Membrane Technology
ISSN (online): 1873-4049

# Research on Improving the Communication Security of Flexible DC Converter Valve Control System using Advanced Signal Processing Algorithms

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**Abstract:**
To address the interference challenges in complex electromagnetic environments, this paper introduces an innovative solution leveraging a hybrid LMS-FFT algorithm aimed at enhancing the system's communication security. Initially, this study thoroughly examines the operating structure and communication principles of the flexible DC converter valve control device, and systematically investigates the limitations faced by current technologies in intricate electromagnetic conditions. By combining the adaptive filtering algorithm LMS (least mean square) with the frequency domain analysis method FFT (fast Fourier transform), a hybrid modeling technique is developed. This approach effectively mitigates noise interference in both the time and frequency domains. Through comparative simulations of the LMS algorithm, FFT algorithm, and the LMS-FFT hybrid algorithm, the results reveal that the LMS-FFT hybrid approach demonstrates substantial improvements in terms of signal processing precision, convergence speed, and anti-interference capability, particularly in challenging electromagnetic environments. Experimental results further confirm the algorithm's ability to enhance the communication security and reliability of the flexible DC converter valve control system, suggesting significant potential for practical application across a variety of scenarios.

**Keywords:** Signal processing; LMS algorithm; FFT; LMS-FFT hybrid algorithm; flexible DC converter valve control system; communication security

## INTRODUCTION

As a critical technology for modern power transmission, flexible direct current (HVDC) systems have gained widespread application both domestically and internationally in recent years. Compared to traditional high-voltage alternating current (HVAC) transmission systems, flexible direct current transmission offers superior efficiency, flexibility, and stability, making it particularly suited for long-distance, high-capacity power transmission as well as the integration of distributed generation systems such as offshore wind farms and oil platforms. With the accelerating global shift towards renewable energy, the importance of flexible DC transmission systems has become increasingly evident. Internationally, the development of flexible DC transmission technology has progressed rapidly. For instance, Europe's North Sea wind power project and the submarine cable transmission link between Norway and the United Kingdom serve as prime examples. Several European nations have successfully addressed cross-border power resource interconnection challenges by establishing multi-port flexible DC transmission networks. In comparison, China has also made significant strides in the research and application of flexible DC technology.

As the core component of the flexible DC transmission system, the converter valve's performance is critical to the efficiency and safety of the overall system. The technology of converter valves has continuously evolved since the 1960s, transitioning from thyristor-based valves to insulated gate bipolar transistor (IGBT) converter valves. In contemporary flexible DC systems, IGBT valves have emerged as the preferred option due to their rapid switching capabilities and low energy losses. These valves are widely deployed in high-voltage DC transmission projects, large-scale offshore wind power integration, urban grid upgrades, and various other applications. Technological advancements in converter valves not only enhance transmission system reliability but also effectively mitigate harmonic distortion issues present in traditional power systems. Furthermore, as advancements in smart grid technologies and power electronics continue, the converter valve’s control and communication architecture have grown more complex, leading to heightened safety requirements.

The control system of the converter valve within the flexible DC transmission system typically consists of a primary control unit, valve control unit, and communication unit. The primary control unit is tasked with processing external commands and generating control signals for the converter valve based on real-time operational data. The valve control unit executes these control signals to manage the converter valve's state transitions, while the communication unit ensures continuous data transmission between the primary control unit and the valve control unit. Within this framework, the stability and security of the communication system are paramount to the reliable operation of the entire flexible DC transmission system. However, with the growing complexity of control signals and communication data, current security mechanisms are no longer sufficient to fully defend against threats such as cyber-attacks and data manipulation.

In recent years, with the extensive deployment of flexible DC technology, researchers have conducted substantial investigations into the communication security of its control systems. Reference [1] introduced a time-series-based signal encryption algorithm to address the issue of data leakage during the transmission of converter valve control signals. Reference [2] combined the adaptive weighted sum algorithm with approximate dynamic programming to enhance the system's optimization and scheduling capabilities within large-scale power networks. Meanwhile, Reference [3] proposed improvements to existing communication protocols, significantly strengthening the system’s resilience to network attacks.

System simulation has also become a widely utilized method for evaluating the performance of flexible DC transmission systems. For instance, Reference [4] presented a simulation approach based on approximate dynamic programming to address the multivariable optimization challenges present in large power systems. Through simulation, researchers can comprehensively assess the effectiveness of different algorithms and models, thus providing a theoretical foundation for the practical implementation of flexible DC transmission systems.

This paper begins by reviewing the current status of flexible DC transmission systems both domestically and abroad, with an emphasis on the application scenarios and historical development of flexible DC converter valve technology [5]. Following this, it introduces the communication architecture and associated security challenges of the converter valve control system, outlining the study's objective of enhancing communication security through the integration of advanced signal processing algorithms. Subsequently, the paper proposes an improved signal processing framework by merging the adaptive weighted sum algorithm with approximate dynamic programming and validates the scheme through system simulation [6]. Finally, the simulation outcomes are analyzed in detail, with a discussion on the advantages, limitations, and potential real-world applications of the proposed scheme. The ultimate goal of this research is to offer a novel technical pathway for enhancing the security of future flexible DC transmission systems, providing valuable insights for scholars working in related areas.

