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Research on Reliability Enhancement Strategy of Flexible DC Converter Valve Based on Advanced Algorithms

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Abstract:
This study is focused on enhancing the communication security of the flexible DC converter valve control system and boosting the overall system's reliability by incorporating a sophisticated adaptive filtering algorithm. Initially, the paper provides an in-depth analysis of the operational structure of the flexible DC converter valve, emphasizing its pivotal role in power transmission and addressing the communication difficulties encountered in complex electromagnetic environments. Building on the strengths of the adaptive filtering algorithm, a mathematical framework for signal processing is developed, effectively mitigating noise disturbances in communications and elevating signal integrity. Furthermore, a standardized control system design for the flexible DC converter valve is implemented, ensuring optimal compatibility in the selection of key components and the design of sub-module boards. By conducting system simulations and sub-module testing, the study thoroughly assesses the communication system's performance under various electromagnetic interference conditions, supplying precise experimental data to validate the robustness and interference resistance of the adaptive filtering algorithm. The findings indicate that the algorithm significantly enhances communication security, providing a solid technical foundation for securing communications in future flexible DC transmission systems.

Keywords: Adaptive filtering algorithm; signal processing; Flexible DC converter valve control system; Communication; Electromagnetic compatibility; Reliability; Anti-interference ability.

INTRODUCTION

Flexible direct current (HVDC) technology has emerged as an efficient and reliable method for power transmission, and in recent years, it has gained extensive application in power systems worldwide. Compared to conventional AC transmission systems, flexible DC transmission offers several advantages, including high transmission capacity, low energy loss, and enhanced regulation capabilities. These benefits make it indispensable for long-distance, large-capacity power transmission and integrating renewable energy sources. A crucial component of the flexible DC transmission system is the converter valve, and the security of its control system's communication is fundamental to ensuring the system's overall stability and reliability.

In contemporary power transmission, flexible DC transmission systems play a vital role. Not only do they enable large-scale, long-distance power transfers, but they also effectively manage the scheduling challenges posed by power fluctuations. As global demand for clean energy increases, flexible DC transmission has become a key enabler of integrating renewable energy sources such as wind and solar power. Particularly in applications that demand stable cross-regional power transmission and urban grid reliability, flexible DC transmission systems have demonstrated significant potential. Enhancing the stability and security of these systems, particularly regarding the communication security of the converter valve control system, is a pressing issue that requires immediate attention.

The flexible DC transmission system relies on real-time data exchange between the converter valve control system and other devices within a complex communication network. The security and stability of these communication channels are directly linked to the reliability of the power transmission system. However, the power environment is rife with electromagnetic interference (EMI), which presents a major challenge to maintaining the stability of communication. EMI can lead to data signal distortion or loss, and in some cases, may even cause system malfunctions, ultimately compromising the normal functioning of the power grid. Furthermore, as cyber-attacks become increasingly prevalent, the communication security of the flexible DC converter valve control system faces growing threats. Cyber attackers can disrupt the converter valve's operation by hijacking data packets or altering control commands, among other tactics. Thus, developing effective strategies to mitigate EMI and bolster data transmission security has become paramount to ensuring the uninterrupted operation of flexible DC transmission systems.

Numerous researchers have undertaken in-depth investigations into the communication security challenges posed by flexible DC transmission systems. In Reference [1], a signal processing method based on linear prediction algorithms was introduced to mitigate the impact of high-frequency electromagnetic interference on converter valve control signals. This approach enhanced signal integrity and improved the system's response speed by filtering out noise. However, this study did not sufficiently address signal transmission challenges under low-frequency interference conditions. In Reference [2], the authors proposed a solution that combines encryption techniques with anti-interference measures, effectively boosting data transmission security and mitigating the risk of data theft or manipulation in electromagnetically complex environments. Yet, this solution exhibited limitations in its anti-interference capability, particularly when confronted with high-intensity electromagnetic pulse (EMP) interference, where communication quality noticeably degraded.

Further research, as seen in Reference [3], introduced an adaptive filtering-based signal processing model tailored to flexible DC converter valve control systems. This model dynamically adjusted filtering parameters, effectively addressing the limitations of traditional filtering methods in managing variable environmental conditions. However, the study did not fully integrate approximate dynamic programming algorithms, resulting in suboptimal real-time response capabilities for the system. In recent years, the combination of approximate dynamic programming and adaptive weighted sum algorithms has garnered significant attention. Reference [4] presented a model integrating adaptive weighted sum algorithms with dynamic programming to solve optimization problems in complex dynamic environments. The algorithm’s adaptive weight adjustment demonstrated excellent anti-interference capabilities, even under high uncertainty. Additionally, Reference [5] explored the application of adaptive dynamic programming in flexible DC transmission systems, proving that the algorithm enhances communication reliability under challenging environmental conditions.

