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Fault Analysis and Protection Strategies for Thyristor-Based 12-Pulse HVDC Transmission Systems—A Review

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Abstract

High Voltage Direct Current (HVDC) transmission systems based on thyristor technology have become indispensable for long-distance bulk power transmission, asynchronous grid interconnection, and renewable energy integration. Among various configurations, the 12-pulse thyristor-based HVDC system is widely adopted due to its reduced harmonic distortion and improved power quality. However, fault analysis and protection coordination remain critical challenges, particularly because DC systems lack natural zero-crossing points, making fault interruption complex. This review paper comprehensively examines the fault characteristics, protection mechanisms, and coordination strategies for thyristor-based 12-pulse HVDC transmission systems. Key aspects including DC line faults, AC side faults, commutation failures, and modern protection schemes such as Voltage Dependent Current Order Limiter (VDCOL), Commutation Failure Prevention (CFPREV), and Low AC Voltage Detection (LACVD) are discussed. The review synthesizes research findings from the past decade and identifies future directions for enhancing system reliability and resilience.

Keywords—HVDC, thyristor, 12-pulse converter, fault analysis, protection coordination, commutation failure, VDCOL

I. Introduction

High Voltage Direct Current transmission systems have emerged as a preferred technology for transferring electrical power over distances exceeding 500 kilometers, where conventional alternating current systems suffer from significant reactive power losses and stability issues [1]. The thyristor-based Line Commutated Converter (LCC) HVDC systems, first commercialized in the 1950s with mercury-arc valves and revolutionized by thyristors in the 1970s, remain the backbone of modern long-distance power transmission infrastructure [2].

The 12-pulse converter configuration, consisting of two 6-pulse thyristor bridges connected in series, has become the industry standard for HVDC applications. This configuration significantly reduces harmonic distortions by canceling characteristic harmonics of orders 5, 7, 17, and 19, leaving only the 11th, 13th, 23rd, and 25th harmonics on the AC side and 12th and 24th harmonics on the DC side [3].

Despite their advantages, thyristor-based HVDC systems face critical challenges related to fault detection and protection coordination. Unlike AC systems where current naturally crosses zero 100 or 120 times per second, DC current has no zero-crossing points, making arc extinction in circuit breakers considerably more difficult [4]. Additionally, the non-linear switching characteristics of thyristors generate harmonics that can degrade power quality and complicate fault diagnosis [5].

This review paper provides a comprehensive analysis of fault types, protection mechanisms, and coordination strategies for 12-pulse thyristor-based HVDC transmission systems, synthesizing research contributions from the last decade.

II. Thyristor-Based 12-Pulse HVDC System Architecture

A typical 12-pulse thyristor-based HVDC transmission system comprises several essential components. The converter stations, located at both ends of the transmission line, employ thyristor valves arranged in 12-pulse configuration—each formed by the series connection of two 6-pulse bridges fed by phase-shifting transformers (wye and delta connections) to achieve the 30-degree phase shift necessary for harmonic cancellation [6].

The transmission medium, spanning distances that can exceed 2,000 kilometers in Ultra-High Voltage DC (UHVDC) applications, may utilize overhead lines, underground cables, or submarine cables depending on geographical and environmental constraints. Smoothing reactors of approximately 0.5 H are placed in series with the transmission line to reduce current ripple and limit the rate of current rise during fault conditions [7].

The control system manages the thyristor firing angles—typically maintaining the rectifier’s delay angle (alpha) around 15–20 degrees and the inverter’s extinction angle (gamma) around 15–18 degrees under normal operation—to regulate power flow, maintain voltage stability, and coordinate protection responses [8].

AC filters and capacitor banks provide reactive power compensation (approximately 60% of transmitted power at full load for a 30-degree firing angle) and filter characteristic harmonics. These filters include high-Q (quality factor) tuned filters for 11th and 13th harmonics and low-Q damped filters for higher-order harmonics [9].

III. Fault Types and Characteristics

A. DC Line Faults

DC line faults represent one of the most severe disturbances in HVDC systems. When a short-circuit fault occurs on the DC transmission line, the fault current rises rapidly—often reaching 2.3 per unit (pu) or higher—while the DC voltage collapses to near zero [10]. Research by Wang et al. demonstrated that traveling wave-based fault detection methods can identify DC line faults within 1–2 milliseconds by analyzing the initial voltage and current wavefronts, significantly faster than conventional overcurrent protection [11].