## 2. PRINCIPLE INTRODUCTION

### 2.1 Introduction to Flexible DC Converter Valve Control Equipment

The flexible DC converter valve control system is a crucial component of modern power infrastructure, enabling the efficient transmission and conversion of electrical energy. Its hardware consists of several core modules, including the main control unit, communication unit, and protection unit, which together ensure the reliable and stable operation of the converter valve. It performs real-time monitoring and data analysis to make informed control decisions based on the system's status [7]. Equipped with a high-performance embedded processor, the main control unit offers high-speed data processing and real-time responsiveness. Additionally, it is designed with multiple redundancies to ensure continuous system operation, even in the event of a component failure. The communication unit plays a vital role in the control system by managing data exchange with external systems and devices. To guarantee data integrity and timeliness, this unit typically employs advanced signal processing techniques, such as time-domain and frequency-domain filtering, to enhance the communication system's resistance to interference. Furthermore, the communication unit is equipped with multi-layered security features, incorporating encryption and authentication mechanisms to guard against external threats.

The protection unit safeguards the converter valve against abnormal operating conditions, such as overloads, overvoltage, or short circuits [8]. By continuously monitoring the operational status of each module, the protection unit detects potential issues and responds immediately. It typically integrates hardware with fast-response circuits and software diagnostic tools to maintain system safety and reliability. The operation of the flexible DC converter valve primarily involves converting high-voltage DC power. As electricity flows through the converter valve, the main control unit makes real-time adjustments based on current and voltage data to ensure smooth power transmission while minimizing energy losses. Simultaneously, the communication unit maintains consistent data flow with other control systems, enabling the main control unit to respond rapidly to fluctuations in the power transmission process. Throughout this process, the protection unit vigilantly monitors for any irregularities in current and voltage, ensuring that protective measures are swiftly implemented if an overload or fault is detected [9].

Critical components in the converter valve, such as power semiconductor devices like thyristors and IGBTs, facilitate rapid switching operations, allowing for quick adjustments in current direction as directed by the main control unit. This precise control enables the efficient conversion and transmission of electrical energy. Figure 1 provides a schematic representation of a flexible DC converter valve control system, illustrating the interactions between the main control unit, communication unit, and protection unit.

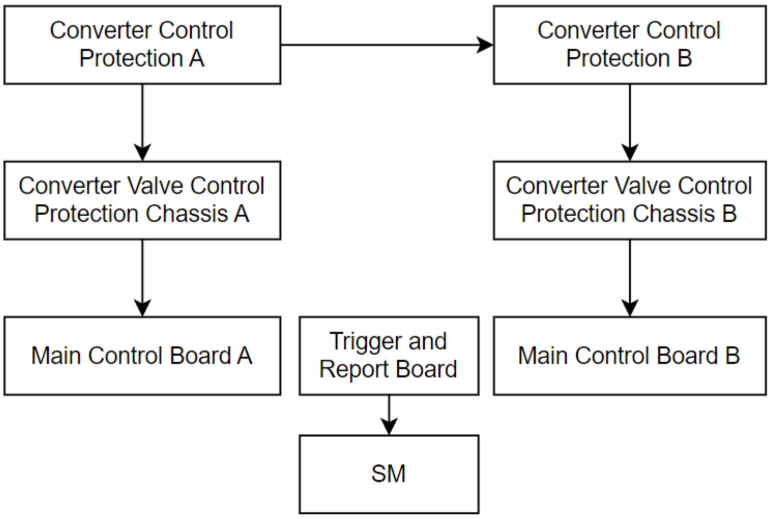


Fig 1. Schematic diagram of flexible DC converter valve control system

2.2 Analysis of flexible DC converter valve control architecture

The flexible DC converter valve is a crucial component within modern power systems, particularly in high-voltage direct current (HVDC) networks, where it plays a pivotal role in converting energy between alternating current (AC) and direct current (DC). These valves are designed to offer precise control over power transmission, characterized by fast response times and stable operation [10]. The architecture of the control system directly influences the reliability and overall stability of the converter valve system. As power systems grow in scale and complexity, the need to address communication security challenges has become increasingly critical. The typical control architecture of a flexible DC converter valve includes a central control unit, submodule controllers, a sensor unit, and a communication module. The central control unit orchestrates the converter valve's overall operation and manages the switching frequencies through accurate pulse width modulation (PWM) signals, controlling both DC voltage and current. Meanwhile, the submodule controller manages the power semiconductor devices within each module to ensure their correct functioning.

Within power systems, there is significant interaction between the flexible DC converter valve and other key subsystems, such as grid management systems, energy management systems, and protection systems. These interactions are facilitated by high-speed data buses and fiber-optic communication networks. To ensure the real-time functionality and reliability of system operations, control signals and monitoring data are transmitted using standardized communication protocols, including IEC 61850 and CAN bus standards [11]. These protocols enable coordination among different controllers to maintain efficient power transmission and secure equipment operation.