Despite the progress made, existing communication security approaches struggle to simultaneously address electromagnetic interference and cyber-attacks effectively. In response to this, the present paper proposes a solution based on an adaptive filtering algorithm to optimize signal processing, thereby improving data transmission stability and security in complex environments [6]. The adaptive filtering algorithm autonomously adjusts its parameters according to changes in the communication environment, effectively suppressing the adverse effects of electromagnetic interference on signal transmission. Coupled with encryption technologies, this method also enhances the confidentiality and integrity of data during communication. The primary objective of this research is to refine the current flexible DC converter valve control system by introducing an approximate dynamic programming model that incorporates an adaptive weighted sum algorithm. This model aims to improve the system's resistance to interference in electromagnetically complex environments and strengthen data transmission security [7]. The research will focus on optimizing the filtering algorithm’s adaptability, enhancing the system's real-time response to EMI, and ultimately improving the communication security of the flexible DC transmission system as a whole.

PRINCIPLE ANALYSIS PART

Introduction to the working structure and principle of the flexible DC converter valve

The key elements of the flexible DC converter valve include the power module, submodules, and the valve control system. The power module typically utilizes a modular multilevel converter (MMC) architecture, comprising several submodules, with each submodule containing a capacitor and a set of switching devices (such as IGBT or GTO). These submodules are interconnected in both series and parallel formations to facilitate efficient power conversion and regulation. The valve control system, in turn, ensures steady-state DC voltage control by modulating the switching on and off of individual submodules [8]. Through the implementation of a high-speed control algorithm, the flexible DC converter valve can dynamically adjust power flow under varying operational conditions, significantly reduce harmonic distortion, and enhance the quality of power transmission. The working mechanism of the flexible DC converter valve is based primarily on the sequential switching of its submodules to regulate DC voltage. With the use of precise pulse width modulation (PWM) techniques, the valve control system continuously adjusts the current distribution among the submodules to ensure stable power delivery. This structure achieves high power conversion efficiency and excellent dynamic response adaptability.

Nevertheless, the flexible DC converter valve is susceptible to a range of interference sources during real-world operation, including electromagnetic interference (EMI), high-frequency noise, signal degradation, network congestion, among others. Such interferences present significant challenges to the communication link stability of the valve control system, especially within complex and fluctuating power environments [9]. The communication system is prone to issues such as transient pulses, overlapping interference signals, and related phenomena, which can lead to disruptions in signal transmission, data packet loss, or transmission delays.

Introduction to key technologies for improving the reliability of flexible DC converter valves

In order to improve the reliability of flexible DC converter valves, a variety of key technologies have been introduced in the design, covering redundant design, electromagnetic compatibility design and data encryption technology.

First of all, redundant design is one of the basic means to ensure system reliability. By introducing redundant modules in key equipment and communication links, the system can automatically switch to the backup module when a module fails, thereby avoiding the occurrence of single point failures and ensuring the continuity and stability of the system. Secondly, electromagnetic compatibility design (EMC) can reduce the impact of electromagnetic interference on the communication system through effective shielding and grounding design. Such designs usually include the use of shielded cables, reasonable wiring, and grounding structure optimization to reduce the conduction and radiation of high-frequency noise [10]. Additionally, the use of filters can assist in mitigating the impact of high-frequency noise on the communication system of the converter valve. Moreover, data encryption technology, which plays a crucial role in ensuring information security, can safeguard against malicious attacks and data manipulation. In the context of power systems, encryption technologies such as AES and RSA protocols ensure the confidentiality and integrity of communication data. These protocols effectively defend against cyber-attacks and prevent data breaches, while simultaneously supporting the reliable operation of the system. The incorporation of adaptive filtering algorithms can further enhance the interference resilience of the flexible DC converter valve's communication network. These algorithms dynamically adjust filtering parameters in response to real-time environmental fluctuations, efficiently suppressing various interference sources [11]. For instance, when electromagnetic noise exhibits frequent variations, the adaptive filter can automatically tune its bandwidth and cutoff frequency based on the interference signal's time-frequency characteristics, thereby optimizing the noise reduction effect. Furthermore, advanced techniques such as time-frequency analysis and multi-resolution analysis can be integrated with adaptive filtering algorithms in signal processing. Time-frequency analysis provides joint time and frequency domain information, making it highly suitable for handling transient interference and noise. Multi-resolution analysis methods, including wavelet transforms, are capable of detecting frequency shifts in interference signals by breaking down the signal's different frequency components. When these signal processing methods are combined with adaptive filtering, the reliability and stability of the flexible DC converter valve's communication system can be significantly strengthened.

