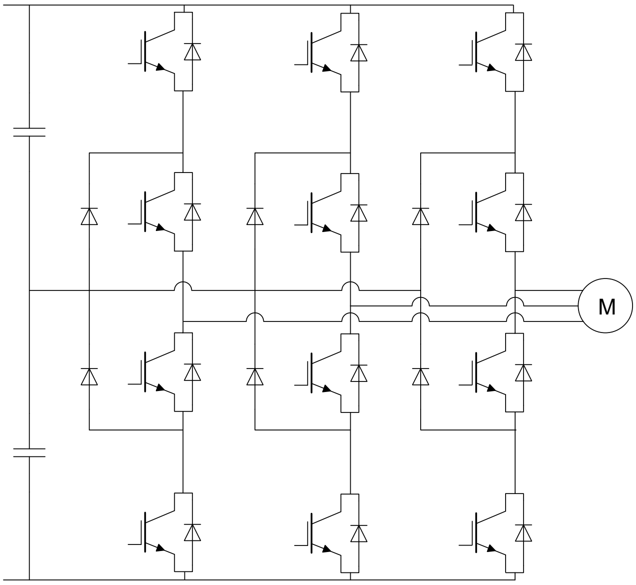

Fig. 4 IGBT-based three-level structure

Representative FACTS devices based on IGBT and other fully controlled devices include STATCOM, SSSC, and UPFC. Among them, STATCOM has significant advantages compared to traditional thyristor SVC [9]. It can continuously and quickly perform reactive power regulation, output high-quality sine wave voltage/current, theoretically with extremely low harmonic content and mainly distributed in high-order frequency bands. It is easy to filter out or significantly reduce harmonic pollution, and the equipment occupies a smaller area [9]. In the topology of STATCOM, although the two-level inverter has a simple structure, it has problems such as high harmonic content in the output waveform, high dv/dt, and large switching losses, which limit its application in high-voltage and high-capacity scenarios. In contrast, three-level topologies such as NPC and T-Type significantly improve waveform quality, reduce dv/dt and device stress, and minimize switching losses by increasing the number of output levels, making them more advantageous in higher voltage levels and high-performance applications, and becoming the mainstream choice for medium to high voltage STATCOM [10].

To meet the demand for higher voltage and power levels, multi-level topologies such as flying capacitors and cascaded H-bridges (CHBs) were widely adopted before the maturity of MMC technology, especially in the medium voltage field. The CHB structure achieves excellent waveform quality and low switching stress through modular cascading, and can be regarded as one of the predecessors of MMC. These multi-level topologies laid the foundation for the development of subsequent MMCs, making them the preferred topology for the new generation of FACTS devices with higher scalability and reliability.

4.2 Difficulties and Solutions in Circuit Design

When designing two-level and three-level topologies based on IGBT devices, the main difficulties in circuit design are as follows: high switching losses, electromagnetic interference, and fault protection. To solve these difficulties, some effective measures can be taken. Firstly, flexible commutation technology is adopted to reduce energy loss during the switching process by using resonant circuits or zero voltage/zero current switching. Secondly, by optimizing the design of the DC bus structure and arranging the power circuit reasonably, high-frequency noise radiation can be reduced to improve electromagnetic interference. Thirdly, in terms of fault protection, real-time monitoring of IGBT working status is achieved through the combination of desaturation detection hardware, and active clamp circuits are introduced to limit overvoltage, thereby improving the reliability of system operation [11].

5. Optimization of Modular Multilevel Converter (MMC) for High Voltage and High Power Applications

5.1 Advantages of MMC Topology Structure

Fig. 5 shows the structure of MMC. The MMC has demonstrated significant advantages in high-voltage and high-power applications due to its unique topology. Modular design improves the scalability of the system, MMC achieves high voltage output by cascading a large number of structurally identical submodules (SMs). Its core advantage lies in the fact that the power semiconductor devices of each submodule only need to withstand the voltage of a single submodule capacitor (much lower than the total system voltage), fundamentally avoiding the severe dynamic switching process voltage equalization problem caused by multiple devices directly connected in series in traditional two-level or three-level converters. At the same time, MMC adopts a step wave approximation sine wave output method, which can achieve high-quality output voltage waveforms at lower device switching frequencies, significantly reducing harmonic content and switching losses [12]. Through the dual advantages of flexible voltage level expansion and the ability to output high-quality waveforms, MMC has become an ideal choice for high-power scenarios such as FACTS.