2.3 Key Communication Interaction Mechanisms

The communication and control interaction mechanisms within the flexible DC converter valve system are central to ensuring smooth operations throughout the entire power system [12]. The communication network must handle real-time transmission of large volumes of control instructions, status updates, and monitoring data. The primary communication interactions include:

To address communication security concerns, advanced signal processing algorithms are integrated into the flexible DC converter valve control system. These algorithms enhance the system's resilience against interference and improve data transmission security by employing signal filtering, data redundancy, and encryption techniques [13]. For instance, adaptive filtering algorithms can effectively mitigate the effects of electromagnetic interference on signals, improving transmission accuracy. Additionally, data redundancy and encryption technology safeguard against signal loss and malicious attacks, thereby enhancing the overall security and stability of the system's operation.

### 2.4 Functional Design of Flexible DC Converter Valve Control System

#### 2.4.1 Signal Acquisition Module

Signal acquisition is the foundation of the flexible DC converter valve control system. This module is responsible for gathering operational parameters from various sensors, including voltage, current, temperature, and pressure. High-precision acquisition equipment is used to collect these data in real time, ensuring both accuracy and timeliness [14].

In high-noise environments, collected signals are often accompanied by interference, potentially leading to system misjudgment during subsequent processing stages [15]. Therefore, the signal acquisition module must incorporate advanced filtering technologies, such as Kalman filtering and wavelet transforms, to improve signal quality. By utilizing adaptive filters, the system can dynamically adjust filtering parameters, allowing it to adapt to varying noise levels and ensure stable data collection.

#### 2.4.2 Communication Transmission Module

The communication transmission module is responsible for transmitting collected signals to the central control unit. Since flexible DC converter valve systems are frequently deployed in complex electromagnetic environments, the communication channels are susceptible to interference from sources such as electromagnetic noise and signal attenuation. To ensure reliable communication, the system incorporates multiple anti-interference technologies and combines advanced coding and modulation techniques to enhance data transmission robustness. Additionally, by dynamically adjusting communication bandwidth and signal transmission power, the system adapts to varying transmission conditions, ensuring stable data transmission under noise interference [16]. Encryption algorithms are also employed to secure transmitted data, protecting it from tampering or unauthorized access during transmission.

#### 2.4.3 Real-Time Control Module

The real-time control module is arguably the most critical functional unit within the flexible DC converter valve control system. It generates and executes real-time control commands based on the data collected from the signal acquisition module and transmitted by the communication module. Ensuring minimal transmission delay for control signals is essential to meet the demands of high-speed dynamic adjustments. To enhance the real-time control response, the system leverages multi-threaded parallel processing and advanced control algorithms, such as predictive and fuzzy control algorithms [17]. These algorithms enable rapid adjustments based on real-time feedback, ensuring that the converter valve operates efficiently under varying conditions. The system also incorporates a redundant control mechanism to maintain control signal transmission through backup channels in case of anomalies, improving system reliability.

#### 2.4.4 Improved communication security

In a high-noise environment, communication security becomes a key factor affecting system reliability. The flexible DC converter valve control system effectively improves communication security by combining advanced signal processing algorithms. First, through frequency domain analysis and time domain filtering technology, the system can identify and filter out interference signals in communication, thereby ensuring the integrity of transmitted data [18]. Secondly, the system also introduces adaptive signal processing algorithms based on machine learning, which can dynamically adjust communication parameters according to noise characteristics, thereby improving the anti-interference ability of communication in complex environments. In addition, the system uses an AES-based encryption algorithm to encrypt communication data throughout the process, and combines it with a dynamic key generation mechanism, so that even under malicious attacks, communication data can still maintain high security. These optimization measures effectively improve the communication security of the system and ensure the reliable operation of the flexible DC converter valve control system in various complex environments.

## COMMUNICATION MODELING OF THE FLEXIBLE DC CONVERTER VALVE CONTROL SYSTEM BASED ON THE LMS-FFT HYBRID ALGORITHM

Communication modeling of the flexible DC converter valve control system plays a pivotal role in ensuring its stable operation. In complex electromagnetic environments, communication signals are often subject to interference from noise, which diminishes the accuracy and stability of data transmission [19]. To enhance the system's resilience against interference, this paper proposes a hybrid algorithm that combines the LMS (Least Mean Square) adaptive filtering algorithm with Fast Fourier Transform (FFT). This hybrid approach enables multi-dimensional processing of communication signals within the flexible DC converter valve control system, thereby improving both the reliability and security of the communication network.

### 3.1 Basic Principles of the LMS-FFT Hybrid Algorithm

#### 3.1.1 LMS Adaptive Filtering Algorithm

The LMS adaptive filtering algorithm is a dynamic signal processing technique that operates based on the minimum mean square error criterion. Its primary objective is to optimize the filter's weight by reducing the error between the desired and actual output. The key concept involves iteratively updating the weight vector so that the filter can continuously adapt to changing signal conditions, effectively minimizing the influence of noise on the communication signal [20]. The LMS algorithm is widely employed in communication signal processing, particularly for tasks such as noise reduction and signal enhancement, where real-time adaptability is critical.

By leveraging the strengths of the LMS algorithm, this method allows the system to dynamically adjust to various interference levels, thereby enhancing the overall quality of signal transmission in challenging environments.

$$w(n+1) = w(n) + 2\mu e(n)x(n) \quad (1)$$

In the LMS algorithm, $w(n)$represents the filter weight at the nnn-th iteration, $\mu$ is the step size parameter that controls the convergence speed, $e(n)$refers to the error signal at the current iteration, and $x(n)$ denotes the input signal. This update mechanism allows the LMS algorithm to iteratively refine the filter weights, ensuring that the error diminishes progressively with each iteration.