B. AC Side Faults

AC system faults, particularly those occurring near the inverter station, can induce 120 Hz oscillations in DC voltage and current due to the unbalanced AC conditions. These faults may lead to commutation failures—a condition where the current in an outgoing thyristor fails to transfer to the incoming valve before the commutating voltage reverses polarity [12]. Li and Zhao’s study revealed that voltage dips as low as 0.7 pu for durations exceeding 10 milliseconds can trigger commutation failures in conventional LCC HVDC systems [13].

C. Commutation Failure

Commutation failure is a unique and critical fault mode in line-commutated converters. Huang et al. classified commutation failures into three categories: transient (recovery within one cycle), sustained (multiple consecutive failures), and simultaneous (failures across multiple bridges). Their research emphasized that the extinction angle (gamma) must remain above a minimum threshold (typically 15–18 degrees) to ensure successful commutation [14].

IV. Protection Coordination Strategies

A. Voltage Dependent Current Order Limiter (VDCOL)

The VDCOL is a fundamental protection feature that reduces the current order reference when DC voltage drops below a predetermined threshold. During a DC fault causing voltage collapse to zero, the VDCOL reduces the reference current from 1.0 pu to approximately 0.3 pu within tens of milliseconds, limiting fault current magnitude and facilitating faster recovery after fault clearing [15].

B. Commutation Failure Prevention (CFPREV)

The CFPREV system actively limits the inverter’s maximum delay angle during AC faults, thereby increasing the commutation margin. Ahmed et al. demonstrated that CFPREV can prevent commutation failures for voltage dips down to 0.6 pu, whereas systems without this protection experience failures at 0.8 pu [16]. The CFPREV achieves this by dynamically adjusting the delay angle limit based on real-time measurements of AC voltage and DC current.

C. Low AC Voltage Detection (LACVD)

LACVD blocks prevent the DC fault protection from erroneously triggering during AC faults. When AC voltage falls below a specified threshold (typically 0.7–0.8 pu), the LACVD inhibits the DC protection logic, allowing the system to ride through the AC disturbance without unnecessary DC line tripping [17].

D. Self-Healing and Fault-Tolerant Designs

Recent innovations include self-healing converter designs capable of bypassing faulty thyristor modules, enabling continued operation under fault conditions without significant performance degradation. Wang et al. proposed a modular redundant architecture where individual thyristor levels can be bypassed, maintaining approximately 95% of rated capacity even with one failed module per bridge [18].

V. Harmonic Mitigation and Power Quality

Harmonics generated by thyristor switching not only degrade power quality but also complicate fault detection algorithms. Xu and Zhang proposed distributed harmonic filtering, where smaller filters deployed at multiple points along the transmission line reduce the total harmonic distortion (THD) more effectively than centralized filters [19]. Active filtering techniques, employing feedback control to adjust filter parameters dynamically, have shown particular promise for systems with variable operating conditions such as renewable energy integration [20].

VI. Future Research Directions

Several promising research avenues emerge from this review. First, the integration of artificial intelligence and machine learning algorithms into protection systems could enable predictive fault detection, identifying incipient faults before they develop into severe disturbances. Second, the development of silicon carbide (SiC) thyristors and hybrid devices combining thyristor robustness with IGBT switching speed promises faster fault response and reduced conduction losses [21]. Third, multi-terminal HVDC systems require decentralized protection coordination strategies where converter stations operate independently while maintaining overall system stability. Finally, as renewable energy penetration increases, adaptive protection schemes capable of handling bidirectional power flows and variable fault current contributions become essential.

VII. Conclusion

Thyristor-based 12-pulse HVDC transmission systems provide efficient, reliable long-distance power transmission, but fault analysis and protection coordination remain critical to their successful operation. DC line faults, AC side faults, and commutation failures each present unique challenges requiring specialized protection mechanisms. The coordinated application of VDCOL, CFPREV, LACVD, and advanced filter designs enables these systems to withstand disturbances and recover rapidly. Continued research into advanced materials, AI-based protection, and multi-terminal coordination will further enhance the resilience of HVDC systems in future power grids.

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