COMMUNICATION SIGNAL MODELING OF FLEXIBLE DC CONVERTER VALVE CONTROL SYSTEM BASED ON ADAPTIVE FILTERING ALGORITHM

Standardized design of valve control system of flexible DC converter valve

Within the flexible DC transmission system, the converter valve control system (VCS) functions as the central control unit, and its design plays a critical role in influencing both the communication performance and system compatibility. To enhance the system's reliability and flexibility, standardization of the valve control system is essential [12]. This section will detail the standardized design approach for the valve control system, focusing on the selection of vital components and the standardized layout of the submodule’s secondary board. Additionally, we will discuss how this approach improves the communication signal's quality and security across the system.

Firstly, the control architecture of the flexible DC converter valve is comprised of multiple modules, including the primary control unit, submodules, and communication modules. During the design phase, selecting the appropriate key components is crucial for ensuring the system's stable operation. A typical architecture of a converter valve control system is illustrated in Figure 1. By adopting a standardized design, the system allows for components from various manufacturers to be interchangeable, significantly increasing the overall compatibility of the system. Moreover, this standardized framework facilitates easier system maintenance and upgrades while reducing long-term operational and maintenance expenses.

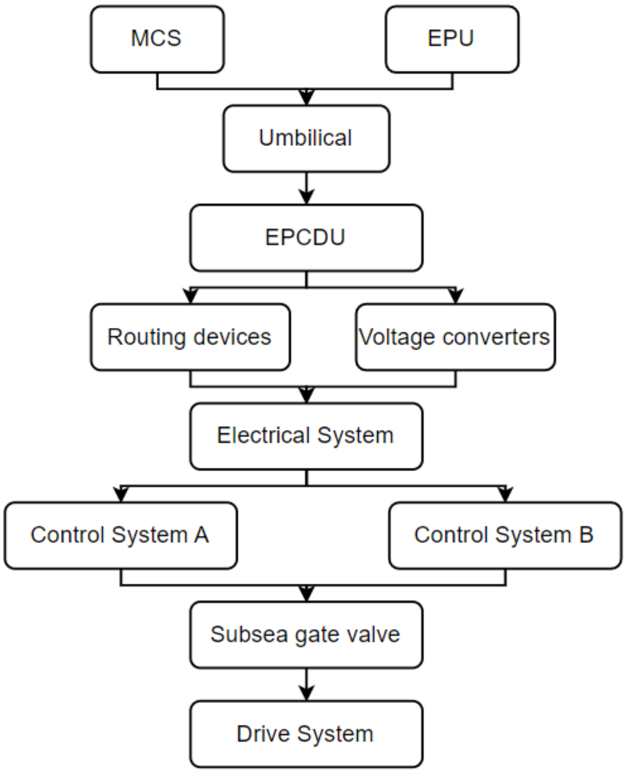

Fig.1 Converter valve control system architecture

$$C_s = \frac{dV}{dt} \cdot \frac{1}{R} \tag{1}$$

The design of the submodule's secondary board is essential in ensuring a standardized system configuration. This board typically includes several critical components, such as a signal processing unit, a communication interface, and a fault detection module [13]. To guarantee reliable communication signal transmission, the secondary board must adhere to a unified communication protocol, such as the IEC 61850 standard. This adherence not only enhances the overall communication efficiency of the system but also minimizes delays in data exchange between different modules. The standardized design of the board further facilitates the integration of advanced features, such as adaptive filtering algorithms, which significantly improve the system's signal processing capabilities. By incorporating these algorithms, the system can dynamically adjust to varying communication conditions, further optimizing the stability and quality of signal transmission in complex operational environments. Standardization also allows for easier upgrades and maintenance, ensuring the system remains flexible and scalable over time, while still maintaining high levels of performance and reliability.

$$P_{\text{comm}} = \frac{\Delta V}{\Delta t} \times Z \tag{2}$$

To further enhance the quality of communication signals, it is essential to focus on the design of the signal processing module [14]. The adaptive filtering algorithm plays a pivotal role in mitigating noise and interference by continuously modifying the filter coefficients in real time. At the hardware level, this module employs FPGA or DSP chips to execute the adaptive filtering algorithm. By leveraging these hardware platforms, it is possible to achieve real-time signal processing and effective noise reduction, thereby bolstering the overall communication security of the system. To maintain communication stability, the system dynamically fine-tunes the filter parameters, ensuring that the signal retains a high signal-to-noise ratio across various noise environments.