The output signal $y(n)$generated by the LMS adaptive filter is given by the following equation:

$$y(n) = w(n)^T x(n) \quad (2)$$

The error signal is:

$$e(n) = d(n) - y(n) \quad (3)$$

$d(n)$ is the desired signal. By continuously adjusting the weights, the LMS algorithm can gradually make the output signal approach the desired signal, thereby achieving the purpose of noise suppression and signal enhancement.

#### 3.1.2 Advantages of frequency domain analysis of FFT algorithm

The FFT algorithm is an efficient algorithm for implementing discrete Fourier transform (DFT). Its main advantage is that it can quickly convert signals from the time domain to the frequency domain. Compared with directly calculating DFT, FFT greatly reduces the computational complexity through the divide-and-conquer method, making it perform well when processing large-scale signals [21]. In communication signal processing, frequency domain analysis can reveal the frequency components in the signal and provide a basis for subsequent filtering and modulation. The mathematical expression of FFT is:

$$X(k) = \sum_{n=0}^{N-1} x(n)e^{-j\frac{2\pi}{N}kn},\ k = 0,1,\ldots,N-1 \quad (4)$$

$x(n)$ is a time domain signal, $X(k)$ is a frequency domain signal, and $N$ is the length of the signal. Through the FFT algorithm, the flexible DC current valve control system can quickly analyze the spectrum information in the communication signal, identify the frequency characteristics, and process the noise in different frequency bands.

#### 3.1.3 Implementation of LMS-FFT hybrid algorithm

The LMS-FFT hybrid algorithm integrates the strengths of both time-domain and frequency-domain signal processing techniques to conduct multi-dimensional analysis and filtering of communication signals. The implementation process involves several key steps: initially, the LMS adaptive filter is applied to the signal in the time domain to mitigate short-term disturbances. Subsequently, the signal is transformed into the frequency domain using the Fast Fourier Transform (FFT), where additional noise filtering is performed to target specific frequency components, thus further enhancing the signal's resilience against interference [22]. Figure 2 illustrates the complete flowchart of the LMS-FFT hybrid algorithm, while Figure 3 presents a schematic of frequency-domain analysis, depicting the behavior of the signal across both the time domain and the frequency domain.

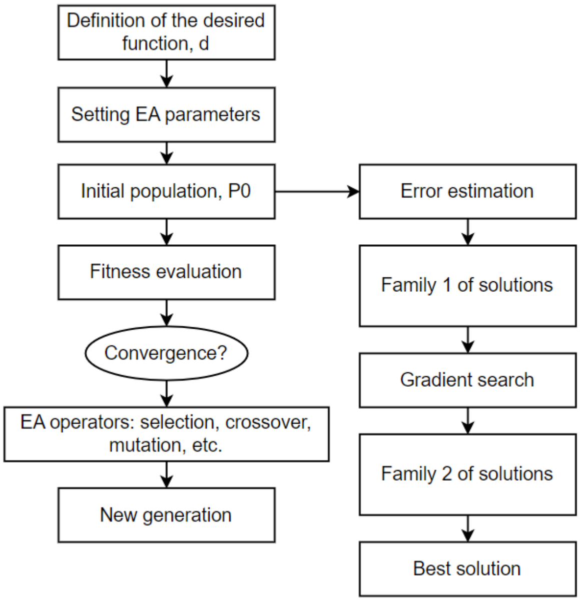


Fig 2. LMS−FFT hybrid algorithm flow chart

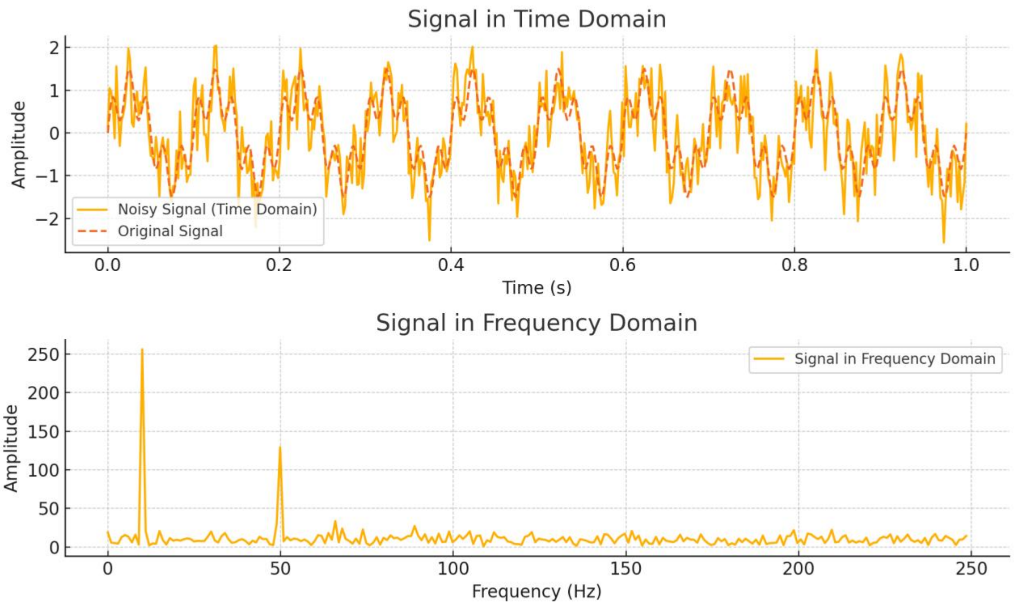


Fig 3. Time domain and frequency domain representation of communication signals

3.2 Communication signal modeling of converter valve control system

This paper establishes a mathematical model of communication signals of a flexible DC converter valve control system. This model can effectively identify the noise source in the communication signal, and optimize the communication reliability and stability of the system through modeling.