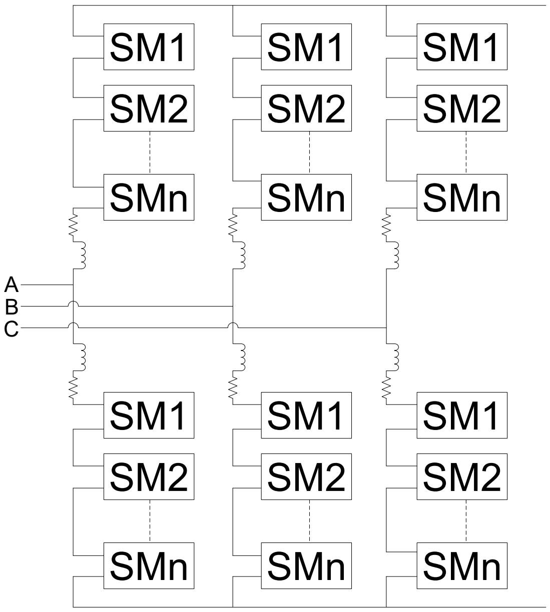

Fig. 5 Modular multilevel converter (MMC)

5.2 Evolution of Submodule Circuit Design

The submodule (SM) circuit topology design of MMC has gone through different stages of evolution. Early half-bridge submodules (HBSM) became the basic topology due to their simple structure, low cost, and low losses [13]. However, their inability to block DC fault currents prevented them from being applied in high-voltage direct current (HVDC) systems. In order to improve the fault crossing capability, two power switching devices were added to the full bridge submodule (FBSM) to achieve self-clearing of short-circuit current on the DC side. However, the doubling of the number of devices resulted in a significant increase in conduction loss and cost [12]. The clamp double submodule (CDSM) proposed thereafter innovatively adopts a diode clamp structure, which retains the low conduction loss characteristics of the half-bridge structure while introducing a small number of passive devices to achieve a DC fault locking function, achieving a better balance between loss, cost, and fault tolerance.

5.3 Design Difficulties of Core Circuit

The core circuit of MMC faces multiple technical difficulties in design. Firstly, the design of capacitor voltage balancing is difficult. Due to the large number of submodules and complex operating conditions, the dynamic imbalance of capacitor voltages can lead to harmonic distortion and uneven device stress [14]. High-precision sampling and balancing algorithms are required to achieve stable control. Secondly, the design of drive isolation faces electromagnetic interference problems in high-voltage environments, especially the cascading structure of submodules, which requires the drive signal to cross large potential differences to ensure real-time reliability during signal transmission, while avoiding common mode noise interference is a key difficulty. In addition, thermal management design is difficult, and high-frequency switching losses and conduction losses of IGBT and diode devices under high-power conditions can cause local temperature rise [15]. The dense layout of modules also limits the heat dissipation space, which puts strict requirements on the design of heat dissipation structures and cooling systems.

6. Conclusion

This article focuses on the core power electronic devices and topology evolution of FACTS, systematically reviewing the development process from semi controlled, fully controlled to modular technology, and analyzing the technological breakthroughs and core difficulties in each stage. In the early application of FACTS, semi controlled devices provided a foundation for the development of basic devices such as static var compensators (SVC) due to their high voltage resistance and high current capability. However, their turn off relies on natural commutation, which limits dynamic response. The core difficulty of system design lies in their turn off dependence on external commutation circuits and harmonic suppression. The maturity of fully controlled devices has promoted the development of higher flexibility FACTS devices, whose active turn off capability has improved response speed and control accuracy. But switch losses, electromagnetic compatibility, and reliability under high voltage stress have become new challenges. The rise of MMC has further optimized the scalability and fault tolerance of FACTS, enabling high-voltage and high-power applications through submodule cascading. However, the real-time and precise balancing control of submodule capacitor voltage, reliable isolation transmission of driving signals under high potential difference, and system thermal management under high power density constitute the core design and control challenges for MMC application in high-voltage and high-power FACTS devices.