$$SNR = 10 \log\left(\frac{P_{\text{signal}}}{P_{\text{noise}}}\right) \tag{3}$$

The implementation of adaptive filters requires reasonable hardware support, and the hardware selection directly affects the performance of the algorithm. Through standardized design, compatibility between different hardware platforms can be ensured, thereby achieving more efficient signal processing and communication security.

$$H(f)=\frac{V_{\text{out}}(f)}{V_{\text{in}}(f)} \tag{4}$$

3.2 Application of adaptive filtering algorithm in communication signal

The adaptive filtering algorithm, which relies on real-time adjustments, is extensively utilized in signal processing. Within the communication signal processing of flexible DC converter valve control systems, this algorithm proves highly effective in suppressing noise and interference, thereby enhancing signal quality [15].

The LMS algorithm, known for its simplicity and efficiency, is a widely adopted adaptive filtering method. Its fundamental principle involves adjusting the filter weights by minimizing the mean square error. The corresponding mathematical model can be expressed as follows:

$$w(n+1)=w(n)+\mu\cdot e(n)\cdot x(n) \tag{5}$$

The variable $w(n)$ represents the weight vector of the filter, while μ denotes the learning rate. The term $e(n)$ refers to the current error, and x(n)x(n)x(n) corresponds to the input signal. By employing an iterative update process, the LMS algorithm progressively converges toward the optimal filter coefficients, enabling it to efficiently mitigate noise in the signal.

$$e(n)=d(n)-w^T(n)\cdot x(n) \tag{6}$$

The Recursive Least Squares (RLS) algorithm exhibits a greater level of complexity compared to the Least Mean Squares (LMS) algorithm; however, it demonstrates superior resilience when addressing environments with elevated noise levels. The primary objective of the RLS algorithm is to minimize the cumulative squared discrepancies for all previously acquired data points. Its corresponding mathematical formulation is:

$$P(n)=\lambda^{-1}\left(P(n-1)-\frac{P(n-1)x(n)x^T(n)P(n-1)}{\lambda+x^T(n)P(n-1)x(n)}\right) \tag{7}$$

The parameter λ represents the forgetting factor, while $P(n)$ denotes the error covariance matrix. In the Recursive Least Squares (RLS) algorithm, the filter coefficients are adapted by continuously updating both the covariance matrix and the gain vector to ensure optimal signal integrity, even in challenging noise conditions.

$$w(n)=w(n-1)+K(n)\cdot[d(n)-w^T(n-1)\cdot x(n)] \tag{8}$$

In real-world scenarios, the performance of adaptive filtering algorithms is influenced by factors such as system noise, interference sources, and the efficiency of communication protocol optimization. For instance, in environments with substantial noise interference, the signal quality may deteriorate markedly due to the overwhelming noise. Under such circumstances, the adaptive filtering algorithm can mitigate the noise's impact to some extent, enhancing signal clarity by dynamically recalibrating the filter coefficients.

$$K(n)=\frac{P(n-1)\cdot x(n)}{\lambda+x^T(n)\cdot P(n-1)\cdot x(n)} \tag{9}$$

The optimization of communication protocols is also an important factor in improving communication security. By adopting more efficient communication protocols, communication delays can be reduced and the stability of signal transmission can be enhanced [16]. On this basis, the adaptive filtering algorithm can further optimize the signal processing effect, so that the system can still operate stably in a high-noise environment. In short, the application of the adaptive filtering algorithm in the flexible DC converter valve control system greatly improves the quality and security of communication signals. By optimizing algorithm parameters, improving hardware platforms and improving communication protocols, the adaptive filtering algorithm can provide more efficient and stable signal processing solutions in complex environments.

FLEXIBLE DC CONVERTER VALVE TEST BASED ON ADAPTIVE FILTERING ALGORITHM

Submodule power cycle test

The power cycle test simulates the operating status of the submodule at different power levels for many times to examine its stability in long-term operation. In the actual operation process, the submodule will inevitably be affected by various power fluctuations, which may come from grid fluctuations, load changes or external environmental interference [17]. The power cycle test simulates these actual operating conditions by artificially setting different power loading stages, and evaluates the reliability and durability of the submodule under long-term operation through long-term testing. The design of this test includes multiple cycles of loading different power levels and collecting communication signal data at different stages of each cycle to ensure a comprehensive evaluation of the impact of power changes and communication performance.