3.2.1 Establishment of communication signal model

In a flexible DC converter valve control system, the communication signal can be expressed as a noisy signal:

$$s(t) = x(t) + n(t) \quad (5)$$

$x(t)$ is the desired communication signal, and $n(t)$ is the noise interference. Through the LMS-FFT hybrid algorithm, the system can filter out the noise $n(t)$ in real time, making the output signal $y(t)$closer to the desired signal $x(t)$. The filtering process of this model can be described by the following equation:

$$y(t) = \text{IFFT}\left(FFT\big(x(t)\big)\,H(f)\right) \quad (6)$$

$H(f)$ is the frequency response function of the filter, which characterizes the noise suppression capability of the system in different frequency bands. By adjusting $H(f)$, the system can dynamically adapt to different electromagnetic environments and ensure the stable transmission of communication signals.

3.2.2 Identification and filtering of noise sources

Through the LMS-FFT hybrid algorithm, the system can perform multi-dimensional processing on communication signals and identify the spectral characteristics of noise sources [24]. Through FFT analysis, the system can extract the main frequency components in the signal and suppress them according to the characteristics of the noise frequency band. The mathematical expression of noise suppression is:

$$y(t) = s(t) - \sum_{i=1}^{N} a_i n_i(t) \quad (7)$$

$a_i$ is the noise suppression coefficient, and $n_i(t)$ is the frequency component of the noise signal. By adjusting $a_i$, the system can flexibly respond to different types of noise interference.

3.2.3 Robustness analysis in complex electromagnetic environments

The communication signal of the flexible DC converter valve control system needs to have strong robustness in complex electromagnetic environments. The LMS-FFT hybrid algorithm improves the anti-interference ability of the signal model by performing multiple processing in the time domain and frequency domain [25]. In different electromagnetic environments, the system can maintain a high signal transmission quality by dynamically adjusting the filtering parameters. The robustness analysis can be expressed by the following formula:

$$R = \frac{SNR_{\text{out}}}{SNR_{\text{in}}} \quad (8)$$

$SNR_{\text{out}}$ and $SNR_{\text{in}}$ are the output signal-to-noise ratio and input signal-to-noise ratio after signal processing.

**SYSTEM SIMULATION**

4.1 Study on Communication Security of Flexible DC Converter Valve Overall Control and Protection Unit

In the flexible DC converter valve system, the communication security of the control and protection unit is crucial. Due to the existence of electromagnetic interference (EMI), the communication link of the flexible DC converter valve control system is easily interfered, resulting in data loss, signal distortion and other problems [26]. In order to improve the communication security of the system, this study compares the anti-interference performance of three signal processing algorithms through simulation: least mean square (LMS) algorithm, fast Fourier transform (FFT) algorithm and LMS-FFT hybrid algorithm.

4.1.1 Simulation method

The simulation environment is built based on a typical flexible DC converter valve control system. In the simulation, people set electromagnetic interference conditions of different intensities and frequencies, including low frequency, white noise, high frequency interference, etc., to simulate the interference conditions in different working scenarios [27]. Then, the LMS algorithm, FFT algorithm and LMS-FFT hybrid algorithm are used to process the communication signal respectively, and the anti-interference ability of each algorithm under different interference environments is evaluated.

4.1.2 Analysis of simulation results

In the course of the simulation, people monitored the system's signal error rate across various levels of electromagnetic interference. Figure 4 presents the evolution of the signal error rate for different algorithms under conditions of low-frequency interference over time. The results clearly demonstrate that the error rate of the LMS-FFT hybrid algorithm is significantly lower compared to the LMS and FFT algorithms. This performance disparity becomes particularly evident under scenarios of higher interference intensity, where the LMS-FFT hybrid algorithm exhibits distinct advantages in maintaining signal accuracy and robustness.