In the future, FACTS technology will develop in three aspects. Firstly, the high-frequency and high-efficiency characteristics of wide bandgap devices will gradually replace silicon-based devices, promoting the evolution of FACTS devices towards higher power density and lower losses. Secondly, the deep involvement of artificial intelligence will optimize the real-time control and fault prediction capabilities of FACTS, adaptively adjust reactive power compensation through machine learning algorithms, and implement equipment health management based on big data. Thirdly, multi physics collaborative design will become inevitable, which integrates the interactive effects of electrical, thermal, mechanical stress and other parameters at the device, topology, and system levels, and combines digital twin technology to achieve comprehensive optimization.

In short, the continuous innovation of FACTS technology requires the joint cooperation of material science, intelligent algorithms, and system engineering to support the higher requirements of flexibility, reliability, and economy for the new power system, and to provide possibilities for the efficient operation of the power grid and the large-scale consumption of renewable energy under the dual carbon goal.

References

[1] Kumar A, Moradpour M, Losito M et al. Wide Band Gap Devices and Their Application in Power Electronics. Energies, 2022, 15(23): 9172.

[2] Utkarsh Pandey, Anshumaan Pathak, Adesh Kumar et al. Applications of artificial intelligence in power system operation, control and planning: a review. Clean Energy, 2023, 7(6): 1199–1218.

[3] T. Jing and A. S. Maklakov. A Review of Voltage Source Converters for Energy Applications. 2018 International Ural Conference on Green Energy (UralCon), 2018, 275-281.

[4] S. Sharma et al. A Comprehensive Review on STATCOM: Paradigm of Modeling, Control, Stability, Optimal Location, Integration, Application, and Installation. IEEE Access, 2024, 12: 2701-2729.

[5] L. F. W. de Souza, E. H. Watanabe and J. E. da Rocha Alves. Thyristor and Gate-Controlled Series Capacitors: A Comparison of Components Rating. IEEE Transactions on Power Delivery, 2008, 23(2): 899-906.

[6] A. Joshi, S. Jangid, N. Joshi et al. An Overview of UPFC Applications in Stability Analysis of Power System. 2024 9th International Conference on Communication and Electronics Systems (ICCES), 2024, 143-146.

[7] S. Rahmani, A. Hamadi, K. Al-Haddad et al. A Combination of Shunt Hybrid Power Filter and Thyristor-Controlled Reactor for Power Quality. IEEE Transactions on Industrial Electronics, 2014, 61(5): 2152-2164.

[8] Radomsky L, Mallwitz R. Review, Comprehensive Analysis and Derivation of Analytical Power Loss Calculation Equations for Two- to Three-Level Midpoint Clamped Inverter Topologies with Hybrid Switch Configurations. Energies, 2023, 16(18): 6710.

[9] Ban H. Alajrash, Mohamed Salem, Mahmood Swadi et al. A comprehensive review of FACTS devices in modern power systems: Addressing power quality, optimal placement, and stability with renewable energy penetration. Energy Reports, 2024, 11: 5350-5371.

[10] K. Komatsu et al. New IGBT modules for advanced neutral-point-clamped 3-level power converters. The 2010 International Power Electronics Conference - ECCE ASIA -, 2010, 523-527.

[11] L. Dulau, S. Pontarollo, A. Boimond et al. A new gate driver integrated circuit for IGBT devices with advanced protections. IEEE Transactions on Power Electronics, 2006, 21(1): 38-44.

[12] Barros LAM, Martins AP, Pinto JG. A Comprehensive Review on Modular Multilevel Converters, Submodule Topologies, and Modulation Techniques. Energies, 2022, 15(3): 1078.

[13] Soomro, Jahangir Badar, Akhtar et al. A Detailed Review of MMC Circuit Topologies and Modelling Issues. International Transactions on Electrical Energy Systems, 2022, 8734010: 17.

[14] S. Fan, L. M. Tolbert, X. Xiang et al. Submodule Voltage Balancing Methods in Modular Multilevel Converters – A Review. 2024 IEEE Energy Conversion Congress and Exposition (ECCE), 2024, 2775-2782.

[15] B. Wang et al. Thermal Performances and Annual Damages Comparison of MMC Using Reverse Conducting IGBT and Conventional IGBT Module. IEEE Transactions on Power Electronics, 2021, 36(9): 9806-9825.