To ensure the precision of power cycle testing outcomes, it is common practice to utilize high-accuracy sensors and data acquisition systems. These instruments enable real-time monitoring of power fluctuations during each cycle, while simultaneously capturing variations in the quality of communication signals. This is particularly critical in flexible DC transmission systems, where communication signal integrity plays a vital role in maintaining overall system stability, as the system's control and monitoring rely heavily on real-time exchanges between various submodules [18]. Any degradation of the communication signal due to noise or interference can lead to transmission errors between submodules, potentially disrupting the entire system's normal operations.

In practical power cycle testing, the application of adaptive filtering algorithms allows the system to effectively suppress noise, maintaining the clarity of the communication signal. Simulation results have demonstrated a significant improvement in signal quality following the implementation of the adaptive filtering algorithm. Figure 2 illustrates the noise reduction effect on communication signals during the power cycle test, where it is evident that noise levels have substantially decreased, and the communication signal's bit error rate has been notably reduced [19]. Additionally, Figure 3 presents the variation in bit error rate throughout the power cycle test, further corroborating the positive influence of adaptive filtering algorithms on communication signal quality through dynamic filter coefficient adjustments.

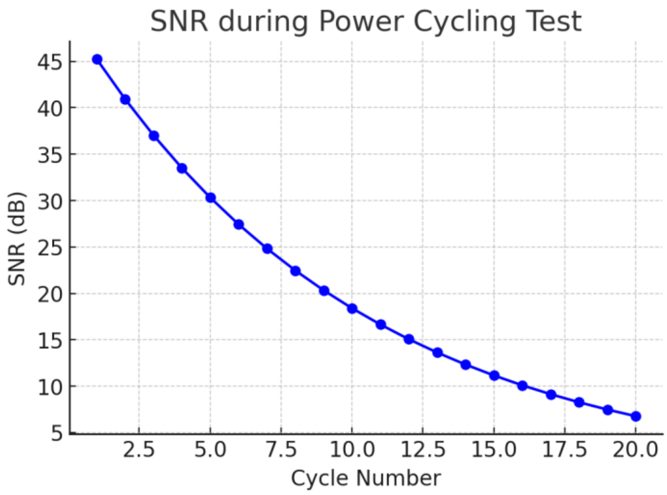

Fig.2 Communication signal noise suppression effect in power cycling test

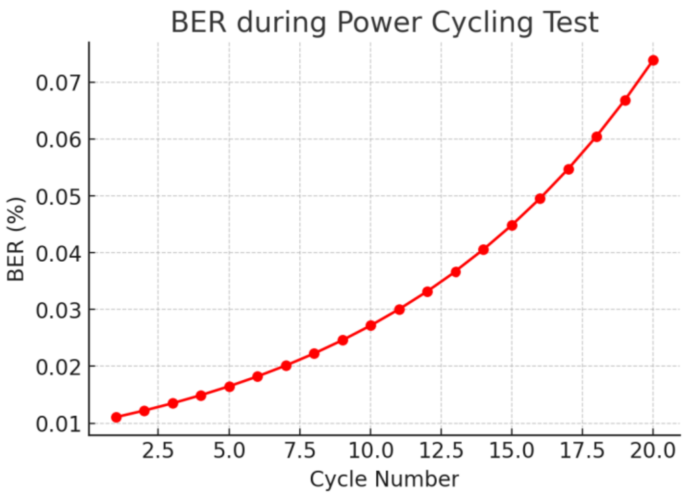

Fig.3 Communication signal bit error rate change in power cycle test

During periods of significant power fluctuations, the adaptive filtering algorithm can promptly react to the noise variations caused by changes in power, adjusting the filter coefficients in real time to effectively suppress noise. This dynamic adjustment mechanism allows the system to preserve the stability of communication signals under complex operational conditions, leading to a significant reduction in the bit error rate throughout system operation. Such capability is critical for maintaining the stable functionality of flexible DC transmission systems, as any disruption in communication may result in loss of control or system shutdown, which could severely impact the entire power network [20]. Additionally, power cycle testing assists engineers in optimizing the design of submodules, enhancing their reliability and performance in practical applications. By continuously refining the test methodologies and integrating advanced adaptive filtering algorithms, the performance of submodules within flexible DC converter valve control systems will be further enhanced, providing robust support for overall system stability.