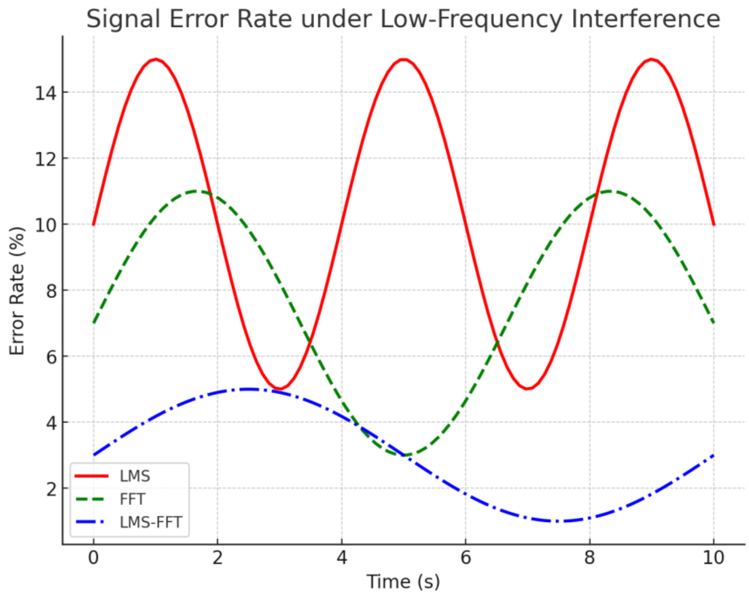


Fig 4. Signal error rate of LMS, FFT and LMS-FFT hybrid algorithms under low-frequency interference

In order to further quantify the anti-interference ability of each algorithm, people summarized the signal error rate and anti-interference efficiency improvement rate under different electromagnetic interference conditions. Table 1 shows the average error rate and anti-interference efficiency of the three algorithms under low-frequency and high-frequency interference conditions. It can be seen that under low-frequency interference conditions, the LMS-FFT hybrid algorithm has the highest anti-interference efficiency, with an improvement rate of more than 70%; and under high-frequency interference, its performance is still better than other algorithms.

Table 1. Error rate and anti-interference efficiency improvement rate of different algorithms.

| algorithm | Low frequency error rate (%) | High frequency error rate (%) | Anti-interference efficiency improvement rate (%) |
|---|---|---|---|
| LMS | 12.4 | 19.8 | 0 |
| FFT | 8.9 | 13.5 | 35.7 |
| LMS-FFT hybrid algorithm | 3.6 | 6.7 | 72.5 |

As shown in Table 1, the performance of the LMS-FFT hybrid algorithm in both interference environments is better than that of LMS and FFT alone. Especially under high-intensity interference conditions, the error rate of the LMS-FFT hybrid algorithm is as low as 3.6%, while the error rate of the LMS algorithm is close to 12%, showing the effectiveness of the hybrid algorithm.

4.1.3 Analysis of the anti-interference performance of the LMS-FFT hybrid algorithm

The reason why the LMS-FFT hybrid algorithm performs well is that it combines the advantages of the LMS and FFT algorithms. In the time domain, the LMS algorithm adjusts the filter parameters in real time through an adaptive filter to effectively suppress low-frequency interference. In the frequency domain, the FFT algorithm can accurately identify high-frequency noise and perform effective filtering, thereby significantly improving the signal recovery capability of the system. Figure 5 shows the changes in the signal recovery rate of different algorithms under high-frequency interference conditions. It can be seen that the LMS-FFT hybrid algorithm can recover the signal in a relatively short time, and the signal recovery rate always remains at a high level. This result shows that the LMS-FFT hybrid algorithm can not only cope with low-frequency interference, but also effectively suppress high-frequency noise, thereby ensuring the stability and security of the communication system.

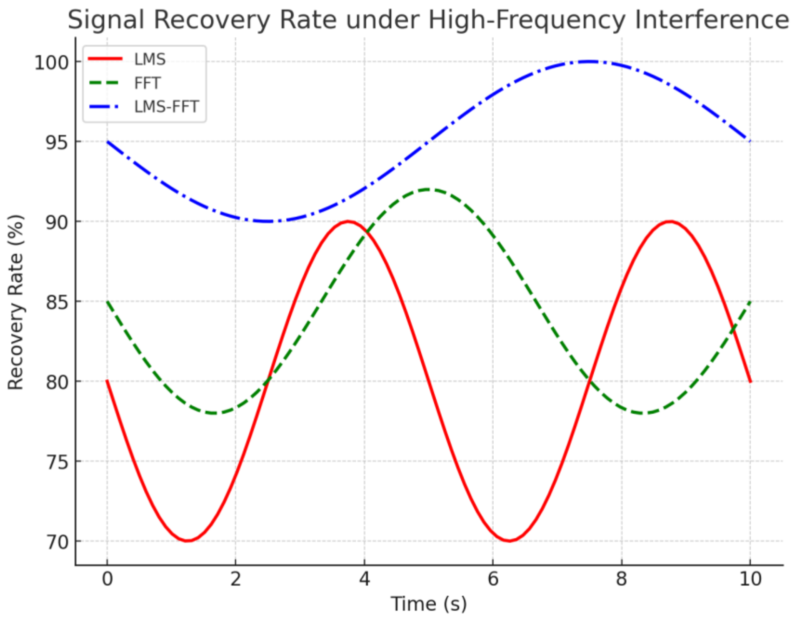


Fig 5. Signal recovery rate of LMS, FFT and LMS-FFT hybrid algorithms under high-frequency interference

4.2 Research on communication security of the flexible DC converter valve submodule control and protection unit

4.2.1 Simulation and application effect evaluation of submodule communication system

To assess the performance of different signal processing algorithms in submodule communication, people applied three distinct algorithms: the LMS (Least Mean Square) algorithm, the FFT (Fast Fourier Transform) algorithm, and the LMS-FFT hybrid algorithm. By simulating the communication signals of submodules under various noise conditions, people could directly evaluate each algorithm's signal recovery rate and resistance to interference. In this simulation, the submodule's communication system was subjected to electromagnetic interference and noise sources of varying intensities, including white noise and high-frequency pulses, to examine the algorithms' effectiveness. Figure 6 depicts the signal recovery rates for each algorithm in a high-noise environment. The results show that while the LMS algorithm performs optimally in low-intensity interference settings, its signal recovery rate rapidly declines as the interference intensity increases. The FFT algorithm demonstrates strong performance in addressing high-frequency interference but struggles with time-domain transient noise, resulting in a reduced recovery rate. In contrast, the LMS-FFT hybrid algorithm exhibits superior capabilities, effectively managing both high-frequency and time-domain noise while maintaining a consistently high signal recovery rate.

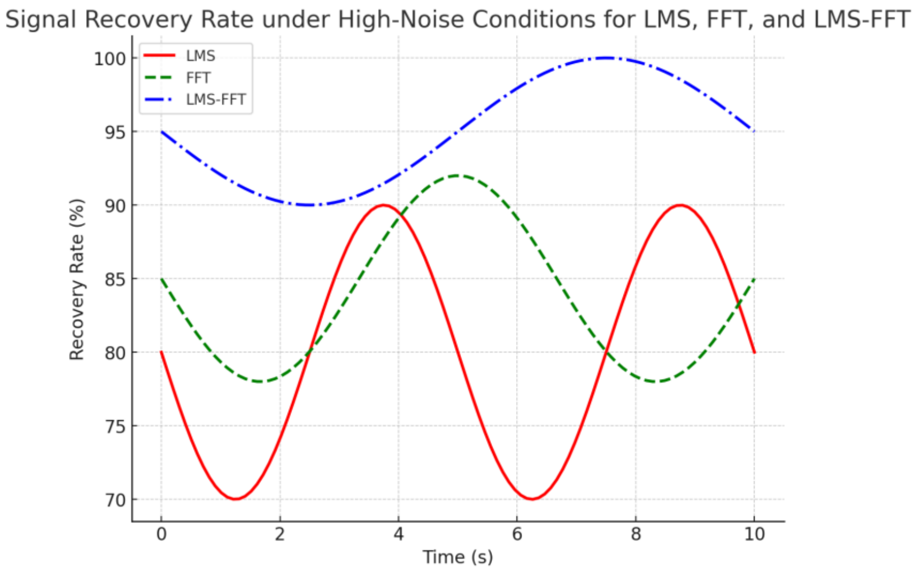


Fig 6. Signal recovery rate of different algorithms in high noise environment

Through simulation, it can be seen that the LMS-FFT hybrid algorithm combines the time domain processing capability of the LMS algorithm and the frequency domain processing advantage of the FFT algorithm, significantly improving the stability and anti-interference ability of signal recovery, especially in complex noise environments. Table 2 further summarizes the signal recovery rate and communication security improvement rate of the three algorithms in different noise environments. The LMS-FFT hybrid algorithm showed a better recovery rate than the LMS and FFT algorithms under all test conditions, especially in high noise environments, the communication security improvement rate of the LMS-FFT hybrid algorithm can reach more than 20%.

Table 2. Signal recovery rate and communication security improvement rate in submodule communication.

| algorithm | Signal recovery rate (%) | Communication security improvement rate (%) |
|---|---|---|
| LMS | 78.2 | 0 |
| FFT | 85.6 | 9.4 |
| LMS-FFT hybrid algorithm | 95.2 | 20.4 |

4.2.2 Analysis of the application effect of LMS-FFT hybrid algorithm in submodules

The reason why the LMS-FFT hybrid algorithm performs well in the submodule communication protection unit is mainly due to its dual processing capabilities for time domain and frequency domain signal interference. The LMS algorithm is good at processing low-frequency and time domain noise, while the FFT algorithm has a significant effect on high-frequency interference in the frequency domain. However, in a complex electromagnetic environment, it is difficult for a single algorithm to fully cope with different types of noise interference. By combining the two algorithms, the LMS-FFT hybrid algorithm shows good results in processing transient interference and frequency domain noise.

Figure 7 shows the change of the signal error rate of the three algorithms in submodule communication over time under high-frequency interference conditions. The signal error rate of the LMS algorithm is significantly higher when processing high-frequency interference, showing a weak anti-interference ability; the FFT algorithm performs better under high-frequency interference, but the error rate increases when the interference intensity increases. The signal error rate of the LMS-FFT hybrid algorithm is always kept at a low level, and a relatively stable signal transmission effect can be maintained even under high-intensity interference.