Submodule Electromagnetic Compatibility Testing

The communication environment within flexible DC converter valve control systems is highly complex, with electromagnetic interference (EMI) being a key factor that compromises communication security. To assess the system's communication performance under various electromagnetic conditions, an electromagnetic compatibility (EMC) test is designed to simulate interference scenarios of different intensities and frequencies, enabling evaluation of the submodule's anti-interference capabilities. The EMC test framework includes laboratory-based simulations of electromagnetic disturbances across different frequency ranges, followed by an assessment of the communication signal quality in high-interference environments [21]. In practical applications, the core of the adaptive filtering algorithm lies in adjusting filter coefficients based on the minimum mean square error (MSE) criterion. The algorithm iteratively calculates errors and fine-tunes parameters in response to feedback, allowing the filter to gradually approach an optimal filtering performance. For instance, under low-intensity electromagnetic interference, the filter can maintain a reduced error coefficient, thereby avoiding excessive signal processing; conversely, when the interference intensity increases, the filter rapidly adjusts the coefficients to enhance its ability to suppress interference signals.

With the rise in electromagnetic interference intensity, the adaptive filtering algorithm effectively mitigates interference components within the communication signal (fig.4). Spectrum analysis reveals that after applying the adaptive filtering algorithm, significant improvements occur in the high-frequency signal components, which were previously heavily affected by electromagnetic interference, leading to an enhanced signal-to-noise ratio (SNR) [22]. This is particularly crucial in wireless communication systems, as they often rely on high-frequency signals, which are highly susceptible to external electromagnetic interference. Figure 5 further demonstrates the effectiveness of the adaptive filtering algorithm in reducing the bit error rate of communication signals across various interference frequencies. While the bit error rate fluctuates with changes in interference frequency, the adaptive filtering algorithm performs well across a broad frequency range, maintaining a low bit error rate in most cases. Notably, in certain critical communication frequency bands, the algorithm's suppression of bit error rates is especially prominent.

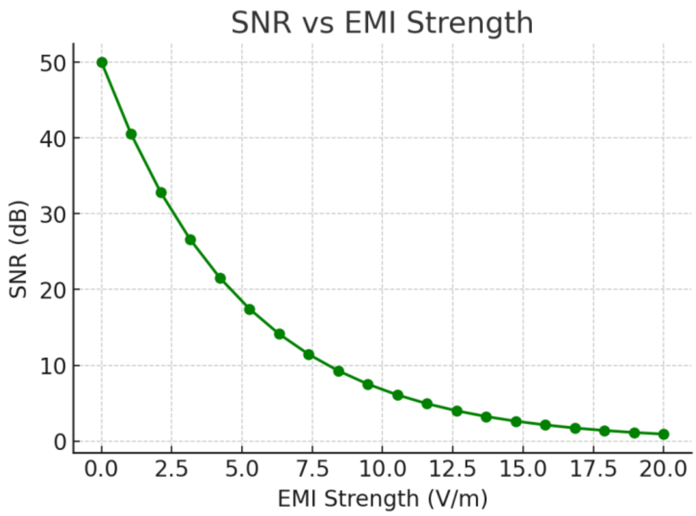

Fig.4 Signal quality under different electromagnetic interference strengths

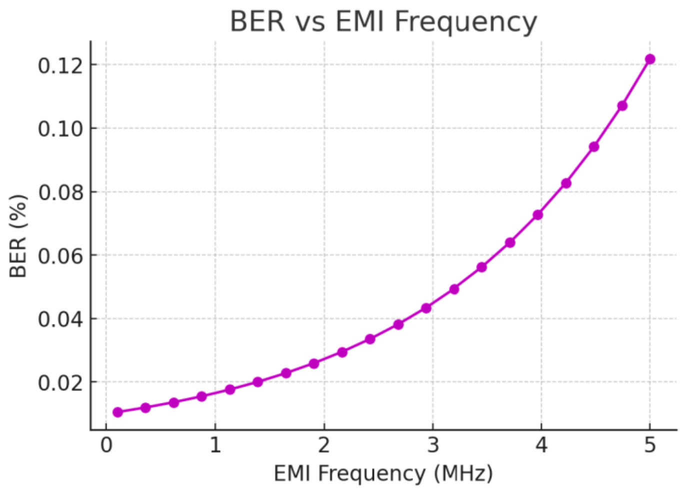

Fig.5 Effect of electromagnetic interference frequency on signal bit error rate

In environments with strong electromagnetic interference, the bit error rate of the communication system often increases dramatically. This occurs because the interference signal overlaps with the communication signal spectrum, making it challenging for the receiver to accurately interpret the transmitted data. By implementing an adaptive filtering algorithm, the communication system can effectively differentiate between interference and valid signals, thereby lowering the bit error rate and enhancing overall communication reliability [23]. Experimental findings indicate that, in the presence of high-intensity electromagnetic interference, the adaptive filtering algorithm significantly boosts the system's resilience to interference, allowing it to maintain high communication quality even in adverse electromagnetic conditions.

The signal-to-noise ratio is a crucial metric that indicates the quality of the communication signal by comparing the strength of the useful signal component to that of the noise [24]. A higher SNR corresponds to a clearer and more distinct communication signal. In contrast, the bit error rate is a measure of the accuracy of data transmission within the communication system. A lower BER signifies higher transmission reliability. In the experiments conducted, the adaptive filtering algorithm was able to sustain a high SNR and substantially decrease the bit error rate, even in environments with significant electromagnetic interference, by dynamically adjusting the filter coefficients to match the changing interference conditions.

Subsystem test and simulation

The adaptive filtering algorithm can respond to different degrees of interference in real time by adjusting parameters, greatly improving the communication quality of the system in a high noise environment [25]. The core of this algorithm is to dynamically adjust the parameters of the filter in real time to cope with changes in external interference. Compared with traditional fixed filters, adaptive filtering algorithms (such as LMS algorithm or RLS algorithm) can automatically optimize their performance in a constantly changing noise environment to ensure accurate signal transmission.

Table 1 lists the key parameters of signal processing in system simulation under different interference conditions, focusing on the changes in signal-to-noise ratio (SNR). In normal operation, the signal-to-noise ratio remains at a high level of 45 dB, which shows that the quality of the communication signal of the system is very good without external interference. Under medium and high-intensity interference conditions, the signal-to-noise ratio drops to 30 dB and 15 dB, respectively. This change directly shows the impact of electromagnetic interference and power fluctuation on signal quality [26]. Especially under high-intensity interference, the electromagnetic interference intensity reaches 20 V/m and the power fluctuation reaches 10%, which greatly reduces the stability of the system communication signal.

Table 1. Changes in signal-to-noise ratio in simulation.

simulation conditions	Signal-to-noise ratio (dB)	Electromagnetic interference intensity (V/m)	Power fluctuation (%)
Normal operation	45	0	0
Medium interference	30	10	5
High interference	15	20	10

To further quantify the performance of communication signals under different interference conditions, Table 2 shows the change in bit error rate. It can be seen that in normal operation, the bit error rate is only 0.01%, indicating that the system communication is stable and reliable. However, under medium and high intensity interference conditions, the bit error rate rises to 0.05% and 0.1%, respectively [27]. This shows that with the increase of interference, the probability of data transmission errors increases significantly, and the increase in power fluctuations and electromagnetic interference frequency are the main reasons for the increase in bit error rate. Under high-intensity interference, the electromagnetic interference frequency reaches 5 MHz, the power fluctuation reaches 10%, and the stability of system communication decreases significantly.

Table 2. Bit error rate changes in simulation.

simulation conditions	Bit error rate (%)	Electromagnetic interference frequency (MHz)	Power fluctuation (%)
Normal operation	0.01	0.1	0
Medium interference	0.05	1	5
High interference	0.1	5	10

The simulation results demonstrate that the adaptive filtering algorithm exhibits outstanding performance across various electromagnetic environments, significantly enhancing the signal-to-noise ratio and reducing the bit error rate. This, in turn, contributes to a substantial improvement in the security and reliability of the communication system. Figures 6 and 7 provide a visual representation of the signal quality and the bit error rate variation trend when the adaptive filtering algorithm is applied in a complex electromagnetic environment [28]. Although the quality of the communication signal is affected under conditions of high-intensity interference, the adaptive filtering algorithm is able to promptly react to external disturbances by dynamically adjusting the filter parameters, ensuring a relative stability in system communication. In particular, Figure 6 highlights the effectiveness of the adaptive filtering algorithm in managing signal processing within challenging environments. As interference intensity rises, the reduction in signal-to-noise ratio is effectively constrained, allowing the communication signal to maintain quality within acceptable limits. This dynamic adjustment mechanism helps the system to maintain robust performance despite fluctuations in the electromagnetic interference levels.