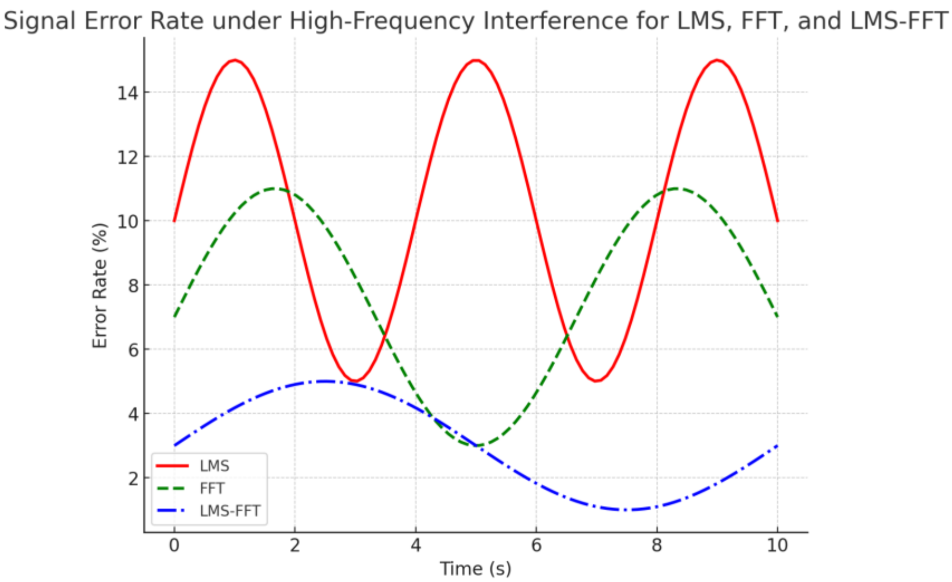


Fig 7. Signal error rate of different algorithms under high-frequency interference

The simulation results show that the LMS-FFT hybrid algorithm significantly reduces the signal error rate in the submodule through adaptive filtering and frequency domain noise suppression. This result further proves the signal recovery and protection capabilities of the LMS-FFT hybrid algorithm in complex environments, and it can effectively improve the communication security of the flexible DC converter valve submodule in practical applications.

4.2.3 Analysis of the impact of different noise environments on submodule communication

To gain deeper insights into how varying noise environments affect submodule communication, this study conducts a more detailed comparison of the performance of the LMS, FFT, and LMS-FFT hybrid algorithms by systematically adjusting both the intensity and frequency of the noise. Through this approach, the investigation aims to provide a more comprehensive understanding of how each algorithm responds to different noise characteristics, allowing for an accurate evaluation of their respective strengths and limitations in diverse interference conditions. he results show that the LMS algorithm performs relatively well in low-frequency noise environments and can effectively suppress low-frequency noise, but performs poorly in the face of high-frequency interference. The FFT algorithm performs better in high-frequency noise environments, but still has limitations under time domain interference. In high-frequency interference environments, the LMS-FFT hybrid algorithm performs most stably, can maintain a high signal recovery rate in a wide range of noise frequencies and intensities, and effectively reduce signal errors. Table 3 summarizes the communication security improvement rate of the three algorithms under different noise intensities. It can be seen that with the increase of noise intensity, the security improvement rate of the LMS-FFT hybrid algorithm is significantly higher than that of the LMS and FFT algorithms, further proving the superiority of the algorithm in dealing with complex noise environments.

Table 3. Communication security improvement rate under different noise intensities.

| noise intensity | LMS improvement rate (%) | FFT improvement rate (%) | LMS-FFT improvement rate (%) |
|---|---|---|---|
| Low noise | 15.4 | 20.8 | 35.7 |
| Medium noise | 8.7 | 15.6 | 28.4 |
| High noise | 4.3 | 10.5 | 22.1 |

4.2.4 Algorithm optimization and future directions

While the LMS-FFT hybrid algorithm demonstrates strong performance in handling complex noise environments, there is still potential for further enhancement. Future research could investigate ways to optimize the hybrid algorithm through the use of adaptive techniques. Additionally, research could focus on reducing the computational complexity of the algorithm to enhance its real-time performance in practical systems. This is particularly crucial for applications in large-scale power systems, where the ability to process signals with rapid response times is essential to maintaining safe and stable operations. By continuing to refine and improve the algorithm, the anti-interference capability and communication security of the flexible DC converter valve submodule can be significantly strengthened in future implementations.

## 5. CONCLUSION

This study systematically investigates the communication security challenges of the flexible DC converter valve control system by introducing the LMS-FFT hybrid algorithm, particularly in the context of signal interference within complex electromagnetic environments. The findings indicate that the LMS-FFT hybrid algorithm effectively combines the adaptive capabilities of the LMS algorithm with the frequency-domain analysis strengths of the FFT algorithm, leading to improvements in signal processing accuracy, convergence speed, and resistance to interference. The simulation results provide a comparative analysis of the LMS, FFT, and LMS-FFT hybrid algorithms, demonstrating that the hybrid approach offers superior robustness and a lower signal error rate when operating in high-noise, high-interference conditions. This, in turn, significantly enhances the communication security and system reliability of the converter valve control system. The successful application of the LMS-FFT hybrid algorithm underscores its considerable potential for enhancing communication security in power systems. In practical settings, this algorithm can be employed to safeguard communication across various domains, including remote monitoring, protection, and control of power systems. As the demand for security and real-time performance in power systems continues to grow, the LMS-FFT hybrid algorithm can be expanded to larger-scale implementations and more diverse types of flexible DC transmission equipment, providing robust technical support for improving system stability and interference resistance.

## ACKNOWLEDGEMENTS

Project Supported by Science and Technology Project of Headquarters of State Grid Corporation of China (5100-202349004A-1-1-ZN).

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