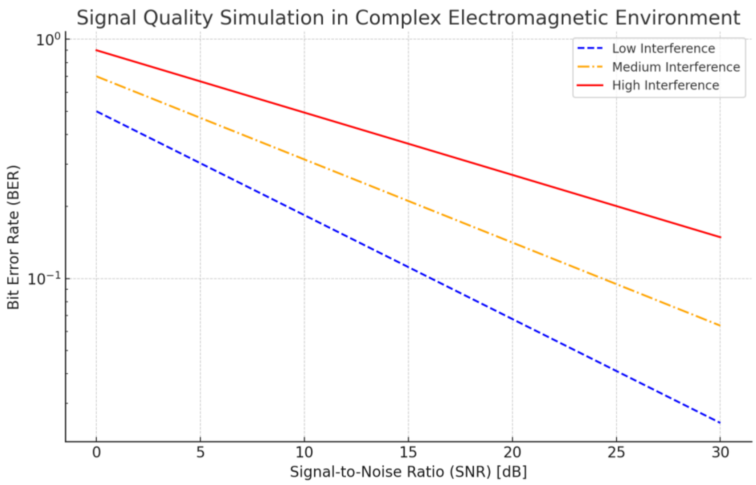

Fig.6 Signal quality performance in complex electromagnetic environment

Figure 7 shows the trend of communication bit error rate during the simulation process. In medium and high intensity interference environments, although the bit error rate increased, the adaptive filtering algorithm effectively slowed down the increase of the bit error rate, making the system communication still have high reliability in harsh environments. These results provide theoretical basis and technical guarantee for future applications in actual flexible DC converter valve control systems.

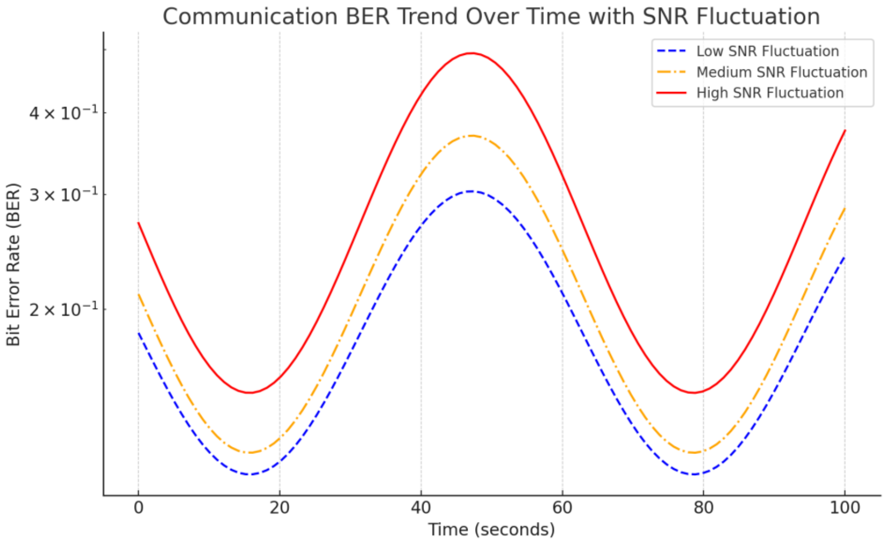

Fig.7 Communication bit error rate change trend in simulation

From these simulation results, it can be seen that the adaptive filtering algorithm can not only perform well in local tests, but also effectively improve the reliability of communication signals in complex system-level simulations. This provides strong support for the application of actual flexible DC converter valve control systems. Especially in industrial environments with complex electromagnetic interference, the quality of communication signals is extremely critical. The application of adaptive filtering algorithms will greatly improve the anti-interference ability of the system and ensure the safe operation of the system.

CONCLUSION

This paper focuses on the communication security issues of flexible DC converter valve control systems and studies the use of advanced signal processing algorithms, especially adaptive filtering algorithms, to improve the communication reliability and anti-interference ability of the system in complex electromagnetic environments. By deeply analyzing the electromagnetic compatibility issues and the impact of different interference sources on communication signals, we propose and verify the effective application of adaptive filtering algorithms in this system.

As the core technology of signal processing, the adaptive filtering algorithm has the ability to dynamically adjust the filtering parameters and can adaptively optimize the characteristics of the filter according to real-time signal changes. Its main advantage is that it can effectively filter out a variety of interference signals in different environments and maintain the stability and reliability of the communication channel. In the flexible DC converter valve control system, the communication signal is often affected by high-frequency electromagnetic interference and random noise in the operation of power equipment. By introducing the adaptive filtering algorithm, the system can quickly identify and suppress these interference signals, significantly improve the communication quality, reduce the bit error rate and data packet loss, and ensure the stable operation of the system in complex environments. The experimental results show that after adopting the adaptive filtering algorithm, the communication anti-interference ability of the flexible DC converter valve control system is significantly enhanced. Compared with the traditional filtering method, the adaptive filtering algorithm shows obvious advantages in real-time, flexibility and accuracy. Its effectiveness is mainly reflected in the following points: First, the adaptive filter can dynamically adjust the frequency response and flexibly respond to interference of different frequencies and types; second, by optimizing the filter design, the signal processing efficiency of the system is improved, thereby ensuring the security and reliability of communication; finally, the adaptive filtering algorithm has a good solution effect on electromagnetic compatibility problems, making the system more anti-interference.

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